DEPOSITIONAL ENVIRONMENTS OF THE ST. PETER SANDSTONE OF THE UPPER MIDWEST

by

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ABSTRACT

The classic St. Peter sandstone, originally interpreted as eolian, has been considered marine since the 1920's. Evidence for both environments is abundant in the Upper Midwest. Two major facies, bedded-to-massive and large-scale cross-bedded are recognized. The large-scale cross-bedded facies has sets up to 10 meters thick separated by bounding surfaces. Near the base of a set, beds parallel the lower surface. Dips increase upward to a maximum of 28 where beds are truncated by an overlying bounding surface. The sand is dominantly fine-grained, but well-sorted lenses and laminae of medium grains are abundant. Sedimentary structures include massive or very thin laminae and adhesion ripples with climbing-adhesion-ripple structures.

Repetitive sequences bounded by flat erosion surfaces characterize the bedded-to-massive facies. The lower part, well-sorted, medium-grained sand in low-angle, parallel laminae and large- to small-scale planar and festoon sets of cross beds, grades upward into finer, less-sorted, massive sand with *Skolithos*.

A third facies was observed in three outcrops at the base of the St. Peter. These exposures consist of sandstone, shale, and indurated claystone with folds and slickensides. This facies is interpreted as a weathering residuum that was post-depositionally altered by local subsidence.

The adhesion structures indicate that the large-scale cross-

bedded facies is eolian. This idea is supported by high-index ripples, displayed as medium-grained lenses with convex tops and flat bottoms in cross-section, which are surrounded by very thin translatent laminae. Grainflows occur as larger lenses with more variable geometry and as thin beds that wedge out down-dip. Fine-grained massive laminae are interpreted as suspension deposits. The bedded-to-massive facies is marine. Skolithos indicates a marine environment in the St. Peter because land animals had not evolved by the Ordovician. The repetitive sequences resulted from episodic erosion and deposition followed by non-deposition and bioturbation. The St. Peter is marine at St. Paul, Minnesota, Mineral Point, Wisconsin, and LaSalle, Illinois. From Madison to Monticello, Wisconsin, the section is entirely eolian. Therefore, reconstruction of pre-Glenwood paleogeography indicates that the Madison-Monticello region was a topographic high. This could reflect pre-St. Peter uplift in eastern Wisconsin. Eolian St. Peter underlies the marine near Dodgeville, Wisconsin so eolian sands were apparently reworked in a marine environment during the Tippecanoe transgression. The Glenwood has abundant evidence of very slow sedimentation which may represent the final inundation of the St. Peter source terrane.

TABLE OF CONTENTS

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INTRODUCTION

The Middle Ordovician St. Peter Sandstone is probably the world's most famous supermature quartz arenite. It overlies the cratonic unconformity at the base of Sloss' (1963) Tippecanoe sequence. In most places, it rests upon the Lower Ordovician dolomites, but it also rests upon Cambrian sandstones locally. It is overlain by the Glenwood and/or Platteville Formations. The upper Midwest outcrop belt extends south and east from the Twin Cities, Minnesota (the type area) to LaSalle, Illinois. The St. Peter wedges out northward in Wisconsin, eastward in Indiana, and westward in Nebraska by erosion. It grades into sandy dolomite in central Kentucky and southern Illinois (Freeman, 1949; Templeton and Willman, 1963). The section thickens toward Missouri with the addition of carbonate and shale beds (Fig. 1), and the St. Peter correlates with part of the Simpson Group of Oklahoma (Dake, 1921; Dapples, 1955). In southwestern Wisconsin and Illinois, it has been divided into three members (from bottom to top): (1) Readstown: sandy clay with shale, sandstone, and chert rubble; (2) Tonti: fine-grained quartz arenite; (3) Starved Rock: medium-grained quartz arenite, which is laterally equivalent to the Glenwood

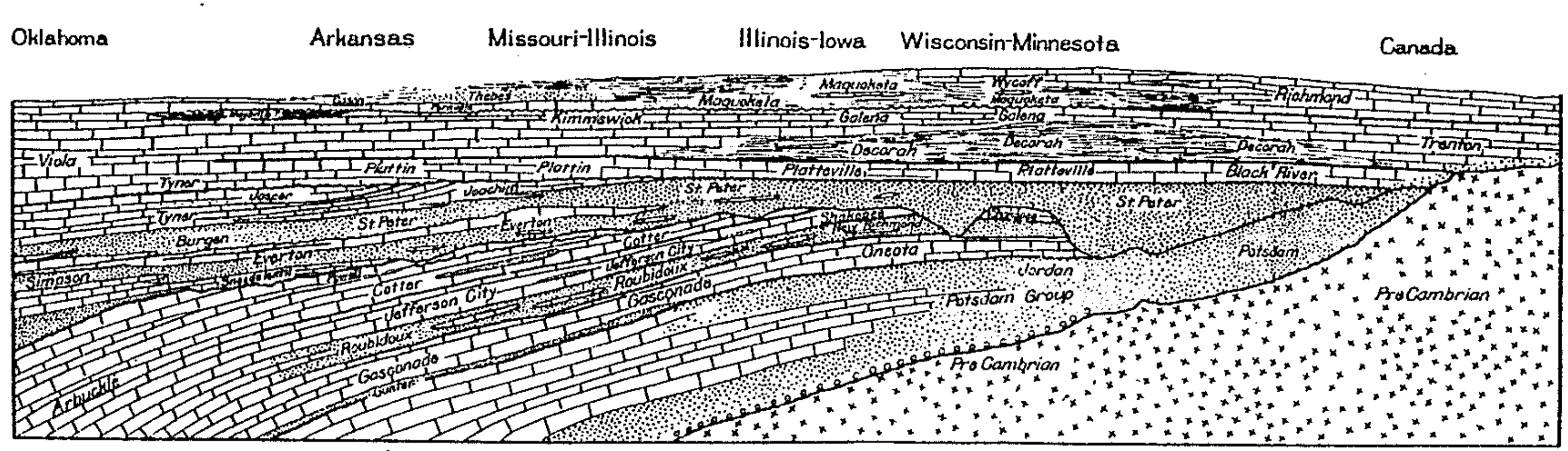
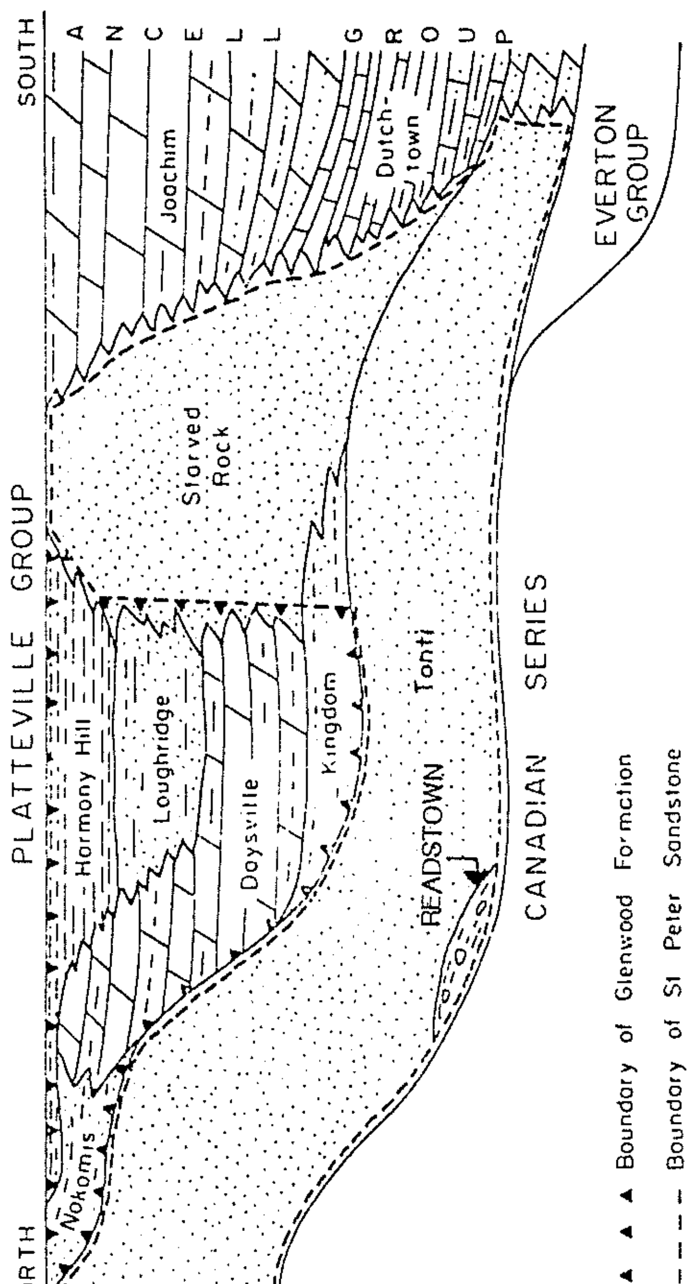


FIGURE 1: Dake's regional cross section. The St. Peter thickens toward Oklahoma with the addition of carbonate beds. Note extreme vertical exaggeration.

Formation (Templeton and Willman, 1963; Ostrom, 1967; Fig. 2).

In 1883, T. C. Chamberlin remarked that "the origin of the formation has been the subject of some diversity." Despite another century of study, mystery persists and the literature records a history of controversy. The greatest controversy concerns the deposition of the St. Peter. Twenhofel and Thwaites (1919) favored a nonmarine origin after they found "residual soils" of the Readstown Member on top of a pre-St. Peter hill. They felt that, in a marine environment, waves would have removed these "soils." Berkey (1906) was one of the first to note the sand's supermature texture and craton-wide extent, and to pronounce it eolian. Good rounding, sorting, and especially frosting of grains were commonly cited as evidence of an eolian origin. Dake (1921), however, argued that the texture was probably inherited, so he rejected all textural arguments. He cited earlier reports of fossils and burrows (Chamberlin, 1883; Sardeson, 1891) as evidence for marine conditions. He also noted that the large-scale cross bedding typical of eolian sands was absent. Dapples (1955) studied regional stratigraphy and expanded on Dake's inference that the St. Peter is a transgressive nearshore deposit. Then the "missing" large-scale cross beds were found in the early seventies in Wisconsin (Pryor

FIGURE 2: Cross section from northern Illinois to southern Wisconsin, which illustrates the members of the St. Peter and the thickness variation in the Glenwood. Note the interfingering of the Glenwood and the Starved Rock Member. Vertical exaggeration is extreme (from Templeton and Willman, 1963).


NORTH
SOUTH
PLATTEVILLE GROUP
ANCELL GROUP
Joachim
Dutch-town
Starved Rock
Harmony Hill
Loughridge
Daysville
Kingdom
Nokomis
Tonti
READSTOWN
CANADIAN SERIES
EVERTON GROUP
Boundary of Glenwood Formation
Boundary of St Peter Sandstone

and Amaral, 1971; Dott and Roshardt, 1972). No other proof of subaerial deposition was recognized, however, and these were interpreted as shallow-marine, sand wave deposits in line with a then-current fashion. Fraser (1976) then claimed that the Starved Rock Member and the Glenwood Formation in Illinois comprise a barrier island-lagoon system (Fig. 2). Recently some authors have reverted to textural arguments based on grain-size analysis (Amaral and Pryor, 1977) and Fourier analysis of grain shape (Mazzullo and Ehrlich, 1980, 1983); but now to prove a marine origin. Finally, in 1980, Dott and Byers discovered adhesion structures in the St. Peter near Madison. These structures are now known throughout south-central Wisconsin, and they prove that part of the St. Peter is eolian. Simultaneously, trace fossils have also been recognized widely, and in Ordovician rocks these are taken to prove a marine origin for other parts of the formation. Seemingly the old-timers were partly right and partly wrong.

FACIES DESCRIPTIONS AND INTERPRETATIONS

In this study, the rocks are grouped into three facies. These are, from the base up: (1) a basal facies consisting of the Readstown and the lowermost Tonti; (2) a large-scale cross-bedded facies; and (3) a bedded-to-massive facies. I shall describe each facies by describing representative outcrops and then interpret the depositional environments. Figures 3-6 are outcrop index maps.

Basal Facies Description

The base of the St. Peter is generally poorly exposed and was observed in only three outcrops. The best exposure is a roadcut on Highway 27, 1.5 miles east of Prairie du Chien, Wisconsin. Massive Tonti sandstone fills a depression over 8 meters deep in the Readstown and Shakopee. Massive, hard, yellow-brown, sandy claystone dips steeply along the undulatory contact. Slickensides found in the claystone parallel the dip of the contact. Folds of sandstone with contorted streaks of hard clay and clasts of silicified oolite form the top of the contact west of the depression. Unbedded sand with clay and some dolomite rubble covers the hillside between the claystone and the Shakopee outcrop. Some of this sand is

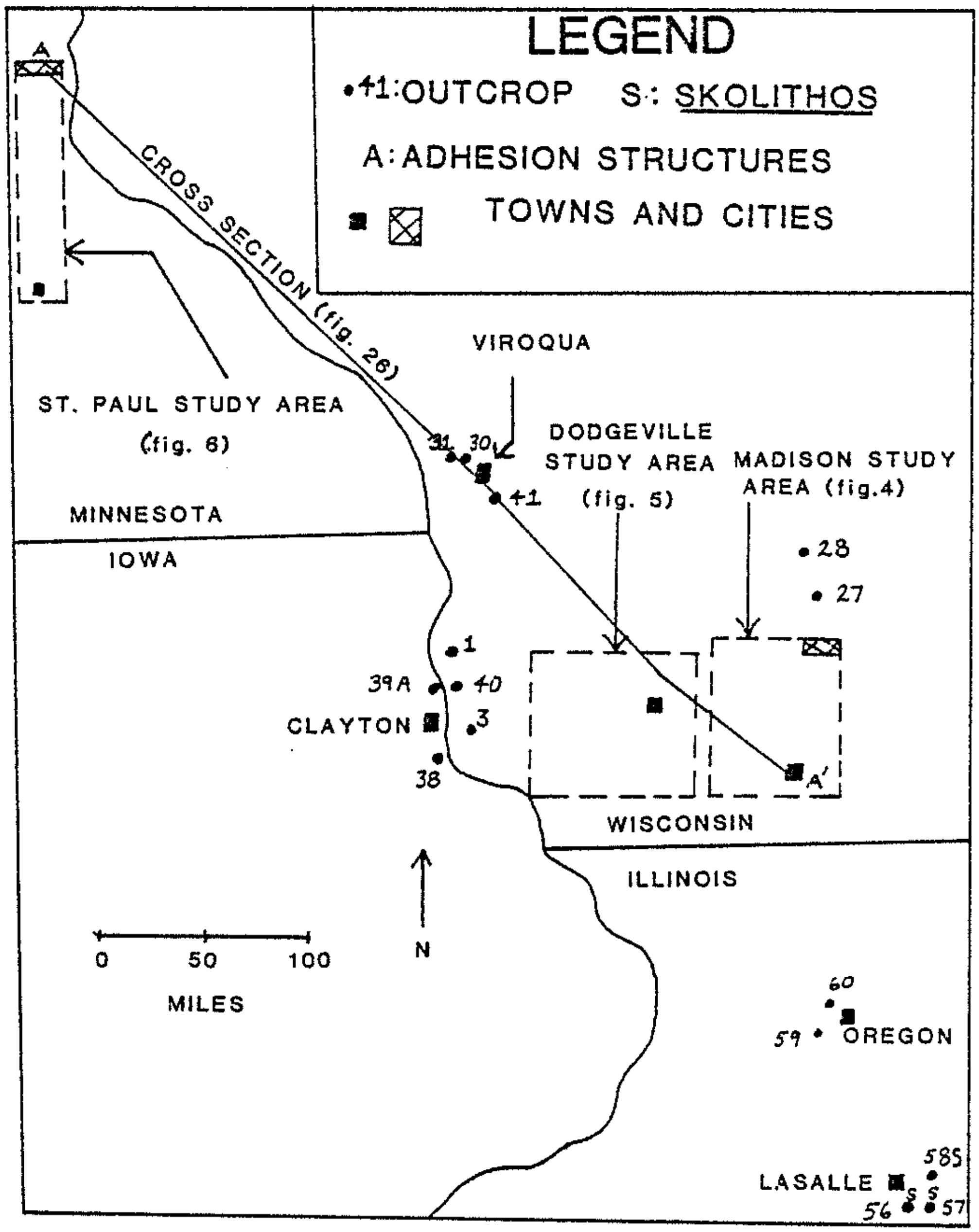


FIGURE 3: Outcrop index map for the upper Midwest. Outcrop numbers correspond to localities listed in Appendix A.

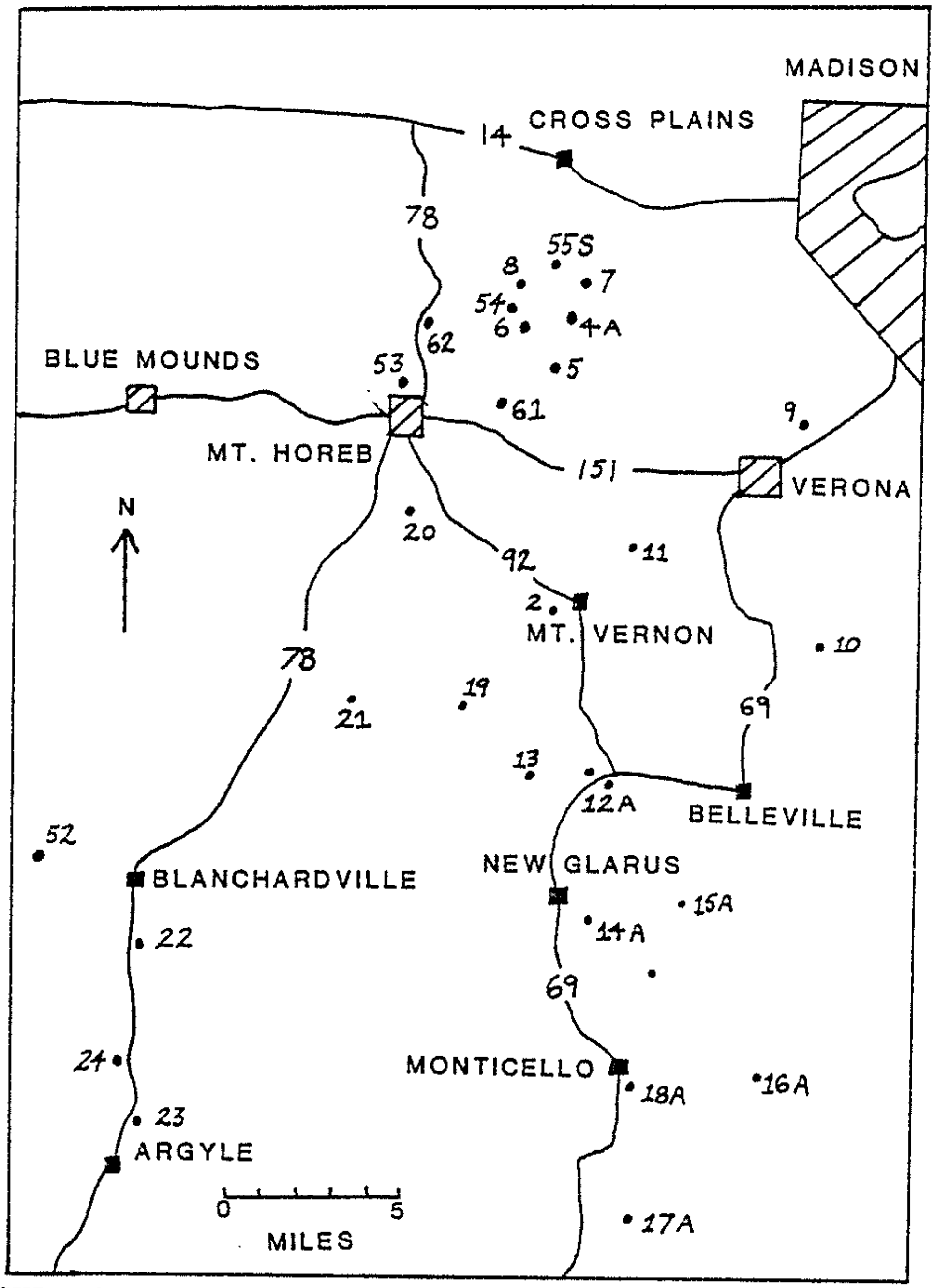
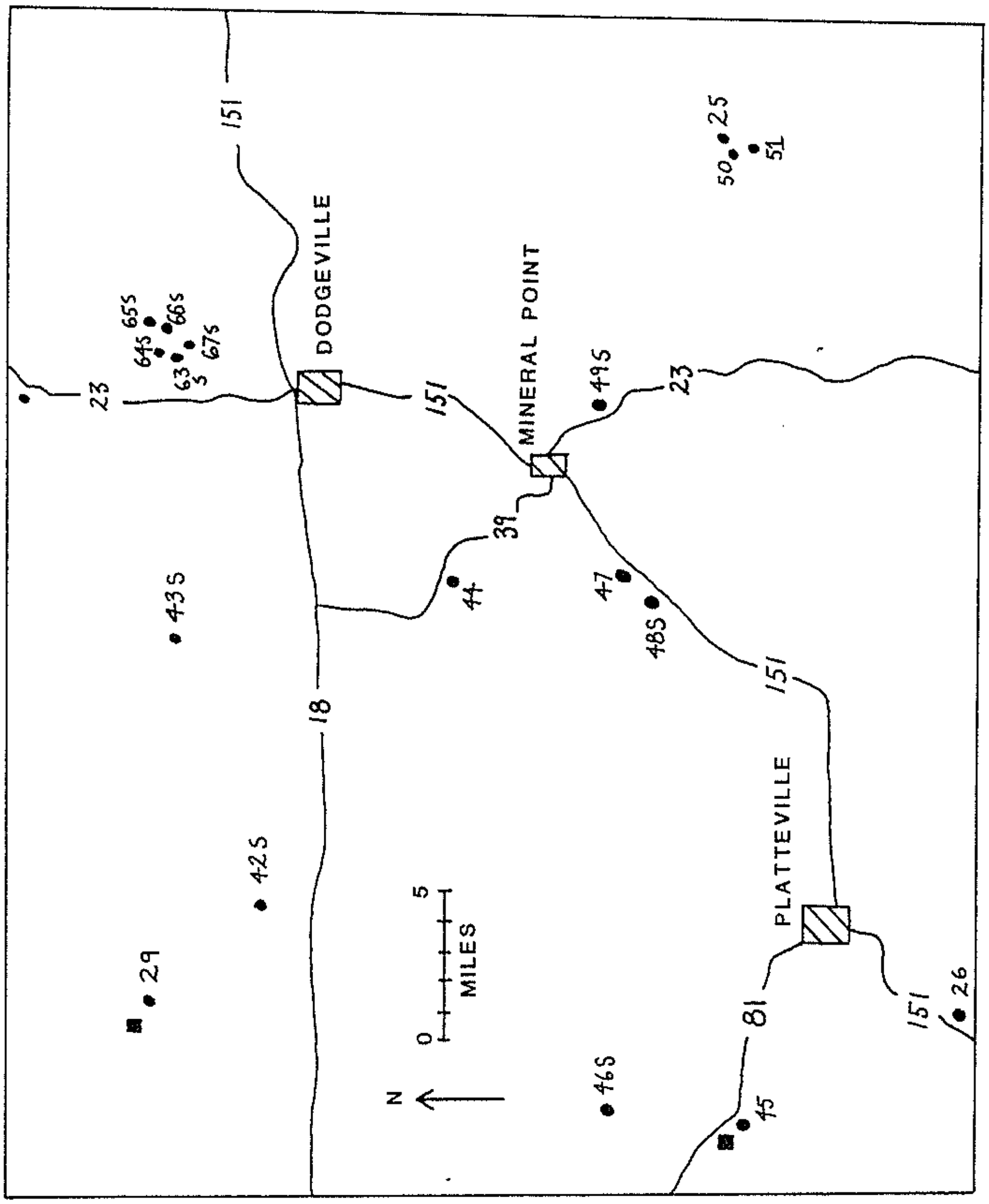


FIGURE 4: Outcrop index map for the Madison study area. See Figure 3 for legend. Outcrops #4-#24 have eolian facies. Outcrops #52-#55 are marine and #61 and #62 have both facies.

FIGURE 5: Outcrop index map for the Dodgeville area. See Figure 3 for legend. Outcrops #25, #26, and #29 have eolian facies. Outcrops #42-#51 are marine and #63-#67 have both facies.


DODGEVILLE
MINERAL POINT
PLATTEVILLE
MILES
0
5
N
151
23
18
39
81
25
50
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42S
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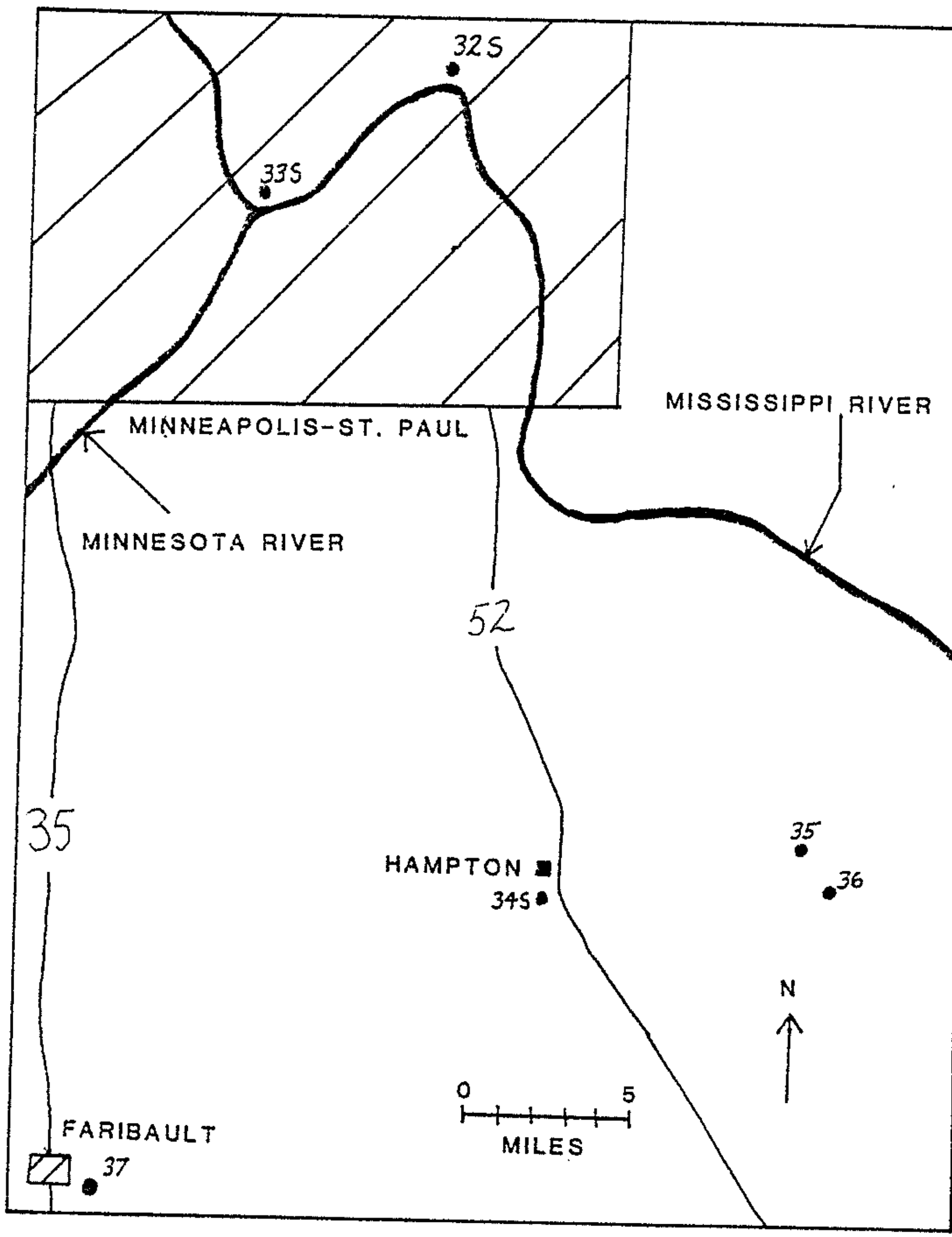


FIGURE 6: Outcrop index map for the St. Paul study area. See Figure 3 for legend. All outcrops are marine.

probably derived from the adjacent New Richmond sandstone, although some is obviously Recent talus derived from the overlying Tonti. Most of the Tonti is massive, but some poorly preserved trough sets of cross bedding can be found higher in the section. These sets are solitary and not laterally extensive. There is no evidence of bioturbation. The lowest Tonti exposure here is about 45 meters below the base of the Platteville.

The basal facies is also exposed above a limestone quarry in the east bluff of the Mississippi River valley southeast of Bagley, Wisconsin. The contact here is relatively flat and the Readstown is less than 1 meter thick. The contact is marked by alternating laminae of silty, fine sand (2-5 millimeters thick) and green clay (2 millimeters thick). The interval is about 0.5 meters thick and there are no folds and no slickensides. The sand and clay are not indurated. The overlying Tonti is white and massive, except for a few isolated trough sets of cross beds about 10 meters above the base. The top of the outcrop appears to be the basal sandstone of the Glenwood, making the St. Peter here only about 15 meters thick.

The third basal outcrop studied is near the top of a roadcut of faulted Prairie du Chien dolomites just west of Mt. Vernon, Wisconsin, on County Highway G. Hard claystone mantles a depression filled with Tonti sandstone, but the Readstown is less than 1 meter thick. Internally, it consists of "plates" about 2 millimeters thick that pinch and swell. No slickensides or folds were found, but the claystone is fractured. The overlying sandstone is well cemented with silica and hematite, especially at the base. One bed of trough sets extends across the top of the otherwise massive outcrop. The sand is medium-grained.

Flint (1956) reported contorted sandstone and sandy shale from the Readstown/Tonti contact, and a thick sandy shale interval with leached chert rubble below the contact. He described drag folds (Flint, 1956, Plate 1) at the contact and faults and shear planes in the Tonti. Several other authors have described similar sediments from outcrops and wells in the upper Midwest (Trowbridge, 1917; Twenhofel and Thwaites, 1919; Thwaites, 1923, 1961; Lamar, 1928; Merriam and Atkinson, 1956; Suter et al., 1959; Buschbach, 1961, 1964).

Basal Facies Interpretation

The following interpretation is not new but is included for completeness. Thwaites (1923), and many others, have called the Readstown a weathering residuum that developed on the Prairie du Chien dolomites. The widespread oolitic chert and noncalcareous clay support this conclusion. The interbedded green clay and quartz sand I saw at Bagley are probably weathering products because selective dissolution of the Prairie du Chien carbonate would produce such deposits. The Prairie du Chien there contains many lenses and thin beds of green clay and quartz sand. While cross bedding is generally absent in the Readstown, it is locally abundant, so some of the residuum was probably reworked by streams (Lamar, 1928).

The Readstown is quite different where it fills depressions in the sub-St. Peter surface. It is thickest there (Suter et al., 1959; Thwaites, 1961), and the folds, slickensides, and indurated claystone only occur near the margins of depressions. Flint (1956) felt that these structures and small-scale faults in the Tonti indicate subsidence following subsurface solution. I found these small-scale faults in the eolian facies only, especially low in the section. Where the marine facies overlies the eolian, the faulting dies out upward. This could indicate that subsurface solution was early. One can imagine a sheet of eolian sand filled with fresh water. Solution could occur in the underlying carbonates until calcium carbonate-saturated marine waters invaded the sand in later St. Peter time. Continued subsurface solution could lead to subsidence of the lower St. Peter to produce the faults and deformed claystone. The base of the Platteville is planar, so subsidence certainly must have stopped by then. The rocks low in eolian sections usually have bands of bright iron stains, which are offset by the small faults. Dake (1921) pointed out that, while there are several generations of iron stains, some are probably related to a water table. The fact that this coloration also fades out upward where the marine facies caps the section supports this suggestion. Trowbridge (1917) reported that the St. Peter in Iowa was brightly colored only where it fills depressions. All of these observations lead me to conclude that the basal facies of the St. Peter is a reworked residuum altered in places by diagenetic effects.

Large-Scale Cross-Bedded Facies Description

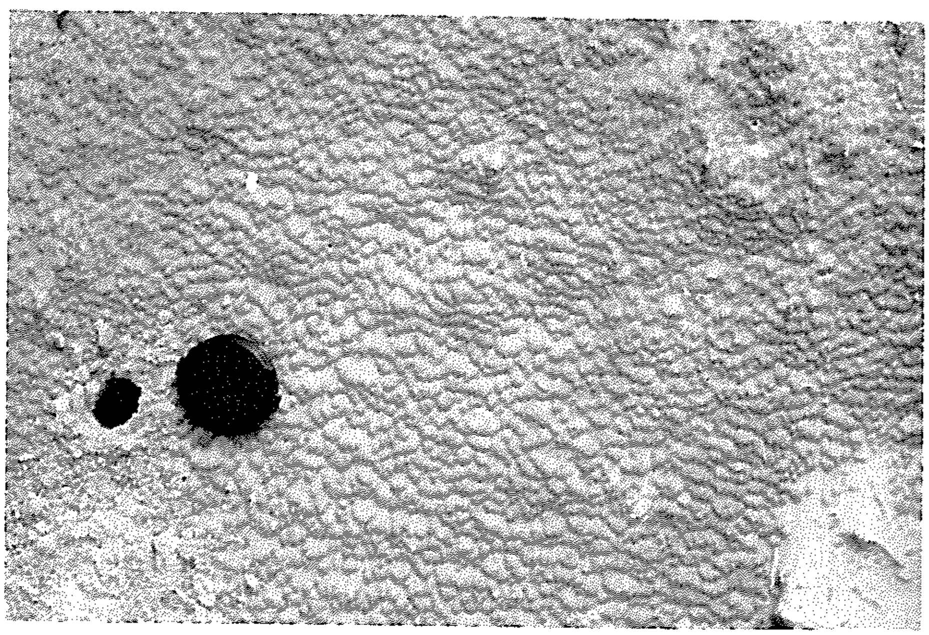
The large-scale cross-bedded facies is exposed throughout southwestern Wisconsin, and adhesion structures have been found throughout the Madison study area (Fig. 4). The best examples (Fig. 7) can be found in a roadcut on County Highway J north of Riley, Wisconsin. This is the outcrop where such structures were first found in the St. Peter. They prove that eolian deposition occurred because they form when wind-blown sand adheres to a moist

FIGURE 7: Adhesion structures in the St. Peter (outcrop #4, Appendix A): a) adhesion ripples (knife is 9 centimeters long); b) climbing-adhesion-ripple structures (scale in centimeters); c) adhesion ripples (right) and climbing-adhesion-ripple structures (left); d) modern adhesion ripples from Sapelo Island, Georgia.

A.

B.

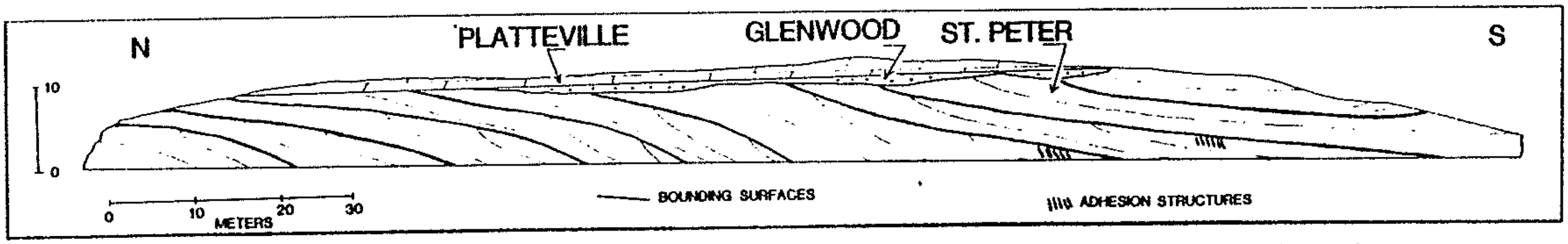
C.



D.

surface. Capillary films of water trap grains on small ridges that have irregular, sinuous crests in plan view. They grow upward into the wind to produce a characteristic internal structure. Kocurek and Fielder (1982) have called the ridges, in plan view, *adhesion ripples* and their internal structure, *climbing-adhesion-ripple structure* (Fig. 7). I will follow their definitions. I shall describe two outcrops of this facies in detail. A long, two-sided roadcut just south of Monticello (Fig. 8A) is the best place to observe the large-scale geometry of the cross beds. A quarry near New Glarus (Fig. 8B) has the best exposures of the small sedimentary structures.

The large-scale cross bedding was first described in detail at the Highway 69 roadcut south of Monticello (Pryor and Amaral, 1971; Dott and Roshardt, 1972). Several large sets are exposed here (Fig. 8). At the extreme north end of the cut the sets have an antiformal geometry plunging northwest, whereas they form a very large trough plunging west on the south end of the west wall. Erosion surfaces that dip from 0° to about 25° define the sets. The surfaces are convex-up in the north part and they become more concave-up southward along the cut until they flatten out into the large trough (Fig. 8A). The apparent thickness of the cross sets also changes along the outcrop. They are thinnest on either end. The spacing of the

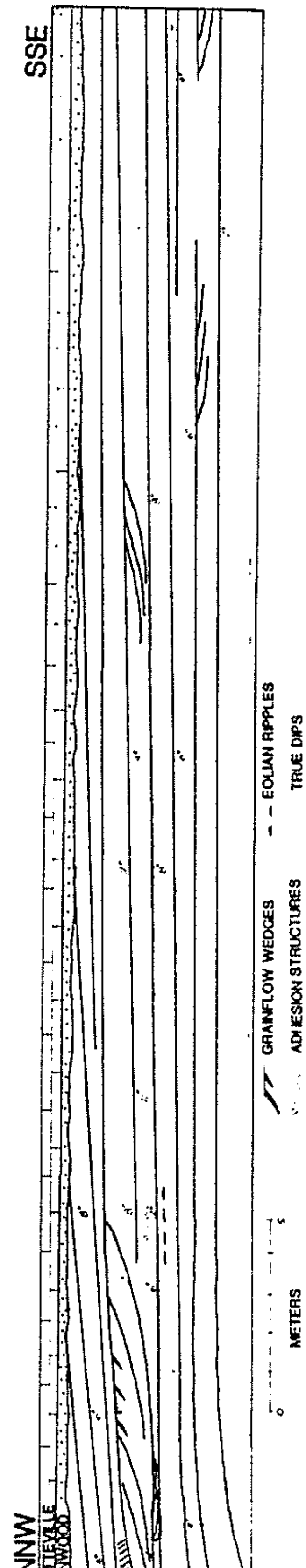


MODIFIED FROM PRYOR AND AMARAL (1971)

A.

FIGURE 8: a) Monticello outcrop diagram (outcrop #18); b) New Glarus outcrop diagram (outcrop #14; see next page)

B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GRAINFLOW WEDGES
ADHESION STRUCTURES
EOLIAN RIPPLES
TRUE DIPS

surfaces is wider near the center of the cut where the sets are up to 15 meters thick, normal to bedding, in the plane of the outcrop. Most internal laminae parallel the dip of their set. Dips are highest at the top of a set where laminae are truncated. I found one dip at 35°, but most are less than 28°. The steep laminae become tangential with the lower parallel laminae down dip (Fig. 9). Adhesion ripples and their climbing structures occur within parallel laminae at Monticello.

Adhesion structures are common in the quarry on the east edge of New Glarus. Figure 8B is a cross section of the top 5 meters of the 27-meter exposure which has sets of climbing-adhesion-ripple structures (Kocurek and Fielder, 1982). These structures resemble small-scale planar sets of cross lamination, but the individual inclined laminae are wavy and irregular in thickness. The set at the north end is surrounded by very thin, parallel laminae just above an erosion surface. This association is typical for this facies. Adhesion ripples can be found on one small rock ledge that crops out of the talus below. Viewed through a hand lens, the sand in adhesion-structure layers appears to have the poorest sorting seen in the outcrop. This is unique in this facies because the other sedimentary structures are sharply defined, well-sorted laminae or lenses.

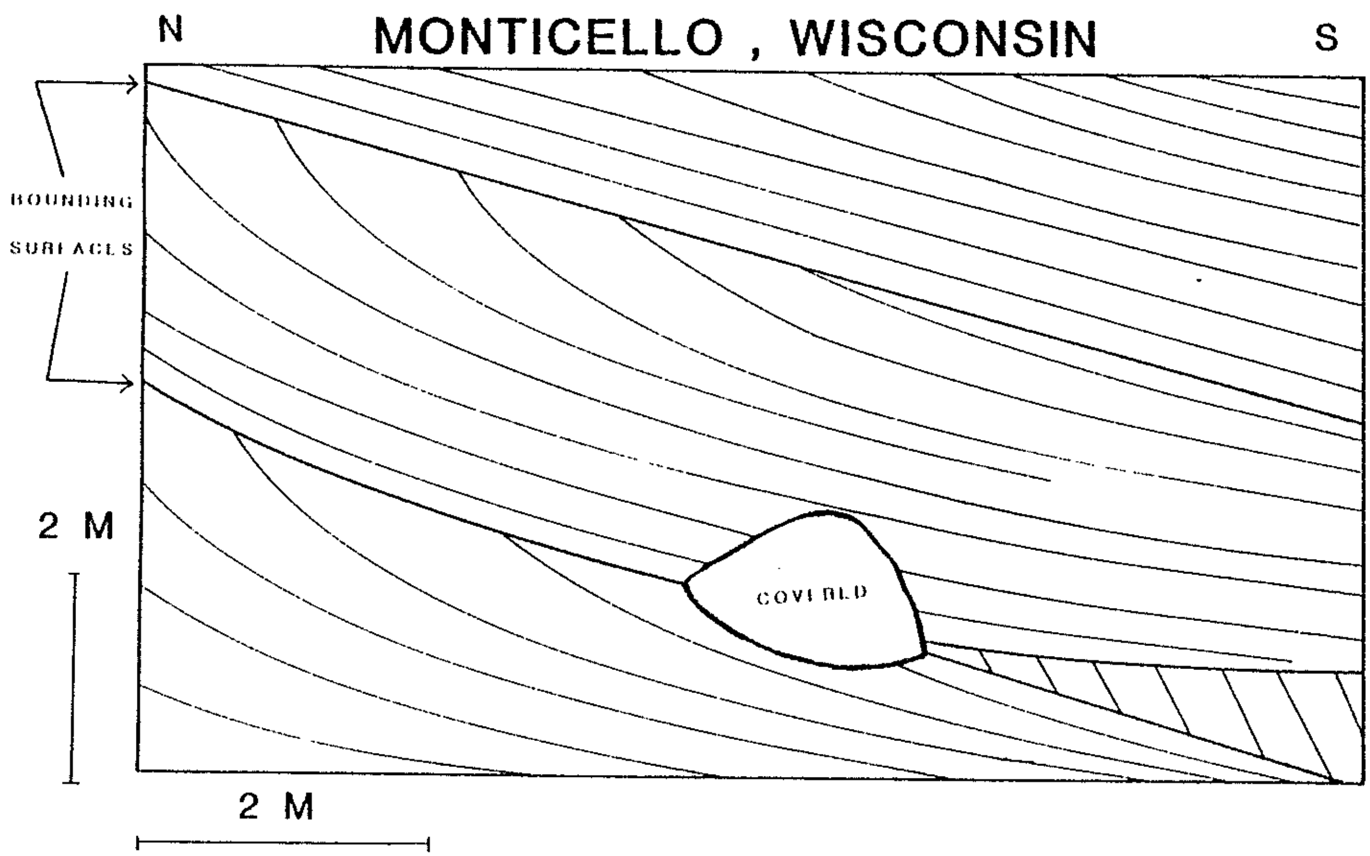
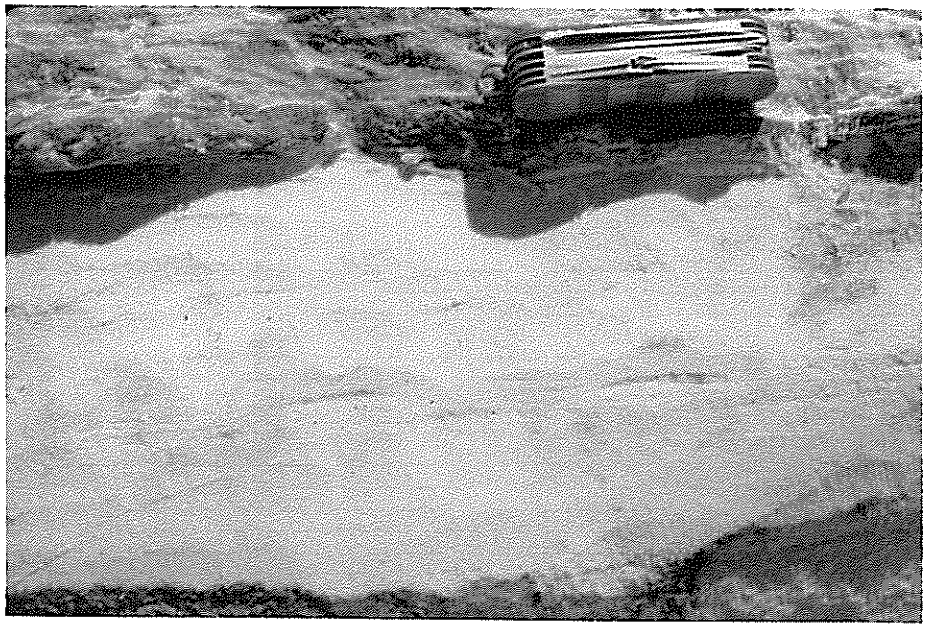


FIGURE 9: Detail of cross beds at Monticello, Wisconsin (outcrop #18, Appendix A). Lower laminae are parallel to the lower bounding surface and upper laminae are truncated by the upper bounding surface.

Small lenses of well-sorted medium grains with convex tops and flat bottoms can be found by careful search in most outcrops of this facies. At New Glarus, these are about 4-5 centimeters wide and 2-3 millimeters high. The medium grains of these lenses are the coarsest in the outcrop. These lenses are thought to be eolian ripple cross sections (Fig. 10), and the best examples are grouped near the north end of the outcrop (Fig. 8). The surrounding layers are of two general types: (1) very thin alternating layers of fine and medium grains and (2) massive strata dominated by fine grains. The very thin laminae are sharply defined and less than 1 millimeter thick. The massive strata have variable thickness, and they often contain thin, faint segregations of medium grains. The massive and very thin laminae comprise more than 90% of this outcrop, and they dominate the facies in general.

Other "patches" of medium grains can be found in the quarry's vertical section. These have a more varied size and shape than the lenses I just described. However, most are roughly lenticular and 3-8 centimeters wide. Others have flat or wavy tops and concave-up or flat bottoms. The largest one I saw has a sheet-like geometry, and is about 1 meter wide and 2 centimeters thick. It has an irregular base with up to 4 millimeters of relief.

FIGURE 10: Eolian ripple cross sections at New Glarus, Wisconsin (outcrop #14, Appendix A): a) "train" of ripple cross sections; note adhesion structures to the left of knife (scale is in centimeters); b) close-up of ripple cross section; cross section is composed of medium grains.



A.

B.

These lenses occur as individuals or in groups. They are separated and mantled by massive fine-grained strata. These "patches" are probably cross sections of medium-grained massive laminae that also occur here as wedges that thin and pinch out down dip where the surrounding laminae become tangential with the lower parallel laminae (Fig. 11). These wedge laminae have the steepest dips, are always truncated, and are somewhat rare. They are interpreted as grainflows (Hunter, 1977) that formed as sand avalanched down an oversteepened slipface.

I measured several pairs of apparent dips and concluded that most of the laminae dip to the east or northeast (into the outcrop). True dips range from 0°-30°. The low apparent dips indicate that this is a strike section of a large bedform or a superimposed set of bedforms. The trough-shaped sets here are not as laterally extensive as those at Monticello.

Most exposures of the large-scale cross-bedded facies are in the Madison region, but similar outcrops have been found from Viroqua, Wisconsin, to Oregon, Illinois. Some of these exposures are notable because they illustrate minor facies elements or because they are problematic. Small- to medium-scale trough sets of cross beds are rare in this facies, but I found a few examples. There is one 30-centimeter-thick bed about half way up the New Glarus

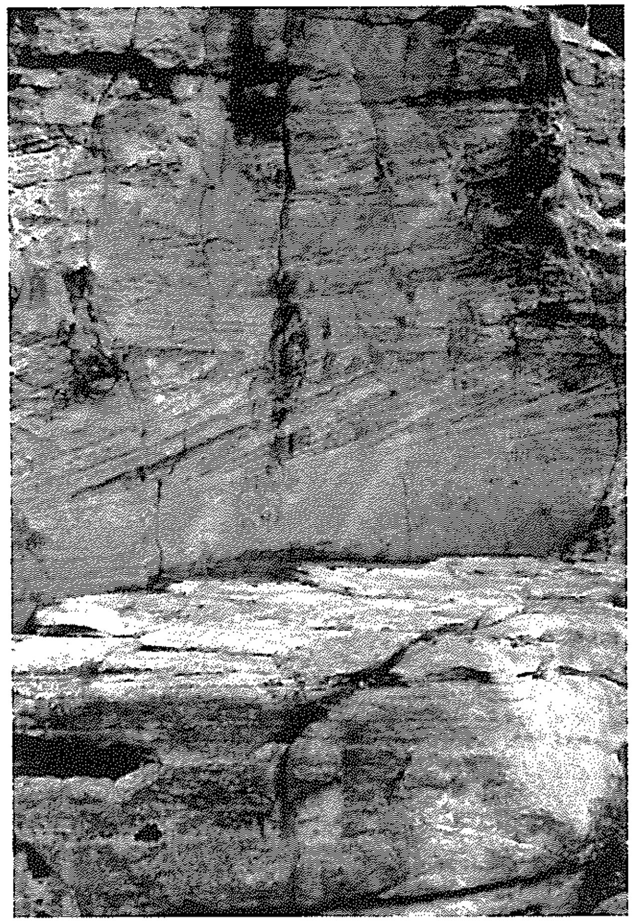
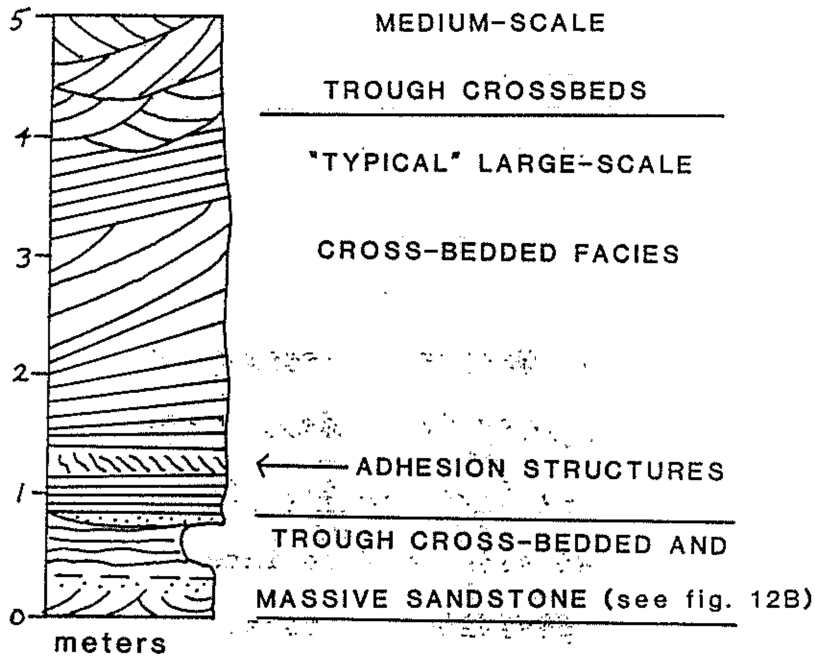


FIGURE 11: Grainflow laminae at Three Chimneys, near Viroqua, Wisconsin (outcrop #30, Appendix A).

quarry with small troughs. It can be traced laterally about 30 meters. The sandstone is fine to medium and well cemented with iron oxide. A roadcut 2 miles north of Argyle on Highway 78 has two zones of trough sets (Fig. 12). The first is at the base and contains small-scale festoon troughs. This is succeeded by a lens of fine to medium sand, 5-15 centimeters thick, which has several large, horizontal, elongate pores with flat roofs and floors (laminoid fenestral porosity?). Above this is an interval of mottled brown and white fine sand and silt with very crude bedding. This is capped in part by a lens of medium sand with a maximum thickness of 8 centimeters. These last two units are truncated by parallel-laminated white sand with one layer of adhesion structures. The second trough zone occurs about 2 meters above the adhesions. The troughs are small- or medium-scale. The lower interval of trough sets and the associated thin lenses may belong to the Readstown Member. Stratigraphic control is not good enough here to prove it. Adhesion structures also occur in an outcrop north of Clayton, Iowa, which is not typical of this facies. Massive sandstone is abruptly overlain by medium-scale trough sets, which grade upward into horizontal parallel laminae (Fig. 13). The adhesion structures overlie the parallel laminae and underlie large-scale trough sets.

A.


5
4
3
2
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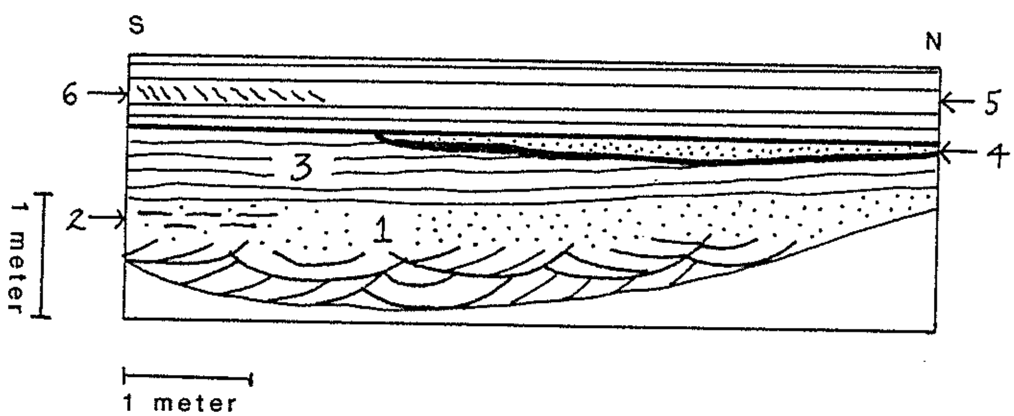
meters
MEDIUM-SCALE
TROUGH CROSSBEDS
"TYPICAL" LARGE-SCALE
CROSS-BEDDED FACIES
ADHESION STRUCTURES
TROUGH CROSS-BEDDED AND
MASSIVE SANDSTONE (see fig. 12B)

B.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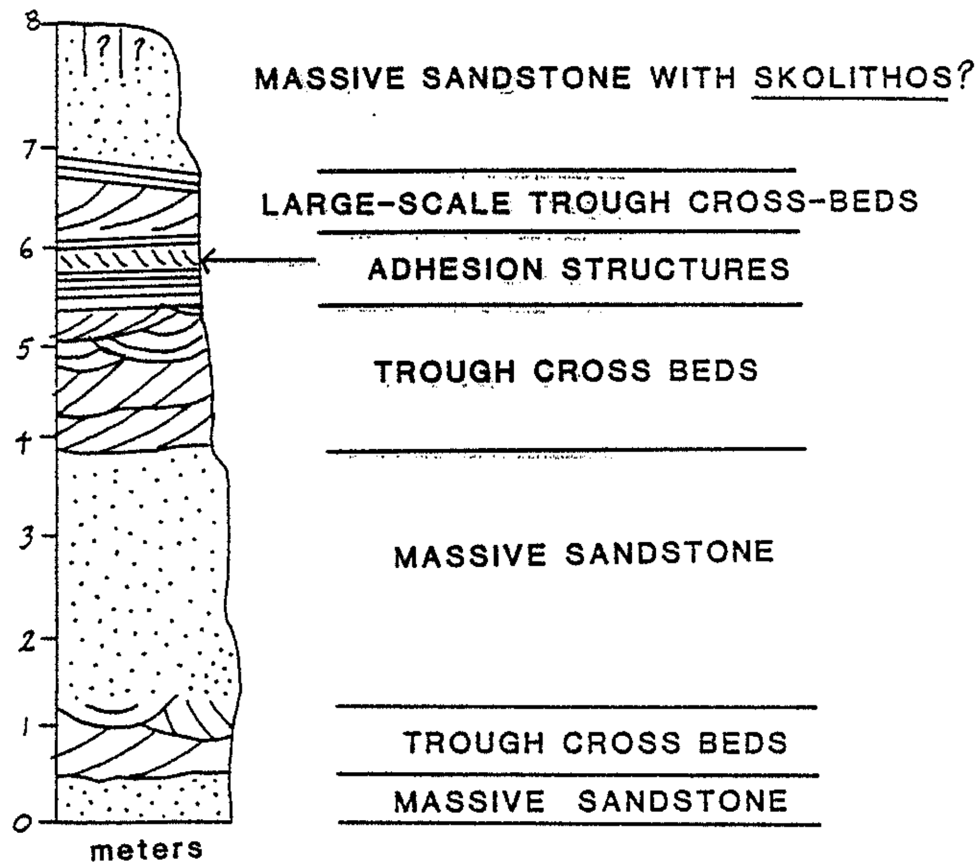


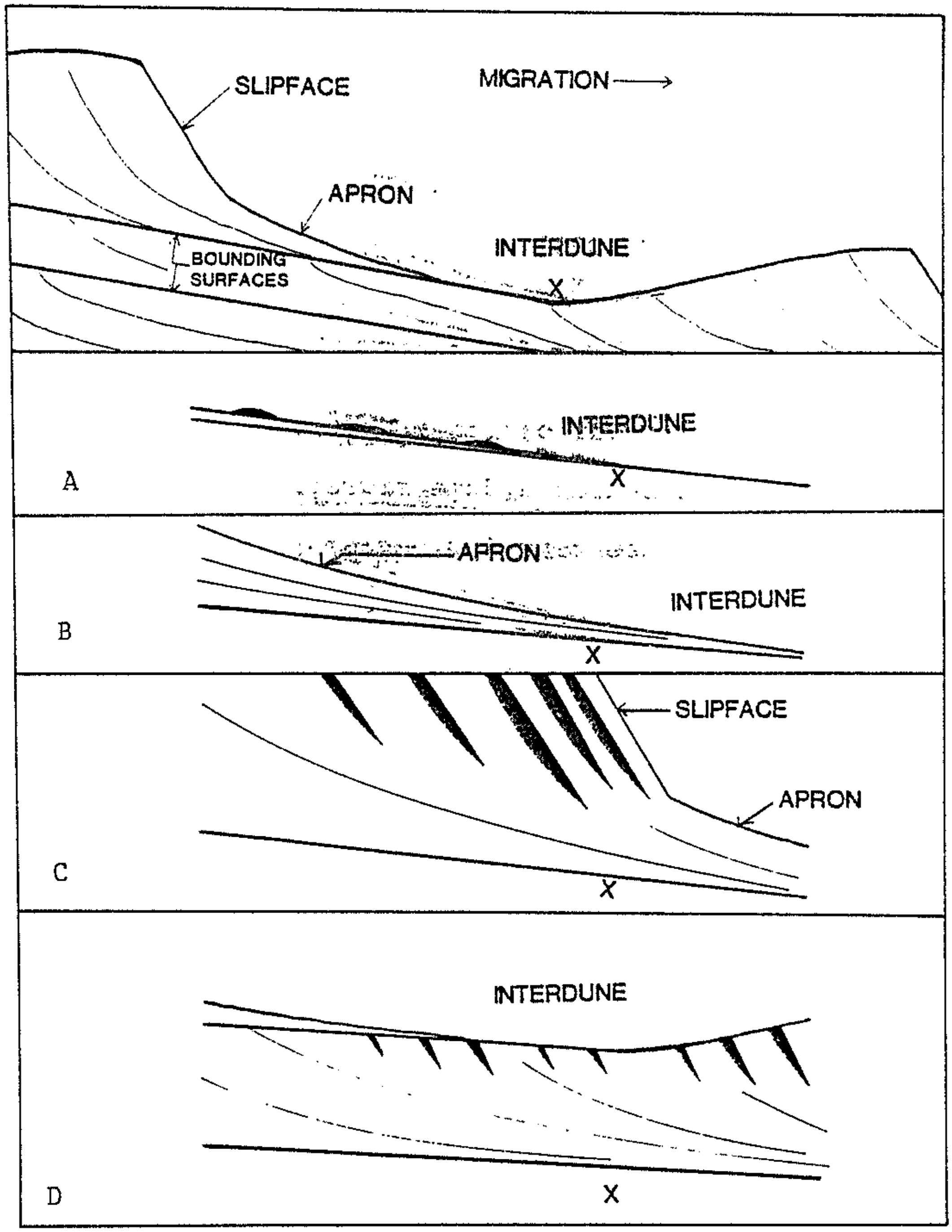
FIGURE 13: Measured section of roadcut north of Clayton, Iowa (outcrop #39, Appendix A).

This outcrop is problematic because it does not fit any of the facies conveniently.

Large-Scale Cross-Bedded Facies Interpretation

Adhesion structures were first described by Reineck (1955) from the German tidal flats. They have been studied in recent environments and wind tunnels (Hunter, 1973; Kocurek and Fielder, 1982). In eolian sandstones, they are most commonly associated with interdune and lower lee face deposits (Glennie, 1972; Kocurek, 1981). They are the only structures that prove eolian deposition in the St. Peter. This leads to the question: Is the rest of the sandstone in this facies of an eolian origin, too? I shall argue that most of it is because the large-scale cross-set geometry and small sedimentary structures are consistent with modern eolian deposits.

The large-scale geometry and relation of cross beds to erosion surfaces at Monticello is the result of the migration of a very large bedform with smaller bedforms superimposed on it. The cross beds are defined by the erosion surfaces, which are interpreted as bounding surfaces. Bounding surfaces form as surfaces of truncation when a series of bedforms migrates together (Brookfield, 1977). I interpret the cross beds to be the deposits of individual dunes and the bounding surfaces to be the migrating interdune areas. This interpretation is based on (1) the configuration of the bounding surfaces; (2) the parallel laminae at the base of the set; (3) the upward increase of dips in the set; and (4) the uppermost, truncated laminae (Fig. 9). The laminae and the surfaces dip the same direction, therefore the dunes migrated down a slope (Fig. 8A). Figure 14 illustrates the deposition of a set as a dune moves past a point. Sand is deposited on the slope upwind of the interdune (Fig. 14A) to produce the lower parallel laminae. Adhesion structures in these laminae show that some of the interdunes were wet sometimes. As the dune migrates, the apron of grainfall and translatent laminae moves over the lower parallel laminae (Fig. 14B). This is recorded in the upward increase of dip. The laminae on top of the apron form on a steeper slope than those at the base of the set. When the slipface arrives at this point, grainflow tongues are deposited near the angle of repose (Fig. 14C). Most of the sand in the dune is then removed as the dune migrates (Fig. 14D) to form the truncated laminae at the top of the set (Fig. 15). These sets are similar to Hunter's (1977, Fig. 10) "cyclic sets of cross strata," and both Horne (1971) and Piper (1970) have described similar sets from the ancient.


SLIPFACE
MIGRATION
APRON
INTERDUNE
BOUNDING SURFACES
X
A
INTERDUNE
X
B
APRON
INTERDUNE
X
C
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D
INTERDUNE
X

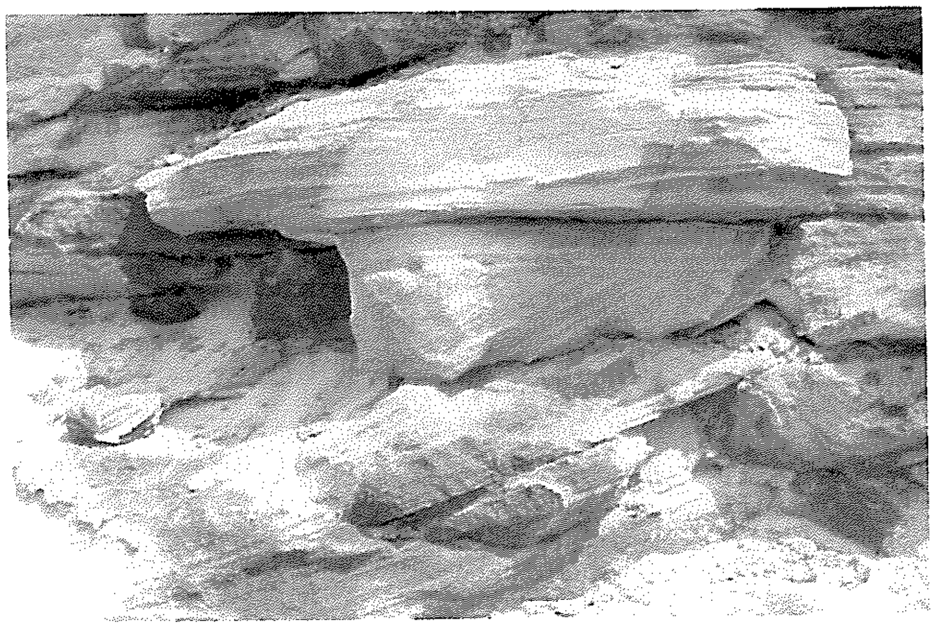
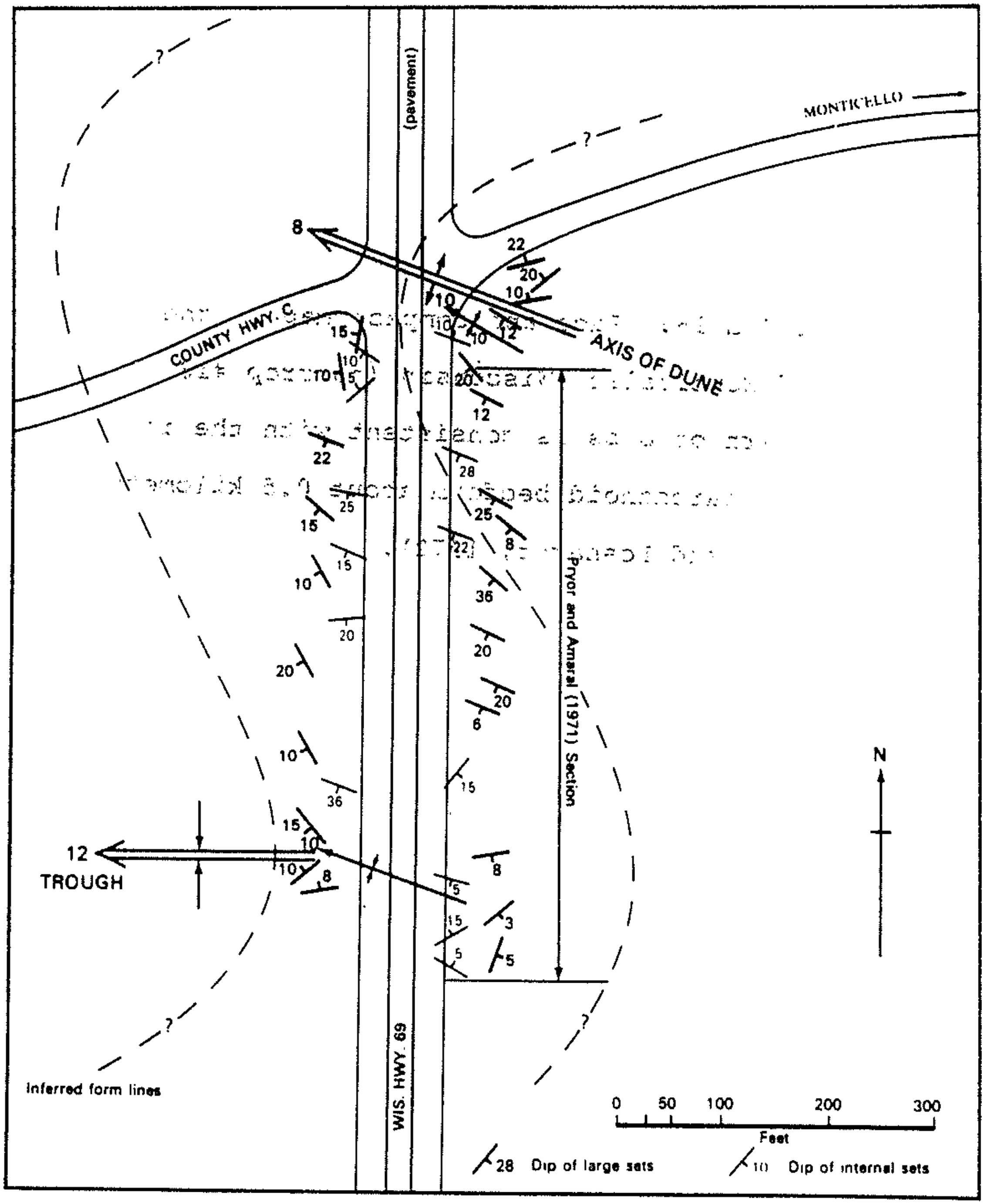


FIGURE 15: Bounding surface at New Glarus (outcrop #14, Appendix A). Note parallel laminae above and truncated laminae below the surface.

Dott and Roshardt (1972) showed that the pattern of dips at Monticello reveals a large barchanoid bedform (Fig. 16). The spacing of the bounding surfaces confirms this. Near the horn (north end) the surfaces are closely spaced. The spacing is wider on the south end. This reflects greater sand transport over the trough area of the bedform than over the horn. The widest spacing occurs in the center where the plane of the outcrop is oblique to the crest of the bedform. This makes the sets look thicker than they actually are. These relations of large-scale geometry, dune deposits, and bounding surfaces indicate the presence of a barchanoid draa with superimposed dunes. There is no way to tell if this was a solitary bedform or if it was part of a sinuous-crested sand ridge. Brookfield (1977) has discussed this style of sedimentation and Wilson (1973) published a photo of a barchanoid draa from a modern erg.

The small sedimentary structures are typical of modern eolian deposits. The small lenses of medium grains have the proper shape and grain size to be eolian ripple-cross sections (Bagnold, 1941; Sharp, 1963). Sharp (1963) impregnated modern ripples and found "pile(s) of relatively coarse sand" as cross sections. At New Glarus, four of these form a train. The ripples appear to have a very low climb angle. Ripple indices on these range from



MONTICELLO
(pavement)
COUNTY HWY. C
AXIS OF DUNE
Pryor and Amaral (1971) Section
TROUGH
WIS. HWY. 69
N
Inferred form lines
0 50 100 200 300
Feet
28 Dip of large sets
10 Dip of internal sets

30-80 (Fig. 17). These numbers are well within the postulated range for wind ripples (Sharp, 1963), and far above that postulated for water ripples (less than 15-20). The existence of definite ripples implies that the very thin laminae are eolian translatent strata (Hunter, 1973). The characteristic inverse grading was not observed in these, but Fryberger and Schenk (1981) made translatent laminae in a wind tunnel that were not graded. Even so, the parallel alternation of very thin laminae of medium and fine grains is consistent with ripple migration (Fig. 17; Fryberger and Schenk, 1981). The medium grains represent the ripple crests that crept over the fines of the preceding trough. The "patches" of medium grains with variable shapes are interpreted as strike sections of grainflow tongues (Fig. 18). They form as sand avalanches down the oversteepened lee face of a dune (Hunter, 1973). The steep laminae that pinch out down dip are grainflows in dip section. The fine-grained, massive laminae are suspension deposits (grainfalls) because they drape grainflows. The faint patches of medium grains in these laminae are probably incipient ripples which were buried by grainfalls.

Two other questions are relevant here. First: Are the outcrops of this facies that lack adhesion structures also eolian deposits? I will argue that they are because

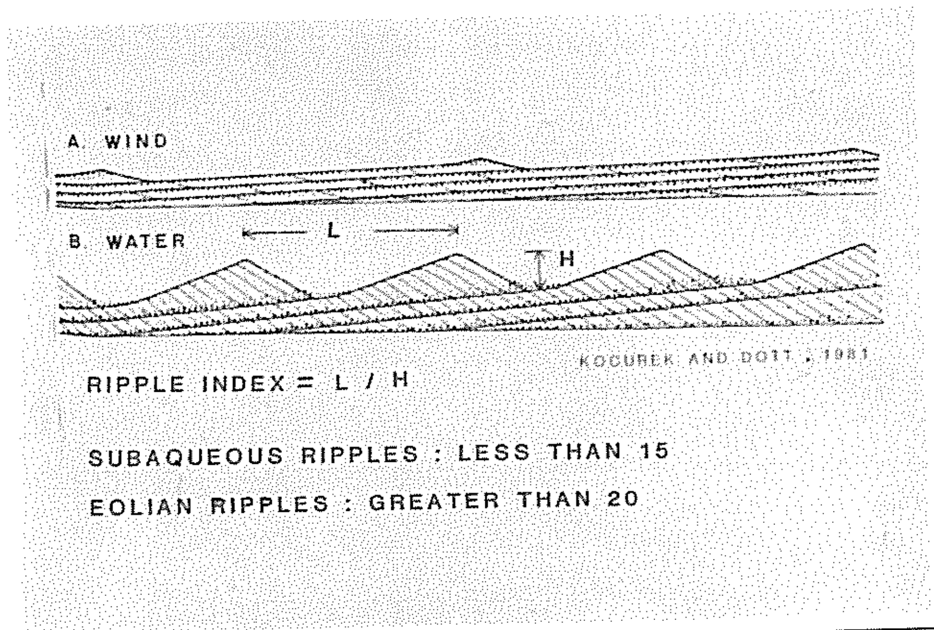


FIGURE 17: Comparison of eolian and subaqueous ripples. Coarse grains concentrate in the troughs of subaqueous ripples and on the crests of eolian ripples (modified from Kocurek and Dott, 1981).

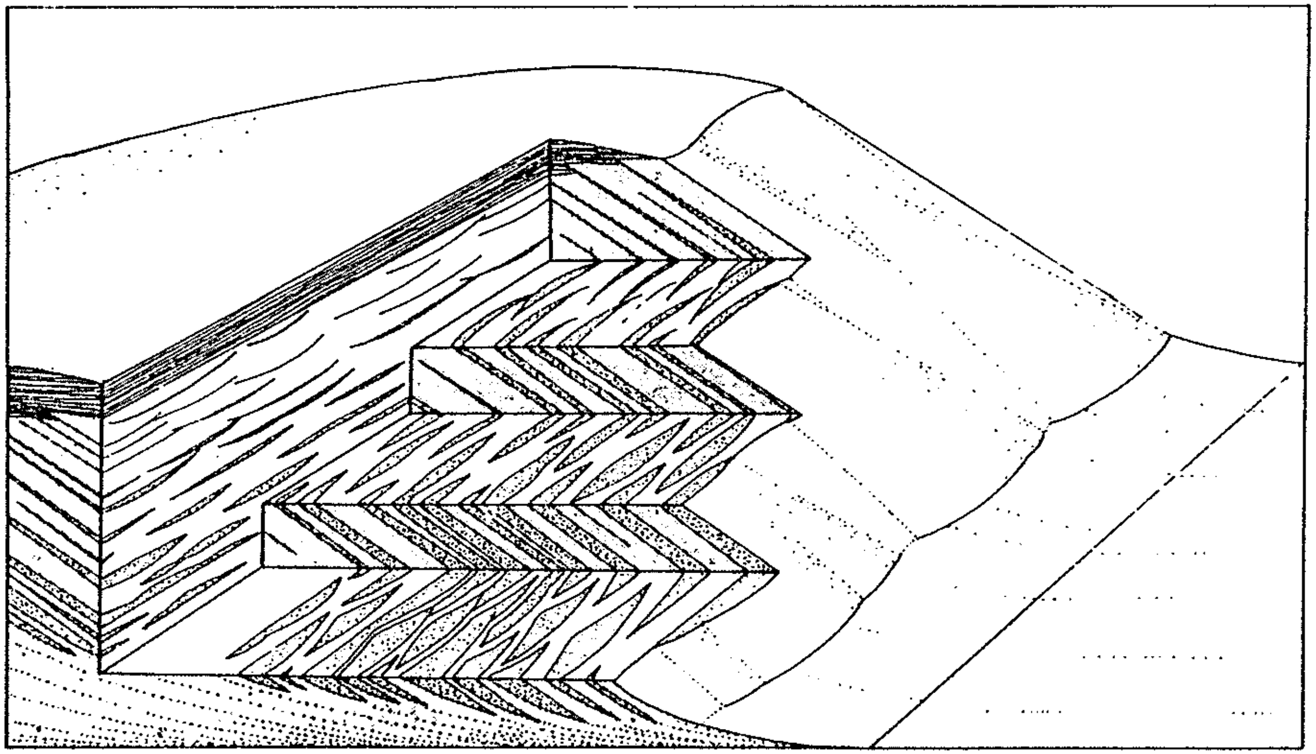


FIGURE 18: Block diagram to illustrate the three-dimensional geometry of grainflows. Notice how they appear as lenses in strike section and as wedges in dip section (from Hunter, 1977).

they are so similar to the proven eolian outcrops. There are counterparts of inferred translatent, grainflow and grainfall laminae; the only thing missing is the adhesion structures. These structures probably occur where they cannot be recognized (Kocurek and Fielder, 1982). Layers of adhesion structures have disappeared at New Glarus since the first time I visited there in June 1982. Weathering processes cement loose sand over the face of some outcrops. The only evidence of bioturbation is at the very top of this facies. A complete lack of bioturbation, although negative evidence, suggests nonmarine environments because land organisms had not evolved by the Ordovician. Large-scale cross beds occur in the marine facies, but they are associated laterally with smaller-scale trough sets and planar beds (Fig. 22). The internal structures of shallow-marine sand waves, as postulated by Allen (1980), do not match those of this facies. Secondly, how do the rare small- and medium-scale trough sets of cross beds fit into an eolian depositional scheme? These sets consist of cross strata that extend down to the basal scour of the set. These strata, compared to eolian grainflows, are less sharply defined and in contact with each other. This suggests near-continuous avalanching, which is characteristic of subaqueous deposition (Hunter, 1976), and these sets are identical to some in the proven marine facies. However, no bioturbation structures are found with these in the eolian facies so they are regarded as fluvial or wet-interdune deposits. At New Glarus, a bed of adhesion structures occurs right above such trough sets. The basal beds of the roadcut north of Argyle (Fig. 12) have fenestral porosity in sand above subaqueous troughs. If this porosity is primary, which is debatable, it could indicate algal mats in a wet interdune area. Adhesion structures occur above these beds, too. The vertical association of subaqueous structures, possible fenestral porosity, and adhesion structures Kocurek's (1981, Fig. 23) ideal drying-up sequence.

Bedded-to-Massive Facies Description

The bedded-to-massive facies consists of repeated packages of sand bounded by relatively flat erosion surfaces. It contrasts with the eolian facies because small- to large-scale trough sets dominate the physical structures and because burrows and biogenic structures are abundant. The basal Glenwood formation will be included in the following discussion because the St. Peter-Glenwood contact is gradational in this facies. I shall again describe specific outcrops.

The type section of the St. Peter is in the bluffs of the Mississippi River valley at the mouth of the Minnesota River (Fig. 6). Throughout the St. Paul area, it is dominated by beds of massive sand 2-3 meters thick, which are separated by erosion surfaces (Fig. 19). Well-preserved physical structures make up less than 5% of the section here. Short, irregular surfaces are common low in the massive zones. These might be relict physical structures. In downtown St. Paul, one thin bed of festoon trough sets overlies an erosion surface about 8 meters below the basal Platteville. The bedding fades out upward into massive, less sorted sand with *Skolithos*. The trace fossils are preserved here as vertical, cylindrical holes, which are commonly iron-stained (Fig. 20). They are commonly truncated by erosion surfaces. Just west of downtown, at the Watergate marina, no bedding is exposed. The sand is massive and *Skolithos* can be found throughout the section. The erosion surfaces are not as conspicuous as they are downtown. These minor differences may be due either to lateral changes in sedimentation or to changes in weathering of the outcrops. *Skolithos* and massive sand were found in the St. Peter throughout southeastern Minnesota, so these two sections are considered representative of that region.

Exposures of the massive facies in the Dodgeville, Wisconsin (Fig. 5), region shows the same pattern of

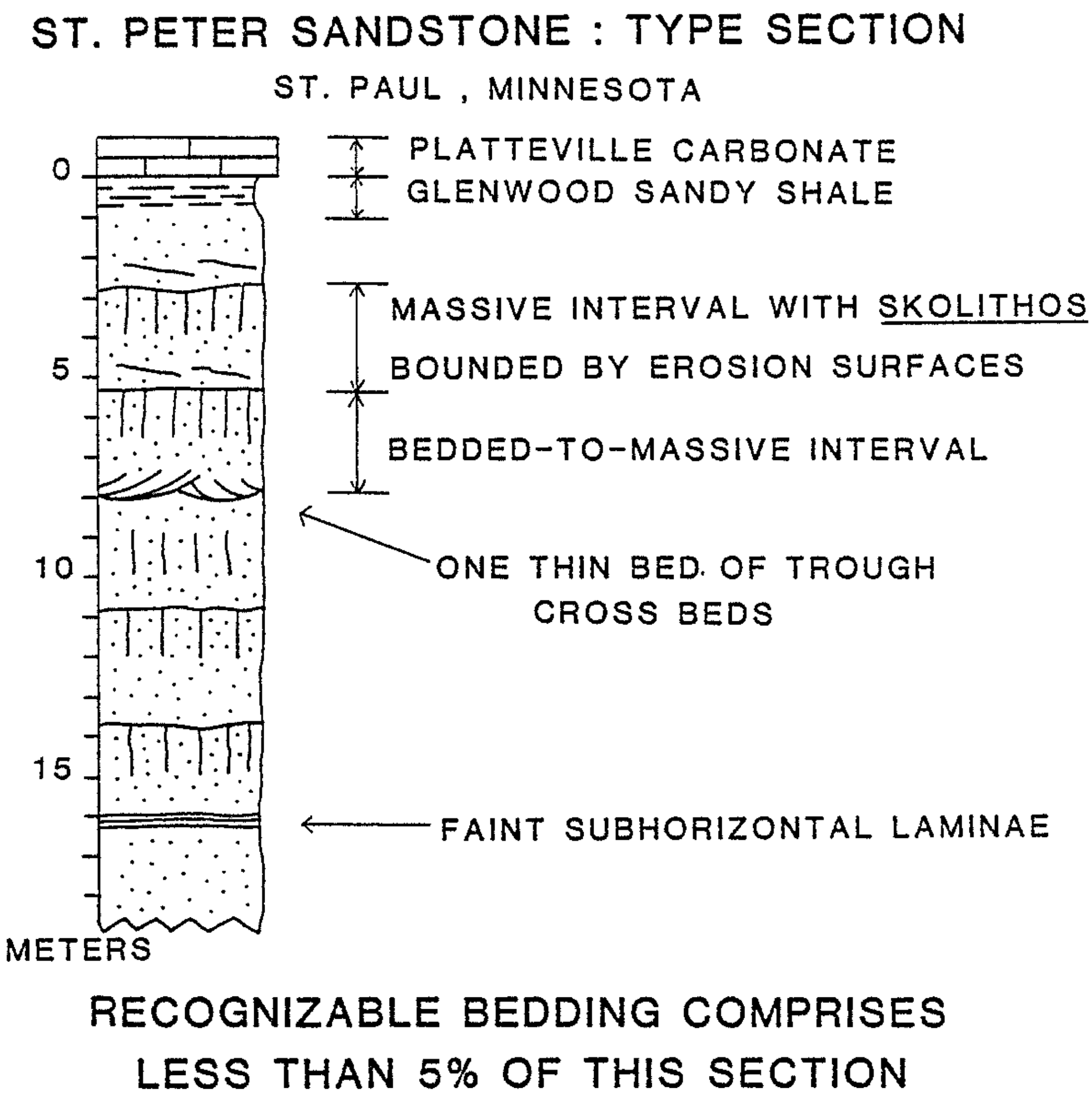


FIGURE 19: Measured section at St. Paul, Minnesota (compiled from outcrops #32 and #33, Appendix A).

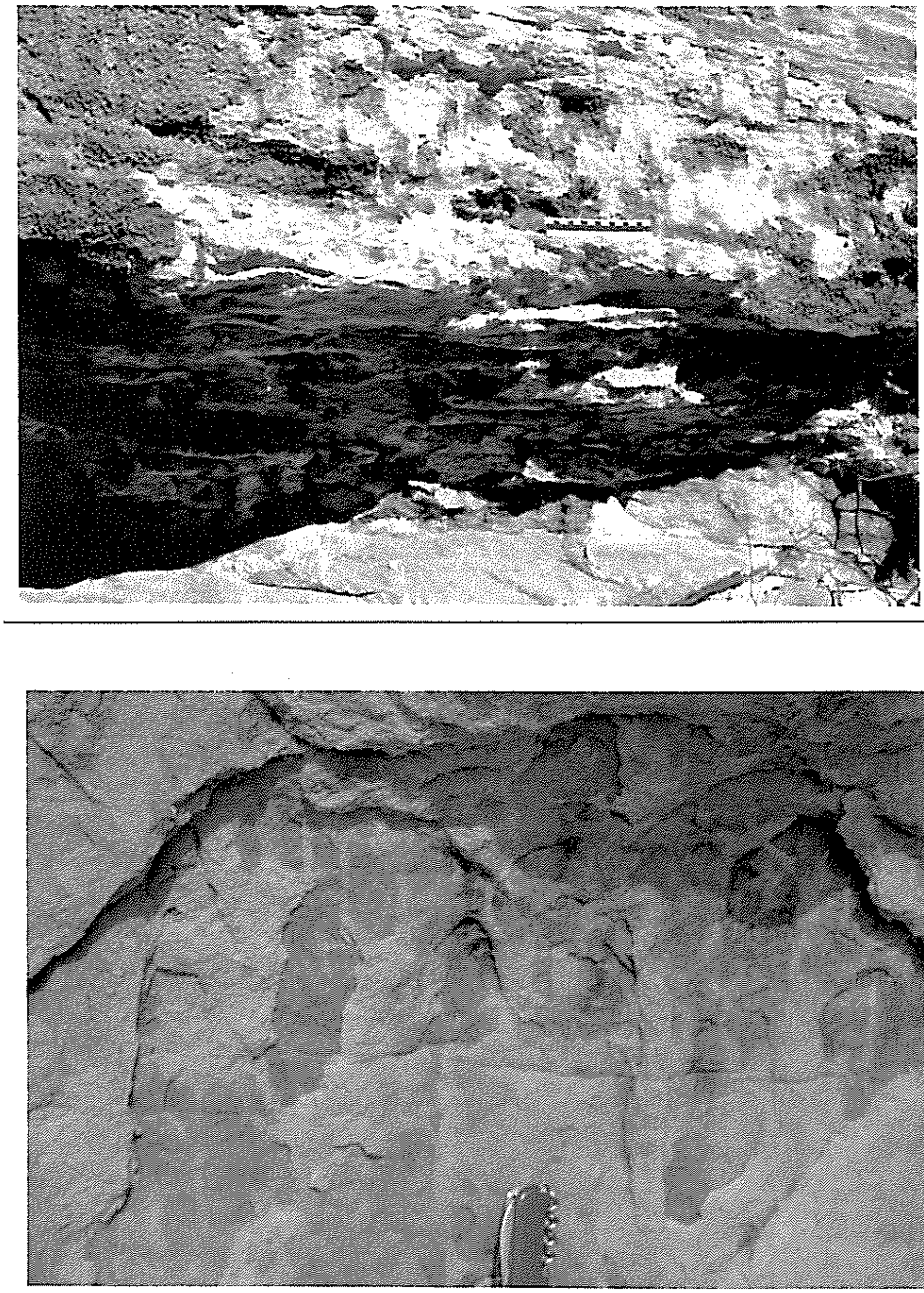


FIGURE 20: *Skolithos* trace fossils: a) vertical, iron-stained holes (outcrop #63, Appendix A); b) vertical patches of medium grains in finer massive sand (outcrop #55, Appendix A).

alternating sedimentation and burrowing as in Minnesota. The amount of preserved bedding varies from place to place. Small- or medium-scale trough sets make up about 35% of an 18-meter section exposed on Highway 151 south of Mineral Point (Fig. 21). At least five erosion surfaces are exposed here and each one is covered by trough cross sets. These bedded zones range from 0.1 to 1.5 meters thick. The middle few meters of the section have thin beds of faint parallel laminae without conspicuous erosion surfaces. About 9 meters above the base of the section, trough sets overlie parallel laminae without an intervening massive zone. Skolithos is apparent in only two massive units. In the lower bed, they are preserved as vertical patches of well-sorted grains, which are slightly coarser than the surrounding sand.

A flat erosion surface truncates numerous Skolithos in a roadcut on Highway 23 at Rock Branch, southeast of Mineral Point. Two bedded and two massive intervals overlie this surface (Fig. 22). Physical structures are visible in about 50% of the exposed section here. They comprise 80% of the lower bedded-to-massive package. Within this interval, large-scale trough sets grade laterally into small trough sets and sets of parallel laminae (Fig. 22). The capping massive zone contains no Skolithos and is very thin. In the second package, medium-scale

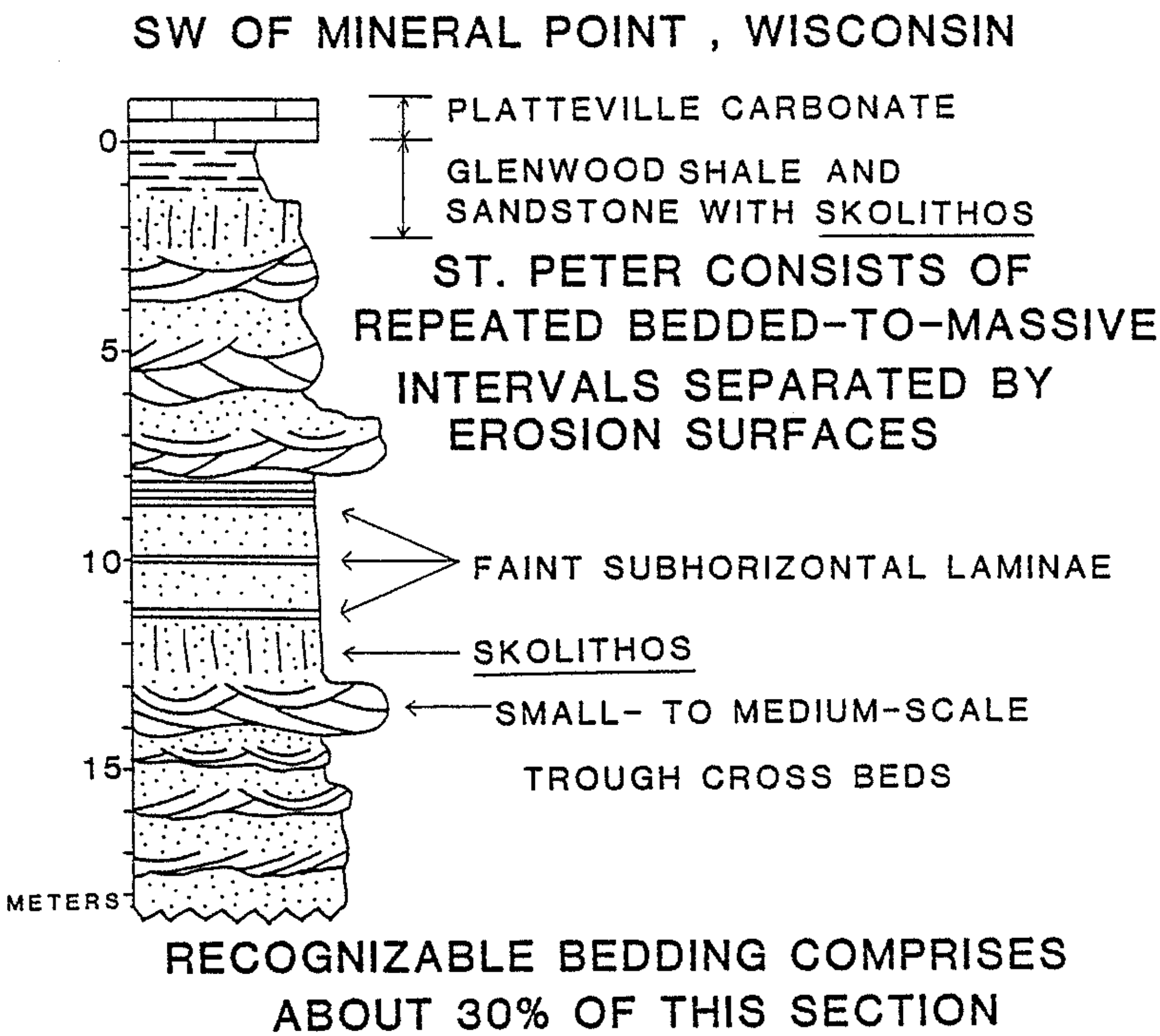


FIGURE 21: Measured section of Highway 151 roadcut southwest of Mineral Point, Wisconsin (outcrop #48, Appendix A).

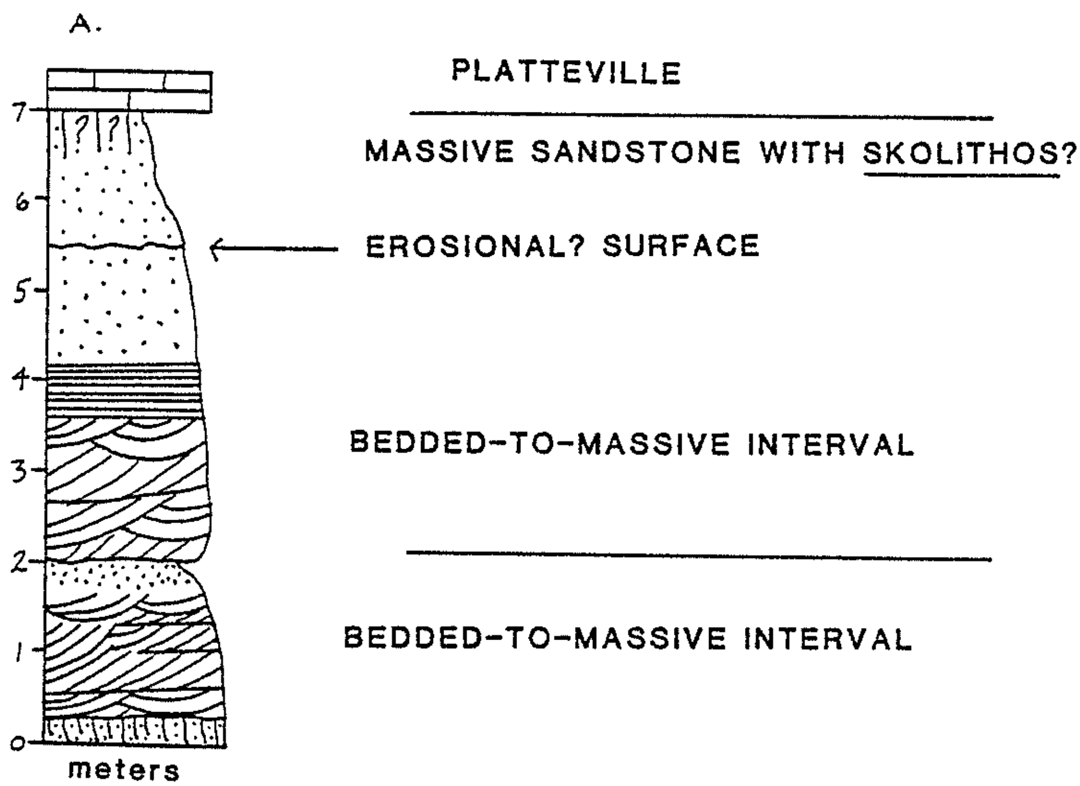
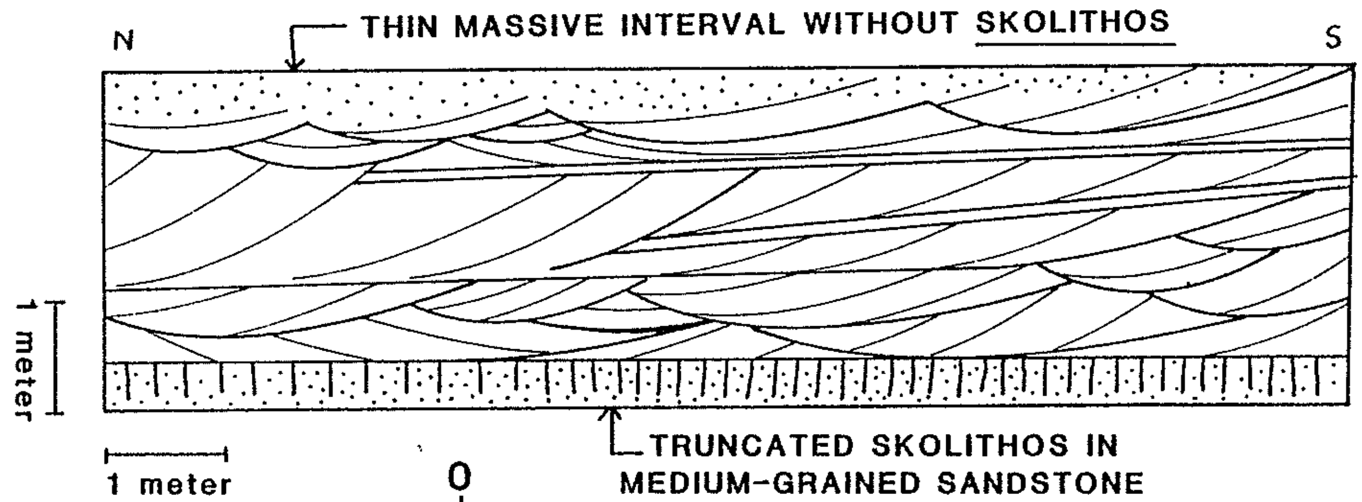
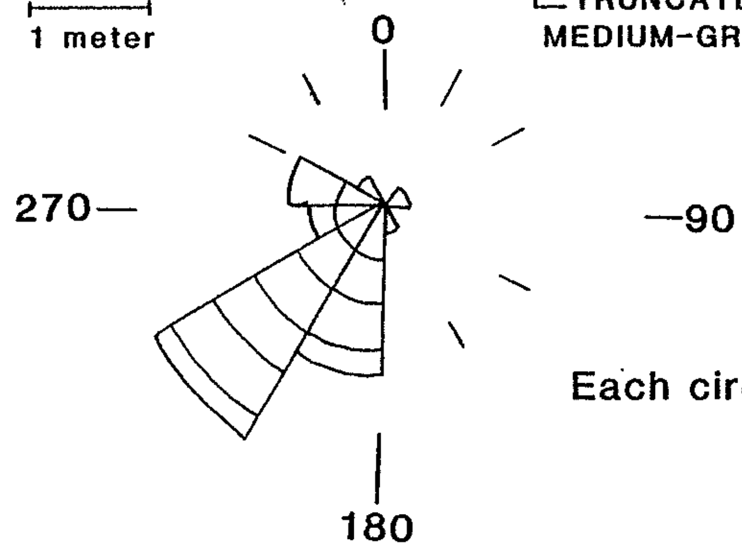


FIGURE 22: Roadcut southeast of Mineral Point, Wisconsin (outcrop #49, Appendix A): a) measured section; b) paleocurrent rose & detail of lower bedded-to-massive interval(see next page).

B.





TROUGH AXES

Each circle represents 2 readings

Total: 29

trough sets grade up into parallel laminae, which in turn fade into massive sandstone. The upper few meters are poorly exposed but the sand appears massive and mottled throughout. Iron stains are abundant near the top. Some of these resemble burrows, whereas others obviously do not. A flat, laterally-persistent surface cuts across the outcrop about 1.5 meters below the top. The upper meter of the St. Peter is exposed in a small roadcut across the creek to the north, where the sand is massive, mottled, and stained with iron. *Skolithos* may be present in this zone, but it is not clearly preserved.

A very similar outcrop can be found on Highway P west of Madison (Fig. 23). The lower part consists of small- to medium-scale trough sets. Bedding fades upward until the sand is massive and mottled with iron stains. *Skolithos* is present within this upper interval; the northernmost of the two roadcuts here has the best *Skolithos*. The upper part of the section is massive, although there are isolated patches of relict bedding. Irregular horizontal surfaces in this massive interval are probably erosional. Some are short or discontinuous, whereas others extend across the whole outcrop.

At Starved Rock State Park, near LaSalle, Illinois, the lower St. Peter section is similar to the bedded-to-massive outcrops around Mineral Point. The upper part

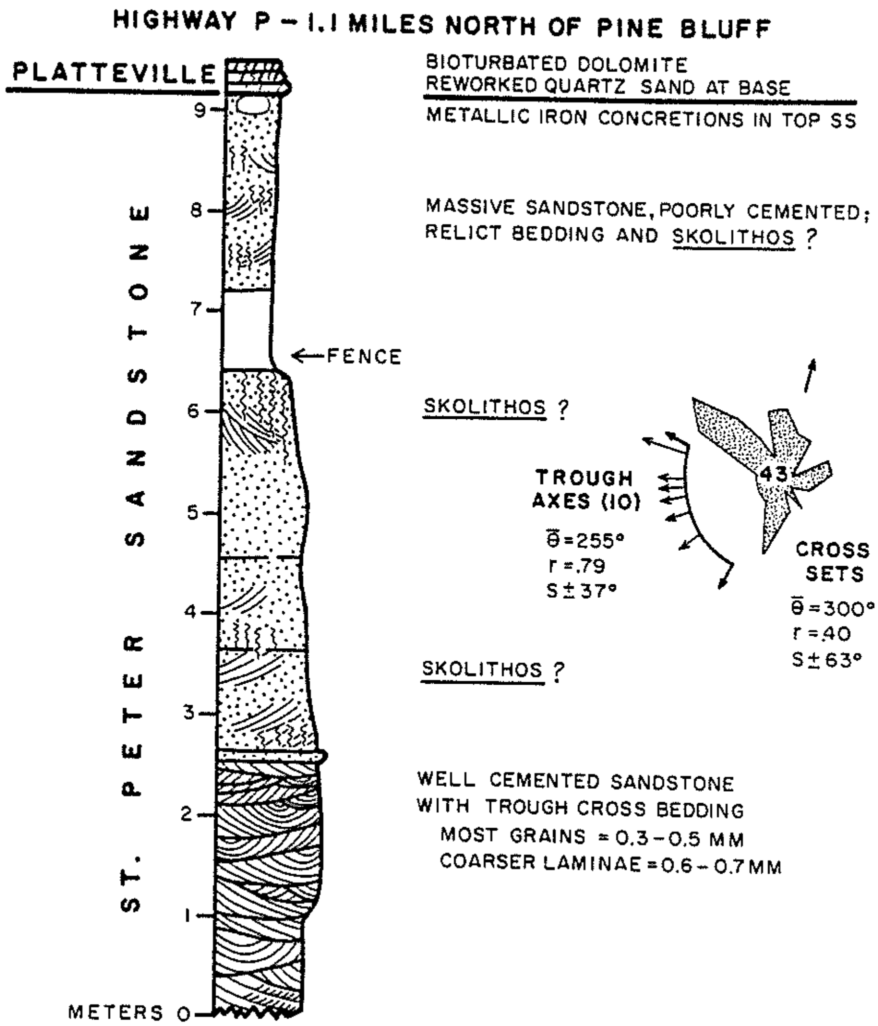


FIGURE 23: Measured section of County P roadcut north of Pine Bluff, Wisconsin (outcrop #55, Appendix A; from Dott and Byers, 1980).

contains more subhorizontal laminae than in any Wisconsin outcrops. The upper set of parallel laminae contains *Skolithos* (Fig. 24), but they are not as abundant as lower in the section. This is the only example of *Skolithos* occurring within strata that also have recognizable physical structures that I observed. This area is also notable because the Glenwood is absent. Still farther south, around Pacific, Missouri, the St. Peter is massive. I saw dense *Skolithos* and flat erosion surfaces in one Simpson sandstone in Oklahoma. Thus, this facies appears to dominate the section throughout the midcontinent.

Bedded-to-Massive Facies Interpretation

The St. Peter has long been considered marine. Recent research on shallow-marine processes and sediments makes more specific interpretation possible. My interpretation will focus upon the sedimentology of the bedded-to-massive sequence and the lateral and vertical variations in bioturbation and bedding style.

The bedded-to-massive sequence is a result of episodic sedimentation. The flat erosion surfaces, which commonly truncate *Skolithos* intervals, suggest scour under upper flow regime conditions over a wide area of the seafloor (Dott, 1978). The absence of escape burrows

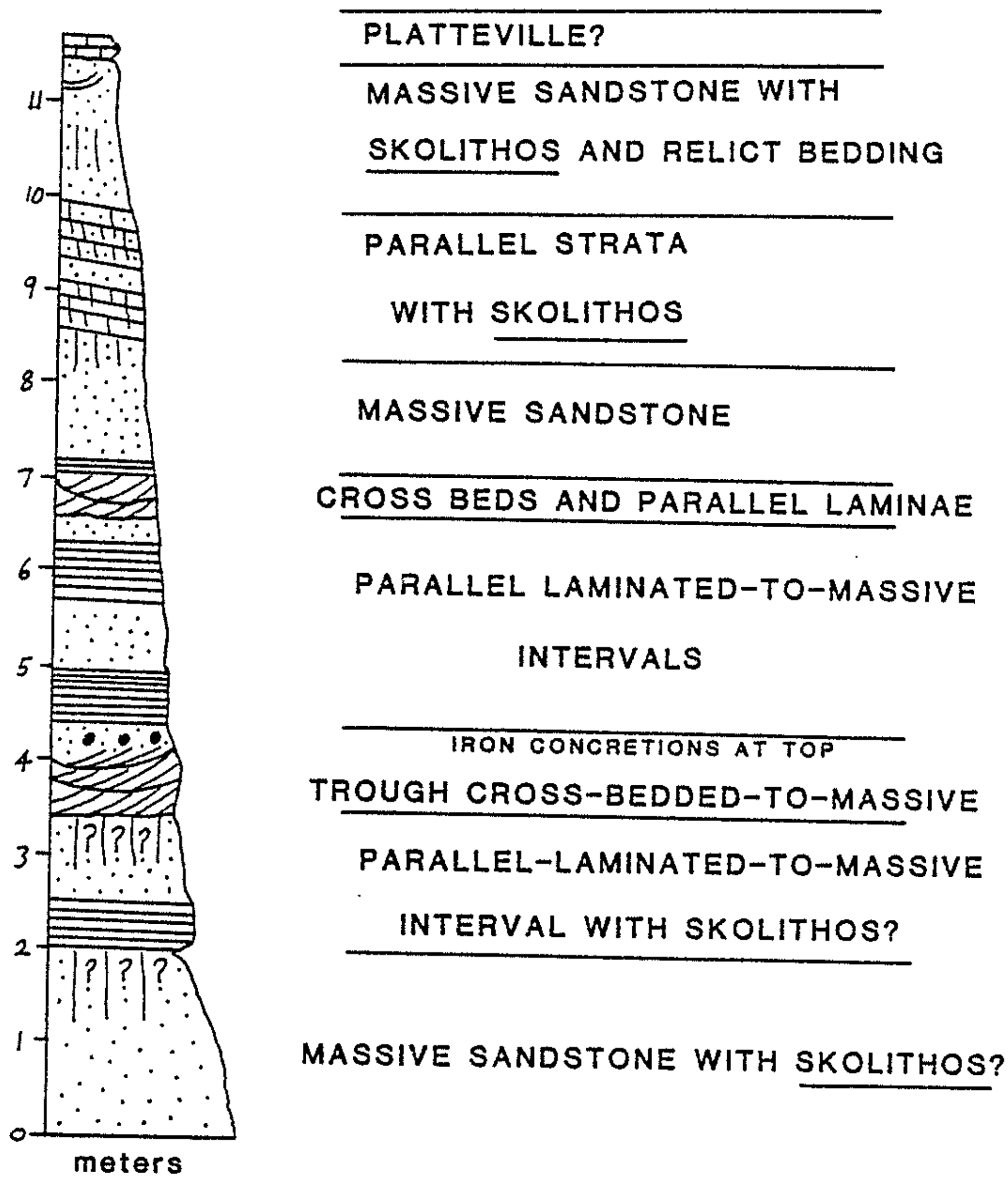


FIGURE 24: Measured section of Highway 178 roadcut near Starved Rock State Park, Illinois (outcrop #56, Appendix A).

indicates complete removal of fauna before deposition (Goldring and Bridges, 1973). Only storm waves and currents seem capable of scouring the sea floor on this scale. The bedding formed in sand deposited as the storm waned. Storms erode beaches and transport sand to the shelf; the sand settles as turbulence decreases and currents make bedforms (McBride and Hayes, 1962; Rodolfo, Buss, and Pilkey, 1971; Reineck and Singh, 1972). During quieter times, organisms re-inhabit the sandy substrate and bioturbation begins. Complete destruction of physical structures implies long periods of time rather than numerous individuals (Howard, 1975), so the massive intervals would represent the bulk of St. Peter time. The bedded-to-massive sequence is inferred to be a record of near-continuous bioturbation punctuated by episodic storm deposition. The erosion surfaces represent peak energy on the sea floor; the massive beds were formed by bioturbation between storms. Similar deposits are known from the Recent (Reineck and Singh, 1972; Sanders and Kumar, 1975) and ancient (Howard, 1972; Goldring and Bridges, 1973; Dott, 1978; Bourgeois, 1980). Numerous tropical storms during St. Peter time would be expected for the Ordovician paleolatitude of the Midwest (Dott, 1974; Dott and Batten, 1976).

The degree of bioturbation and style of bedding in this facies varies around the upper Midwest. This leads to the inevitable questions: Where was the shoreline? How deep was the water? The small percentage of preserved bedding in the Twin Cities area (Fig. 19) indicates extreme bioturbation. This could happen in an environment below average storm wave base where scour would be relatively infrequent so only the greatest storms would stop bioturbation there. Sediments of the modern "offshore facies" of Howard and Reineck (1972, 1981) are completely bioturbated; all cores in this facies have less than 10% bedding, but shells and burrows are abundant. Shell molds found by Sardeson near St. Paul support an offshore setting for the Twin Cities. The erosion surfaces and physical structures show that some storms did affect the sea floor there. The record of storm effects and the occurrence of Skolithos suggest that the sand was deposited in the upper offshore.

The bedded-to-massive sequences at the Highway 151 roadcut southwest of Mineral Point (Fig. 21) are similar to sediments from modern offshore-shoreface transition environments (Howard and Reineck, 1972, 1981). Each bed is bioturbated, but most have some physical structures, too. The local abundance of Skolithos is consistent with a lower shoreface environment (Frey and Howard, 1969).

The paleocurrents are westerly, which is consistent with transport of sand by storms from my postulated paleo-shoreline to the shelf.

The lower bedded-to-massive package in the Highway 23 roadcut (Fig. 22) is more complicated. The truncated Skolithos at the base indicates storm effects on the shoreface, but the overlying cross beds are not typical of modern storm deposits (Reineck and Singh, 1972; Sanders and Kumar, 1975; Howard and Reineck, 1981). The large-scale set is especially problematic. Sanders and Kumar (1975) note the absence of high-angle cross strata in Atlantic shelf storm deposits; instead, low-angle parallel laminae seem to be the structure favored by Holocene storms. High-angle cross strata are found in bars, dunes, and sand waves on energetic modern shelves (Clifton, Hunter, and Phillips, 1971; Dalrymple, 1980), but they seem to result mostly from fairweather wave and tidal processes. Some may require superimposed storm currents to migrate, however (Field et al., 1981). The structures in this interval formed as a bedform with superimposed megaripples and a slipface at least 1 meter high (based on preserved cross-bed thickness) migrated offshore toward the west. The "outer rough" facies (Clifton et al., 1971) of the Oregon coast has similar bedforms, but these migrate on the shoreface toward the beach. Orientation of trough axes in this outcrop (Fig. 22) indicate fairly unidirectional currents to the west-southwest. This is away from my postulated paleoshoreline. Alternatively, this sequence could have formed sand waves, associated with a tidal channel, which migrated over scoured foreshore deposits. Howard and Reineck (1972) report abundant trough cross bedding in their "shoal facies," which is seaward of a tidal inlet. This facies extends from the beach out to the upper offshore. The lack of *Skolithos* in the overlying massive interval could support a tidal channel setting because Goodwin and Anderson (1977) have noted, in a paleoecological study, that *Skolithos* is absent from trough-cross-bedded deposits of tidal channels. *Skolithos* does occur in the rocks they studied, but not in that particular facies. The tidal channel interpretation would reconcile better the paleocurrent pattern with my paleoshoreline. Despite the ambiguity of detailed interpretation, it seems that part of the St. Peter around Mineral Point was deposited in a shoreface environment. On modern shelves, this environment occurs in water depths from about 1-10 meters (Howard and Reineck, 1972, 1981). The offshore environment in Minnesota was probably in water deeper than 10-15 meters. This pattern suggests a paleoshoreline east of Dodgeville (Fig. 25).

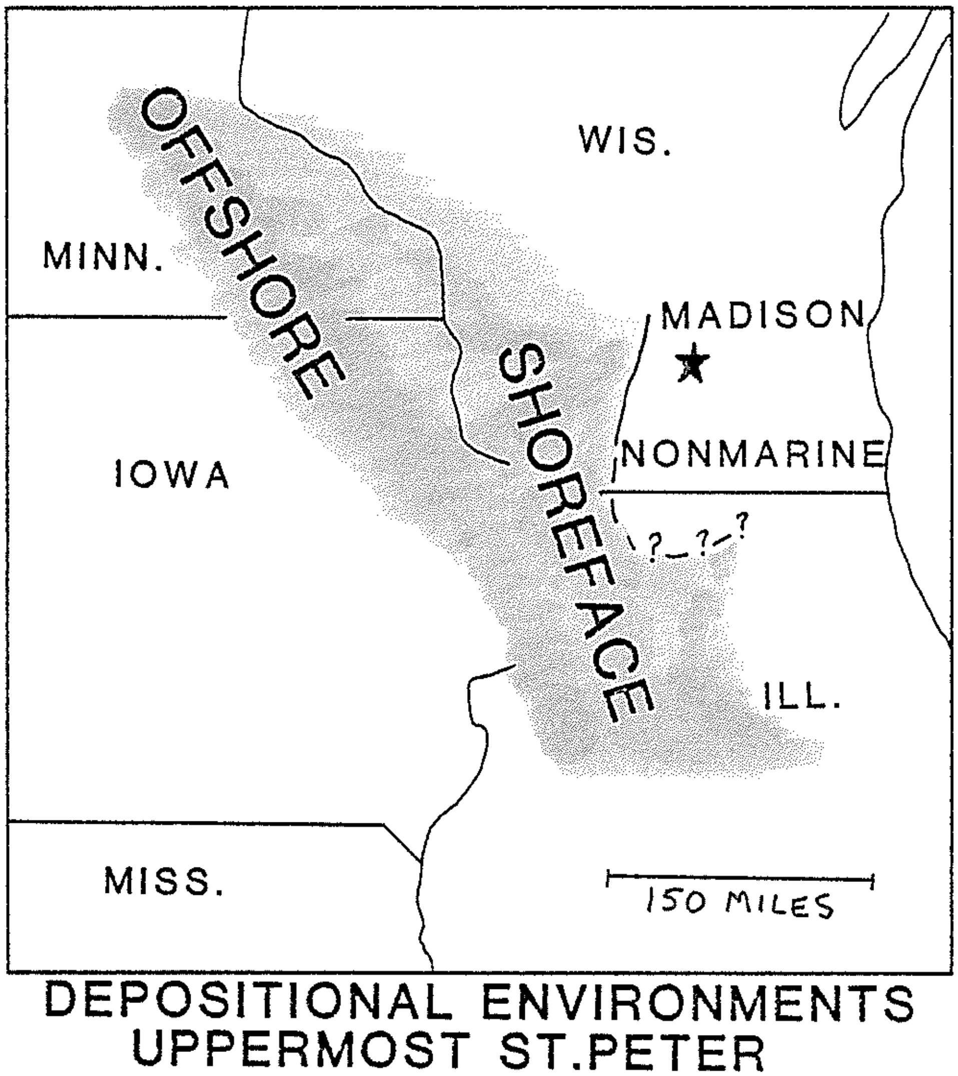


FIGURE 25: Paleogeographic map for the time represented by roughly the upper 10 meters of the St. Peter section.

The only marine deposits seen that indicate close proximity to a shore are the uppermost beds near Lasalle, Illinois (Fig. 24). There the parallel-bedded sand is similar to modern foreshore deposits (Howard and Reineck, 1972). The abundance of Skolithos in this outcrop suggests that the depositional environment was probably low in the foreshore, near the shoreface.

Most marine outcrops have thick massive zones near the top of the St. Peter. The roadcut south of Cross Plains (Fig. 23) is the best example. The upper 6 meters contains numerous Skolithos and several flat to wavy surfaces which may be erosional. Some burrows appear to cut these surfaces while others look truncated. This interval probably has several amalgamated beds of complete bioturbation which again suggests an offshore environment only rarely affected by disturbances such as storms. The vertical shift from shoreface to offshore probably records part of the Tippecanoe transgression.

The section exposed in the canyons of Starved Rock State Park in Illinois looks like the inferred shoreface deposits of the Dodgeville area, so the vertical pattern at Starved Rock suggests upward shoaling. The foreshore deposits at the top are consistent with Fraser's (1976) barrier island interpretation for the upper St. Peter here (Starved Rock Member). Templeton and Willman (1963) describe how the Glenwood interfingers with the Starved Rock on the north, which implies that the Starved Rock Member is younger than the rest of the St. Peter that I studied. The Glenwood thickens southward from Monticello to a maximum of about 50 meters in Illinois just north of where it grades into the Starved Rock (Fig. 2). Fraser (1976) concluded that the Glenwood was a lagoonal deposit formed behind the Starved Rock barrier. Even though the section suggests upward shoaling, it still records the transgression. Apparently, the sea deepened too rapidly because no beach lamination or subaerial deposits have been found, at least where I studied the Starved Rock Member. Barrier growth could not keep pace with rising sea level.

Summary of Facies Interpretation

The basal facies is considered to be a partially reworked weathering residuum because it consists of oolitic chert rubble, clay, and quartz sand, all of which are identical with their counterparts in the underlying Prairie du Chien dolomites. Slickensides, folds, indurated claystone, and small-scale faults indicate that this facies was affected by post-depositional differential compaction.

The large-scale cross-bedded facies is interpreted as eolian because it contains adhesion structures, eolian-scale ripples, and laminae typical of eolian deposits. The geometry of the large sets is comparable to that within bedforms in modern ergs.

The bedded-to-massive facies is interpreted as marine because Skolithos indicates a marine environment for Ordovician strata. Bedded-to-massive sequences are common in modern shelf deposits, and the degree of bioturbation and style of bedding is typical of modern offshore and shoreface environments. The geographical distribution of environments suggests a paleoshoreline somewhere between Dodgeville and Madison, Wisconsin, but the exact position cannot be pinpointed (Fig. 25).

STRATIGRAPHY AND DEPOSITIONAL HISTORY

Around St. Paul, Minnesota, and LaSalle, Illinois, the entire exposed St. Peter section is marine. The marine facies overlies the eolian in outcrops near Dodgeville and Mt. Horeb, Wisconsin (Fig. 5). Outcrops of the eolian facies can be found low in the section throughout southwestern Wisconsin (Fig. 26). These relationships indicate that part of the eolian St. Peter was reworked in a marine environment during the Tippecanoe transgression.

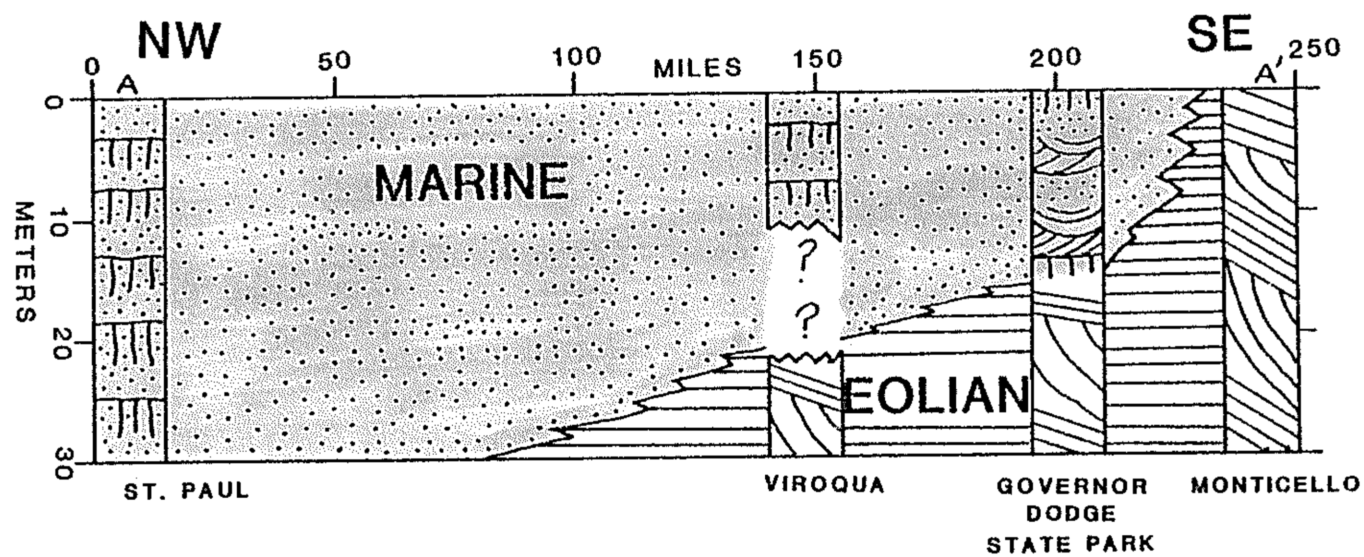


FIGURE 26: Cross section from St. Paul, Minnesota to Monticello, Wisconsin (see Figure 3 for location of cross section).

Section at Governor Dodge State Park

The vertical shift from nonmarine to marine environments is recorded in the cliffs of Governor Dodge State Park (Fig. 27). Up to 15 meters of the eolian facies is exposed in the bottom of the cliffs, especially in the northern part of the park. A good exposure can also be found in a roadcut on the north side of Cox Hollow Lake, also in the park. A thick, iron-oxide crust obscures the top of the section in most of the park, but the details can be observed in a roadcut on the northern entrance road. The transition from eolian to marine environments is marked by a massive bed with numerous truncated Skolithos at the top (Fig. 27). Above the erosion surface, parallel laminae and trough sets alternate with beds of massive sand as in the Mineral Point outcrops. The section is capped with about 0.5 meters of the shale lithology of the Glenwood (Harmony Hill Member?).

The massive transitional bed at the base of the marine facies is similar to the Quaternary sediment cover of the Atlantic shelf. Pilkey et al. (1979) described from cores a thin (typically less than 4 meters), thoroughly bioturbated, sediment layer. This layer lacks Tertiary fossils so the combined effects of storms and bioturbation have only reworked the upper few meters of

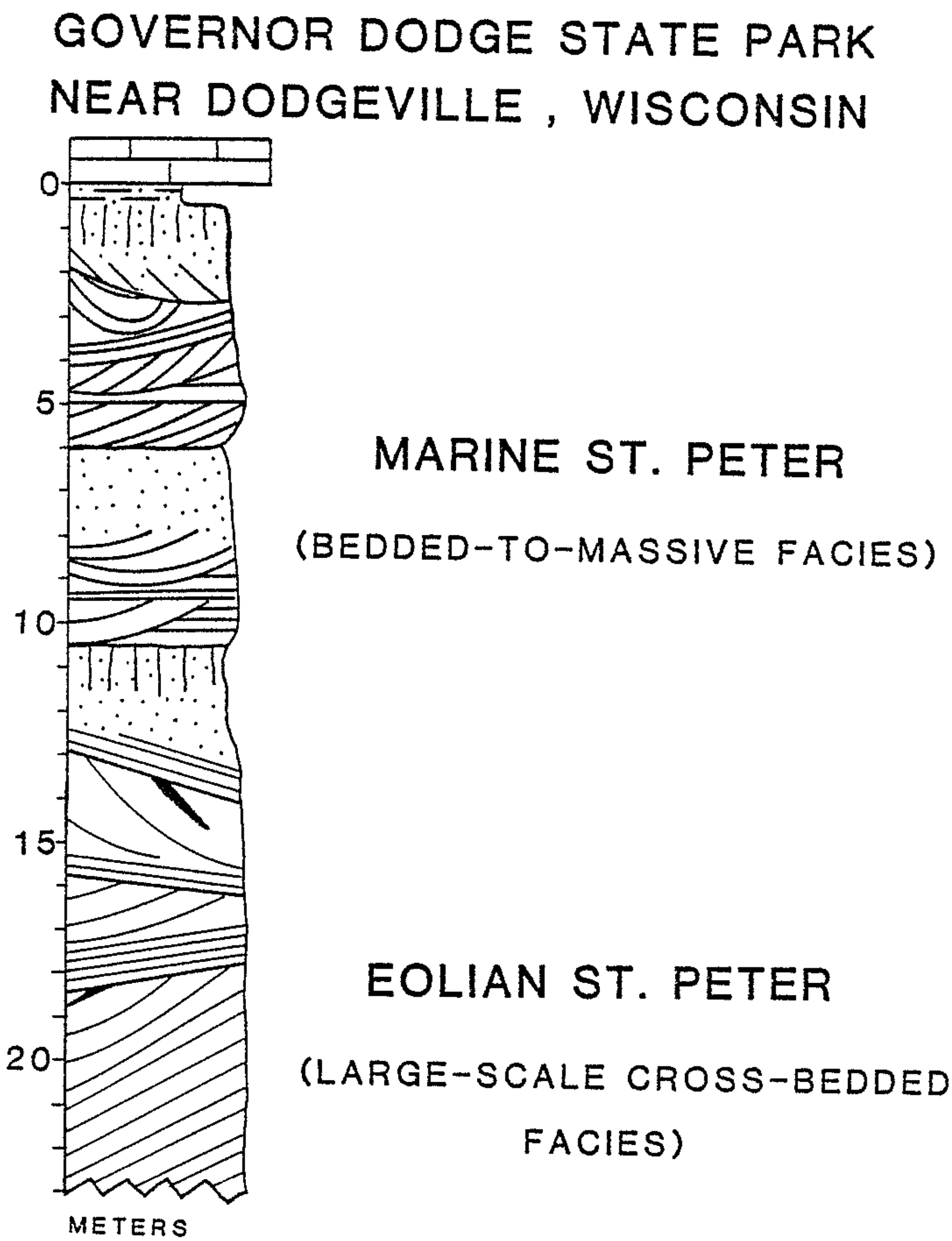


FIGURE 27: Measured section at Governor Dodge State Park (compiled from outcrops #63-#67, Appendix A).

the Cenozoic deposits. The massive transition bed at Governor Dodge probably represents the initial offshore deposits of the Middle Ordovician transgression in southwestern Wisconsin. A depositional history of the St. Peter can be postulated based on interpretation of this section.

Development of the Basal Unconformity

One of the great traditions of Midwestern geology is speculation on the origin of the sub-St. Peter surface. T. C. Chamberlin (1883) was probably the first to do so in print. He described how the St. Peter fills depressions in the "billowy surface" of the Prairie du Chien Group and how the section is "frequently interrupted by the formations above and below coming together," especially in northeastern Wisconsin. He concluded that the dolomites had been eroded and that a period of nondeposition followed. Trowbridge (1917) must have envisioned a landscape carved by rivers because he described an "upland" and a "valley" phase in the St. Peter. Twenhofel and Thwaites (1919) favored subaerial erosion because they described a "residual soil" in the Readstown Member. Dake (1921) accepted their conclusion and stated that the upper Midwest must have been exposed longest because relief is greatest on the unconformity here. By the 1950's, enough wells had been drilled to make detailed speculation possible. Soon, pre-St. Peter "uplifts" were discovered throughout the midcontinent. Merriam and Atkinson (1956) described a "filled sinkhole" from wells in eastern Kansas that developed on the flanks of an uplift in southeastern Nebraska. Suter et al. (1959) published an isopach map that suggests a well-developed fluvial drainage pattern on the flank of an uplift in north-central Illinois. Flint (1956) argued that post-depositional subsurface solution and compaction produced the sub-St. Peter relief, and that there was no evidence of unconformity in southwestern Wisconsin. Buschbach (1964) pointed out that the pattern of pre-St. Peter depressions does not make a good stream network in most places. Linear interconnected depressions were only found in northeastern Illinois where the St. Peter rests upon eroded sandstones and shales of the upper Cambrian Tunnel City Group. Buschbach's (1964) cross section (my Fig. 28) shows a north-facing scarp of the Prairie du Chien Group, which is roughly coincident with the Sandwich fault zone. He postulated a mature karst landscape north of the scarp and isolated sinkholes south of it. The Readstown is thicker north of the scarp. Palmquist (1969) used a gravity study to delineate several "linear interconnected depressions" in the pre-St. Peter surface

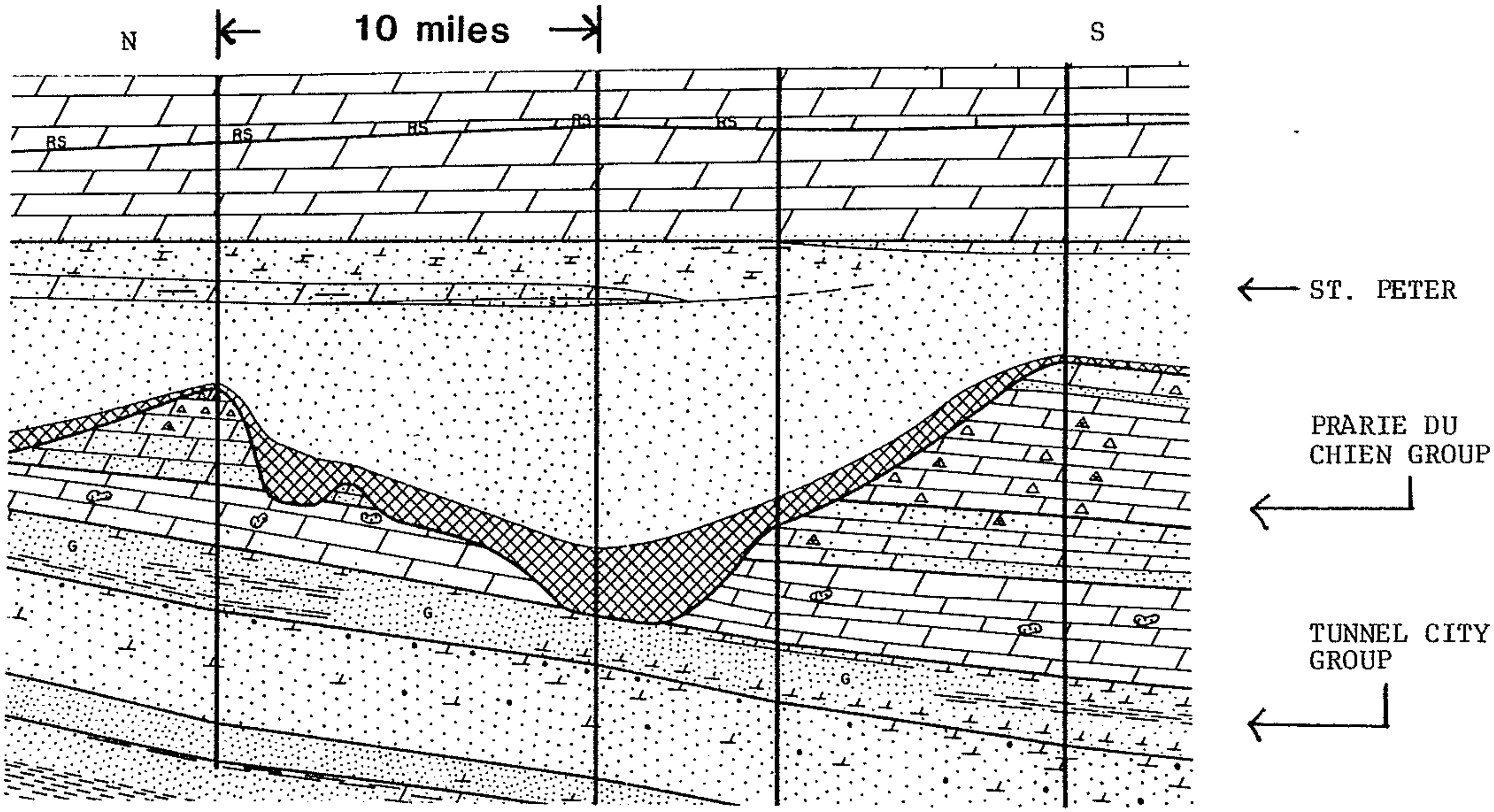


FIGURE 28: Cross section from well data illustrating inferred scarp of the Prairie du Chien Group in northern Illinois (from Buschbach, 1964).

of southwestern Wisconsin, which he chose to interpret as fluvial channels. Grether and Clark (1980) showed that conodonts in the Readstown are reworked Prairie du Chien conodonts, thereby verifying the existence of the unconformity.

The base of the St. Peter is poorly exposed in outcrop, and tends to cave in wells, so we shall never know many of the details. With that in mind, I proudly join the ranks of speculators. The deposition of the St. Peter was preceded by a long period of erosion due, in part, possibly, to uplift throughout the craton (Cady, 1920; Dake, 1921; Templeton and Willman, 1952; Merriam and Atkinson, 1956; Ostrom, 1970). Subaerial exposure of the Lower Ordovician dolomites led to the development of a mature karst landscape mantled with the residuum of the Readstown, which was only locally reworked by streams.

Deposition of the St. Peter

In some places, the friable Cambrian sandstones and shales were eroded so they probably formed river valleys between dolomite highlands. In the absence of land plants, some fluvial sand was reworked into eolian deposits. Presumably, the valleys extended to the Tippecanoe sea and acted as "pipelines" for the delivery of eolian and fluvial sand to coastal environments. Eventually, sand filled the valleys and began to blow across the uplands where some settled in sinkholes to form the massive, lower Tonti sandstones. By late Tonti time, an erg had developed in the upper Midwest, and only the highest outliers of Prairie du Chien dolomite penetrated the sand sheet. The remnant of this erg is outlined on the facies map for the top of the St. Peter (Fig. 29). The eolian facies can be found in outcrop throughout southwestern Wisconsin and, possibly, parts of northern Illinois, so the erg must have been more extensive in early-St. Peter time. The marine facies overlies the eolian everywhere that I studied the St. Peter, except in the Madison-Monticello region, where the entire section is eolian. This region must have been a topographic high throughout St. Peter time. Perhaps this was on the flank of the Wisconsin arch, but Ostrom (1970) has postulated a broader pre-St. Peter uplift in the Milwaukee area. The facies distribution in Figure 21 could support his conclusion.

Large areas of the midcontinent were inundated as the sea advanced northward from the margin of the continent during the Tippecanoe transgression. On the highlands, sand was blown to shorelines, where it accumulated as beaches and coastal dunes. During storms, waves would erode the dunes, beach, and bioturbated shoreface, and sand would be deposited on the shelf. The variation in

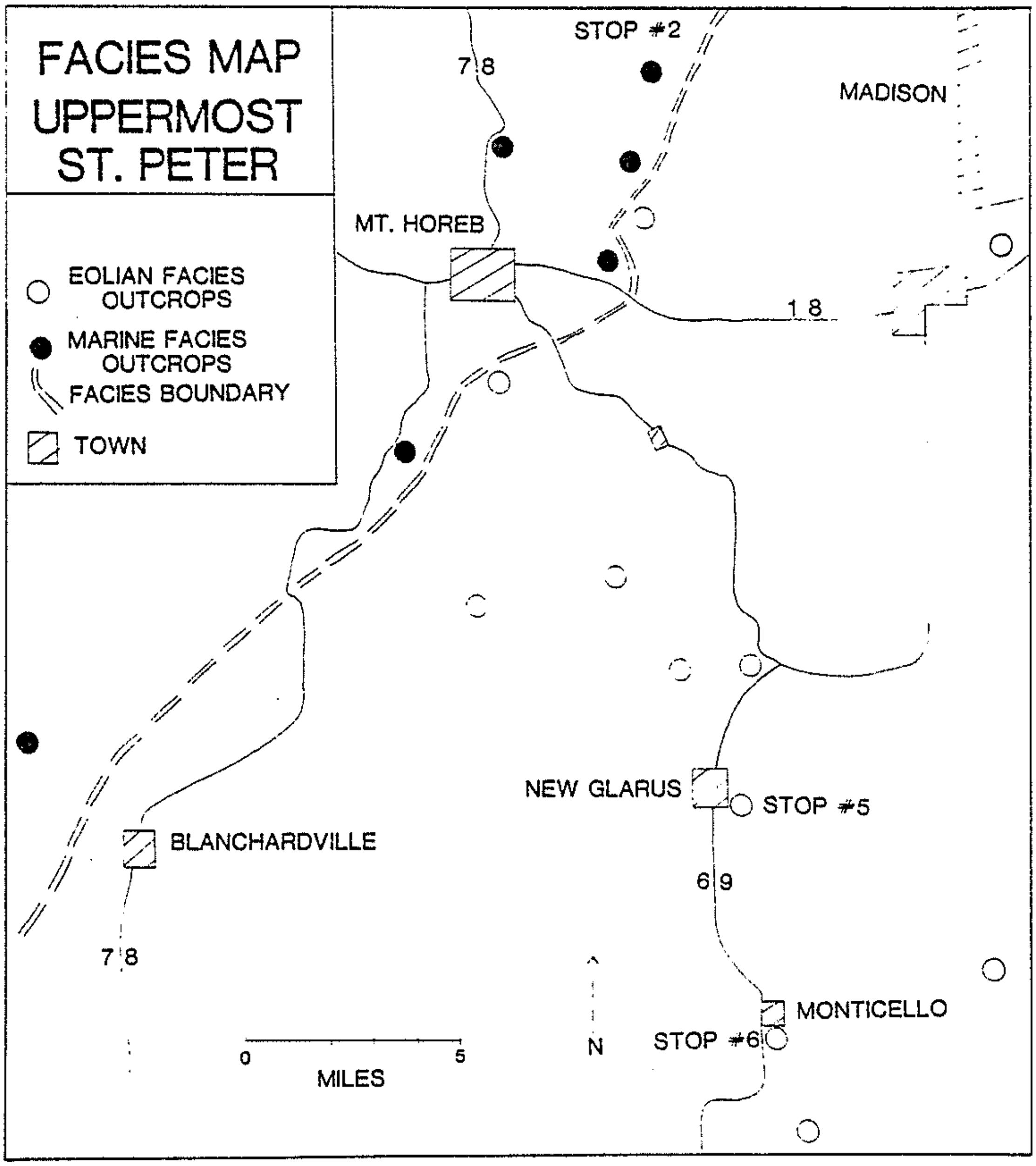


FIGURE 29: Facies map of the Madison study area.

the magnitude, path, and direction of storms could account for some of the great dispersion in the regional paleocurrent pattern (Roshardt, 1964; Dott and Roshardt, 1972). As sea level continued to rise, more and more of the eolian sand was reworked into shoreface and offshore deposits, and the sea flooded all but the highest land (Fig. 25). A slower rise of sea level and/or continuing uplift led to the growth of the Starved Rock barrier system across northern Illinois (Fig. 30). Apparently it now absorbed the brunt of the storms, so the Glenwood accumulated in the quiet waters behind it. The glauconite, phosphate, and the volume of shale in the Glenwood suggest very slow sedimentation, especially when the lack of mud in the St. Peter is considered. Near Schultz, south of Monticello, Wisconsin, the Glenwood consists entirely of a thin conglomeratic sandstone with clasts of thoroughly cemented, fine-grained sandstone. This indicates pre-Glenwood cementation of the St. Peter. In this outcrop, one boulder of sandstone has been bored and filled with the coarser Glenwood sand and there are several probable mineralized hardgrounds. All of these features suggest nondeposition or very slow sedimentation. The overlying dolomite has large, partitioned vugs which could be evaporite molds. These rocks probably represent the edges of the Madison-Monticello erg, which was getting

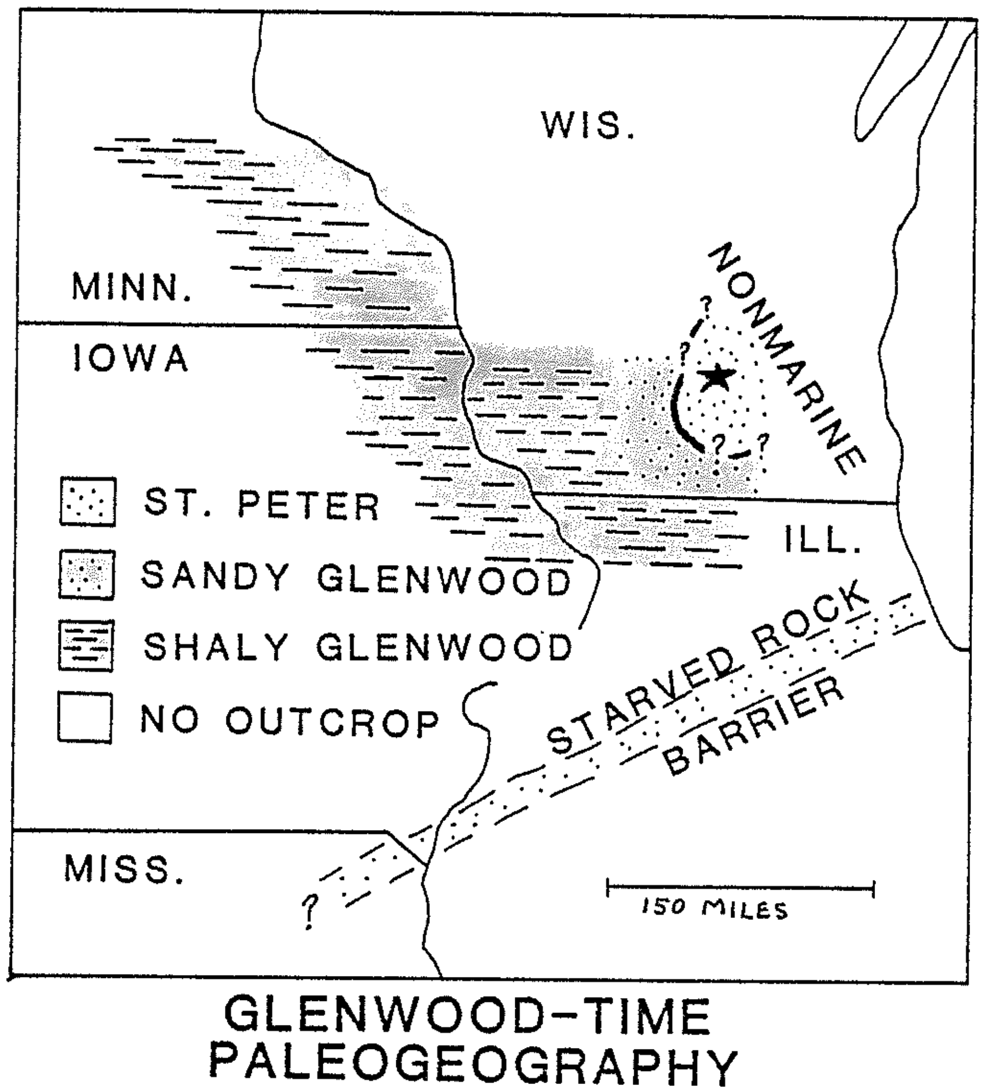


FIGURE 30: Paleogeographic map for Glenwood time.

reworked in shallow subtidal (?) to supratidal (?) environments as the transgression progressed. If evaporites did exist, they would support a restricted lagoon model for the Glenwood. More work is needed on this problem but it seems that the Glenwood represents the last influence of the siliciclastic source terrane of the upper Midwest. The waters were clear enough for the "carbonate factory" to produce the Platteville dolomites thereafter.

Summary

The depositional scheme I propose for the St. Peter involves eolian and marine sedimentation. Sand derived largely from subaerially exposed Cambrian sandstones was blown to the margins of a coastal erg. Storms eroded the coastal dunes and beaches and transported sand to shoreface and offshore environments, where it was partially or completely bioturbated. Ordovician beach deposits were not preserved because storms eroded them. The ongoing Tippecanoe transgression allowed the shoreface deposits to be preserved as repeated sequences of bedded-to-massive storm deposits, which pass vertically into offshore deposits.

APPENDIX A

OUTCROPS STUDIED

The outcrops are listed by facies. [A] indicates adhesion structures and [S] indicates *Skolithos*. All towns are in Wisconsin unless otherwise stated.

Basal Facies Outcrops

1. Roadcut on Highway 27 east of Prairie du Chien (NE¼, NE¼, sec. 29, T.7N., R.6W., Prairie du Chien quad.)
2. Roadcut on County Highway G southwest of Mt. Vernon (SW¼, SW¼, sec. 34, T.6N., R.7E., New Glarus quad.)
3. Quarry southeast of Bagley (NW¼, SW¼, sec. 27, T.5N., R.6W., Bagley quad.)

Eolian Facies Outcrops

4. [A] Roadcut on County Highway J north of Riley (center of east half of boundary of secs. 26 & 35, T.7N., R.7E., Cross Plains quad.)
5. Quarry northwest of Klevenville (NW¼, NW¼, sec. 3, T.6N., R.7E., Cross Plains quad.)
6. Roadcut on County P south of Pine Bluff (NW¼, NW¼, sec. 34, T.7N., R.7E., Cross Plains quad.)

7. Roadcut on County S east of Pine Bluff (west end of boundary of secs. 23 & 26, T.7N., R.7E., Cross Plains quad.)
8. Roadcut on County S west of Pine Bluff (NE¼, NW¼, sec. 28, T.7N., R.7E., Cross Plains quad.)
9. Quarry northeast of Verona (SE¼, SW¼, sec. 6, T.6N., R.9E., Madison quad.)
10. Roadcut on gravel road just west of County D (SW¼, SW¼, sec. 7, T.5N., R.9E., Evansville quad.)
11. Roadcut on County G northeast of Mt. Vernon (west end of boundary secs. 26 & 35, T.6N., R.7E., New Glarus quad.)
12. [A] Two roadcuts on Highway 69 north of New Glarus. Adhesion occur in the western roadcut (largest) near the top (S½, sec. 36, T.5N., R.7E., New Glarus quad.)
13. Roadcut on County U and outcrop behind farmhouse, northwest of New Glarus (SE¼, NW¼, sec. 34, T.5N., R.7E., New Glarus quad.)
14. [A] Large roadcut in extreme southeastern New Glarus (SE¼, NE¼, sec. 23, T.4N., R.7E., New Glarus quad.)
15. [A] Small roadcut on farm road east of New Glarus (intersection of road and railroad, boundary of secs. 16 & 21, T.4N., R.8E., New Glarus quad.)
16. [A] Roadcut on County EE east of Monticello (center western half of boundary of secs. 11 & 14, T.3N.,

R.8E., Monroe quad.)

17. [A] Roadcut on Sulzer road east of Schultz (center of S½, sec. 31, T.3N., R.8E., Monroe quad.)

18. [A] Roadcut on Highway 69 south of Monticello (NW¼, NW¼, sec. 18, T.3N., R.8E., Monroe quad.)

19. Roadcut on County A northwest of New Glarus (center of north boundary of secs. 16 & 21, T.5N., R.7E., New Glarus quad.)

20. Roadcut on County JG south of Mt. Horeb (center of N½, sec. 25, T.6N., R.6E., New Glarus quad.)

21. Roadcut on County A at Forward (center of NW¼, sec. 23, T.5N., R.6E., Blanchardville quad.)

22. Roadcuts on Highway 78 south of Blanchardville (NE¼, NE¼, sec. 35, T.4N., R.5E., Blanchardville quad.)

23. Roadcut on Highway 78 north of Argyle (SE¼, NE¼, sec. 14, T.3N., R.5E., South Wayne quad.)

24. [A] Roadcut on Highway 78 north of Argyle (SE¼, SE¼, sec. 11, T.3N., R.5E., South Wayne quad.)

25. Roadcut on gravel road east of Yellowstone Lake dam (center of W½, sec. 6, T.3N., R.5E., Blanchardville quad.)

26. Roadcut on Highway 151 at Blockhouse Creek (SW¼, SE¼, sec. 27, T.5N., R.6W., Dickeyville quad.)

27. Outcrop at Gibralter Rock northwest of Lodi (SE¼, NE¼, sec. 13, T.10N., R.7E., Baraboo quad.)

28. Outcrop east of Baraboo (W½, SE¼, sec. 25, T.12N., R.17E., Baraboo quad.)

29. Outcrop at Castle Rock (NE¼, NW¼, sec. 32, T.7N., R.1W., Boscobel quad.)

30. Outcrop northwest of Viroqua: Three Chimneys (NE¼, NW¼, sec. 16, T.12N., R.4W., Viroqua quad.)

31. Outcrop west of Three Chimneys (SW¼, SW¼, sec. 11, T.13N., R.5W., Viroqua quad.)

Marine Facies Outcrops

32. [S] St. Paul, Minnesota - Watergate marina. North bluff of the Mississippi River at the mouth of the Minnesota River (type section for St. Peter) (SE¼, SW¼, sec. 21, T.28N., R.23W., St. Paul quad.)

33. [S] St. Paul, Minnesota. North bluff of Mississippi at downtown St. Paul (SW¼, SW¼, T.29N., R.24W., St. Paul quad.)

34. [S] Railroad cut south of Hampton, Minnesota (E½ of sec. 17, T.113N., R.18W., Hastings (Minnesota) quad.)

35. Outcrop northwest of Miesville, Minnesota (SE¼, NE¼, sec. 31, T.114N., R.17W., Hastings (Minnesota) quad.)

36. Roadcut on private road just west of Miesville, Minnesota (SE¼, SE¼, sec. 11, T.113N., R.17W., Hastings (Minnesota) quad.

37. Outcrop at Treasure Cave Cheese Co., Faribault, Min-

nesota (SE¼, NE¼, sec. 31, T.110N., R.20W., Faribault quad.)

38. Roadcut on gravel road southeast of Clayton, Iowa (SW¼, sec. 1, T.93N., R.3W., Clayton (Iowa) quad.)

39. [A] Roadcut on road between Clayton and McGregor, Iowa at Magill Creek (SE¼, SE¼, sec. 22, T.94N., R.3W., Clayton (Iowa) quad.)

40. Roadcut on County C east of Wyalusing State Park (Wisconsin) (S½, NE¼, sec. 22, T.6N., R.6W., Bagley quad.)

41. Roadcut on Highway 27 south of Viroqua (NW¼, NW¼, sec. 16, T.12N., R.4W., Viroqua quad.)

42. [S] Roadcut on County I north of Montfort (SE¼, NE¼, sec. 13, T.6N., R.1W., Montfort quad.)

43. [S] Roadcut at campground in Black Hawk Lake Recreation Area (NW¼, SW¼, sec. 5, T.6N., R.2E., Muscoda quad.)

44. Roadcut on Highway 23 northwest of Mineral Point (SW¼, SW¼, sec. 25, T.5N., R.2E., Dodgeville quad.)

45. Roadcut on Highway 81 east of Ellenboro (NW¼, NW¼, sec. 34, T.4N., R.2W., Ellenboro quad.)

46. [S] Roadcut on gravel road just south of County A at the east bluff of the Platte River (west boundary of SW¼, SW¼, sec. 11, T.4N., R.2W., Ellenboro quad.)

47. Highway 151 roadcut southwest of Mineral Point (SW¼,

NW¼, sec. 15, T.4N., R.2E., Mineral Point quad.)

48. [S] Highway 151 roadcut at Iowa/Lafayette County line (NW¼, NE¼, sec. 21, T.4N., R.2E., Mifflin quad.)

49. [S] Roadcut on Highway 23 southeast of Mineral Point at Rock branch (NE¼, SE¼, sec. 8, T.4N., R.3E., Mineral Point quad.)

50. Roadcut on Park Road, north shore of Yellowstone Lake (SE¼, NW¼, sec. 1, T.3N., R.4E., Blanchardville quad.)

51. Outcrop at Yellowstone Lake dam (SE¼, SE¼, sec. 1, T.3N., R.4E., Blanchardville quad.)

52. Roadcut on County K west of Blanchardville (center of sec. 8, T.4N., R.4E., Blanchardville quad.)

53. Roadcut on County JG at Stewart County Park (SE¼, SE¼, sec. 2, T.6N, R.6E., Cross Plains quad.)

54. Roadcut on County J southwest of Pine Bluff (west end of boundary of secs. 28 & 33, T.7N., R.7E., Cross Plains quad.)

55. [S] Two roadcuts on County P north of Pine Bluff (S½, SW¼, sec. 15, T.7N., R.7E., Cross Plains quad.)

56. Highway 178 roadcut south of LaSalle, Illinois (boundary of secs. 20 & 21, T.33N., R.2E., LaSalle quad.)

57. Outcrops in Ottawa and Kaskaskia Canyons, Starved Rock State Park, Illinois (W½, sec. 23, T.33N., R.2E., Ottawa quad.)

58. Quarry just west of entrance to Buffalo Rock State Park (NE¼, SE¼, sec. 18, T.33N., R.2E., Ottawa quad.)

Possible Eolian Outcrops

59. Roadcuts along Rock River and Castle Rock, Highway 2 north of Dixon, Illinois (boundary of secs. 19 & 20, T.23N., R.10E., Dixon quad.)
60. Outcrop east of Oregon, Illinois, just south of Highway 64 (NE¼, NW¼, sec. 8, T.23N., R.11E., Oregon quad.)

Marine Facies over Eolian Facies in Outcrop

61. Roadcut on County P south of Klevenville (center of sec. 9, T.6N., R.7E., Cross Plains quad.)
62. Roadcuts on Highway 78 northeast of Mt. Horeb (S½, sec. 25, T.7N., R.6E., Cross Plains quad.)

Outcrops 63-67 are inside Governor Dodge State Park, Wisconsin:

63. [S] Roadcut on northern entrance road (SE¼, SW¼, sec. 34, T.7N., R.3E., Spring Green quad.)
64. [S] Two outcrops in bluffs (NW¼, NW¼, sec. 35, T.7N., R.3E., Spring Green quad.)
65. [S] Outcrop in bluff (NE¼, SW¼, sec. 25, T.7N., R.3E., Spring Green quad.)
66. [S] Outcrop pinnacle (NE¼, NW¼, sec. 36, T.7N., R.3E., Spring Green quad.)

67. [S] Deer Cove picnic area: roadcut to east and outcrop to west along trail (NW¼, NW¼, sec. 11, T.7N., R.3E., Spring Green quad.)

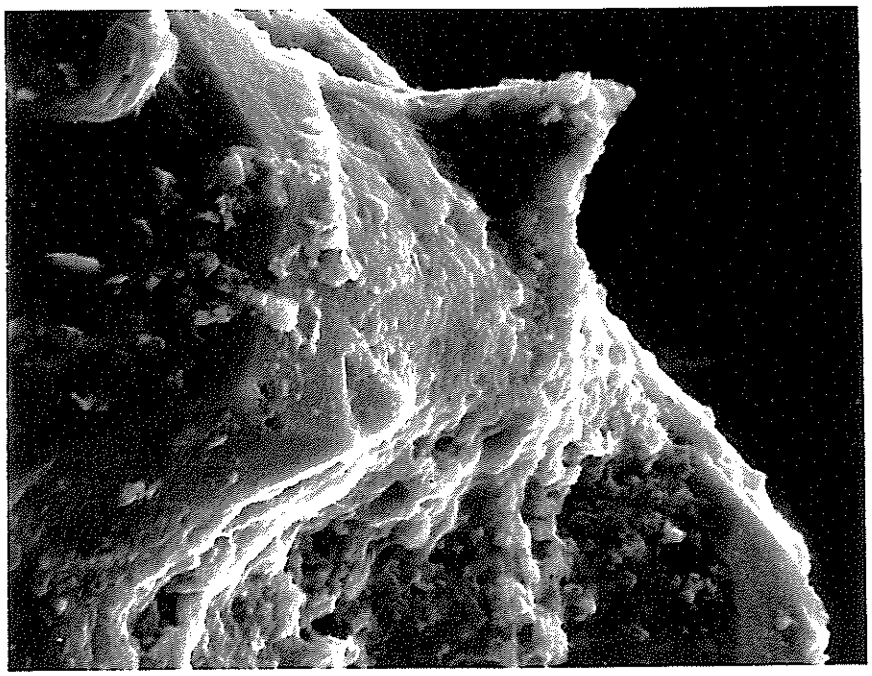
APPENDIX B

SCANNING ELECTRON MICROSCOPE STUDY OF QUARTZ GRAIN SURFACE TEXTURE

This study was not exhaustive or quantitative. I simply wanted to determine whether the surface textures of the eolian grains are obviously different from those of the marine grains, which is what should be expected according to some literature (e.g., Krinsley and Doornkamp, 1973). Sand from beds with adhesion structures and Skolithos were sampled to insure environmental control. The grains from both facies have textures formed by both mechanical abrasion and diagenesis.

Broken cleavage plates and "dish-shaped concavities" (Krinsley and Doornkamp, 1973) are thought to indicate mechanical abrasion. They were found in samples from both environments. Quartz commonly exhibits cleavage when viewed with the high magnification of the scanning electron microscope. Mechanical abrasion can break cleavage plates to produce a series of parallel ridges with small depressions between them (Fig. B-1). Krinsley and Doornkamp (1973) report these from all depositional environments. The so-called "dish-shaped concavities" are

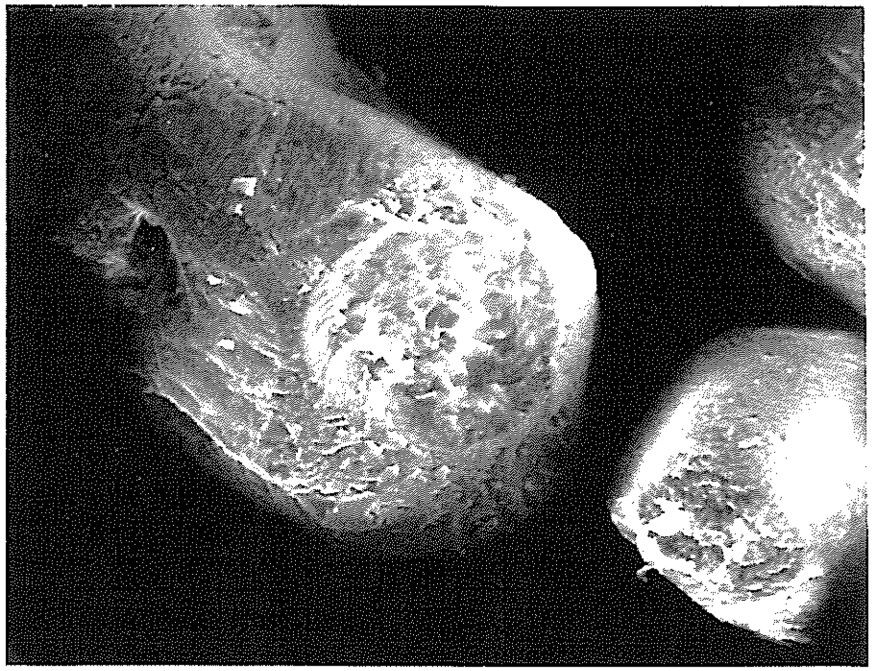
FIGURE B-1: Broken cleavage plates. Notice subhedral overgrowth in upper left center and lower right corner (outcrop #61, marine facies, 1000X).



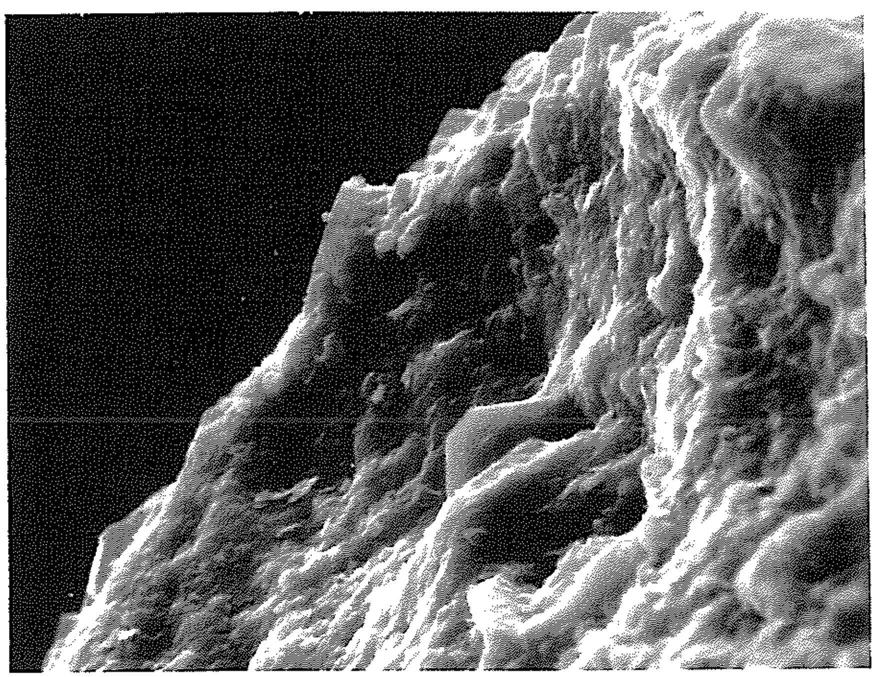
round or elliptical depressions in the grain surface. Krinsley and Doornkamp (1973) imply that these features form only in eolian environments by "mechanical chipping" during sand storms. Most of the depressions I observed were floored with broken plates (Fig. B-2a, B-2b), so the abrasion explanation seems plausible. All of my samples exhibited these features.

The diagenetic textures in St. Peter samples are the result of precipitation and dissolution. Quartz overgrowths are abundant, and they form flat surfaces, pyramidal terminations, and plates that have grown on broken cleavage surfaces (Fig. B-3, B-2b). Precipitation has produced smooth surfaces in areas of broken plates by filling in the depressions (Fig. B-4a, B-4b). Many grains, in all samples, are covered with very small (less than 5μ) particles which are commonly rhombohedral or flat and hexagonal (Fig. B-5). The regularity of form suggests that these are also precipitated crystals of layered silicates, carbonates, and/or feldspar. Authigenic feldspar as well as carbonates have been observed in thin sections of the St. Peter. Meniscus cements between grains were also found (Fig. B-6), and these indicate precipitation in a vadose environment. The crack in the cement of Figure B-6 is probably the result of dissolution and, while this was the only such example observed, other dis-

FIGURE B-2: Dish-shaped concavities: a) eolian grain; notice broken plates on left margin of depression (outcrop #14, 2000X); b) close-up of depression on a marine grain. Lower margin of depression is out of the photo. Notice the subhedral overgrowth on broken plate near the center (outcrop #61, 2000X).



A.



B.

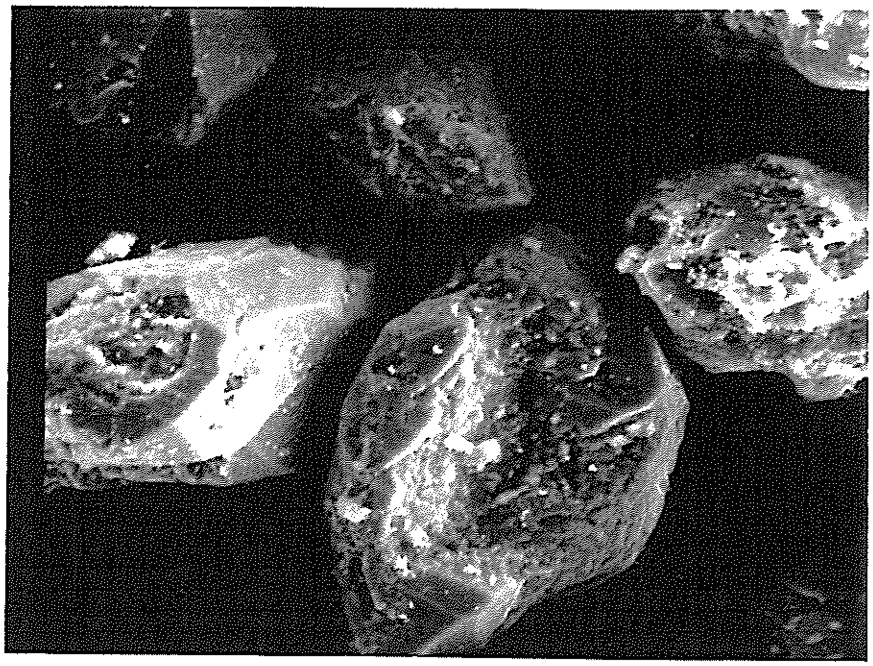
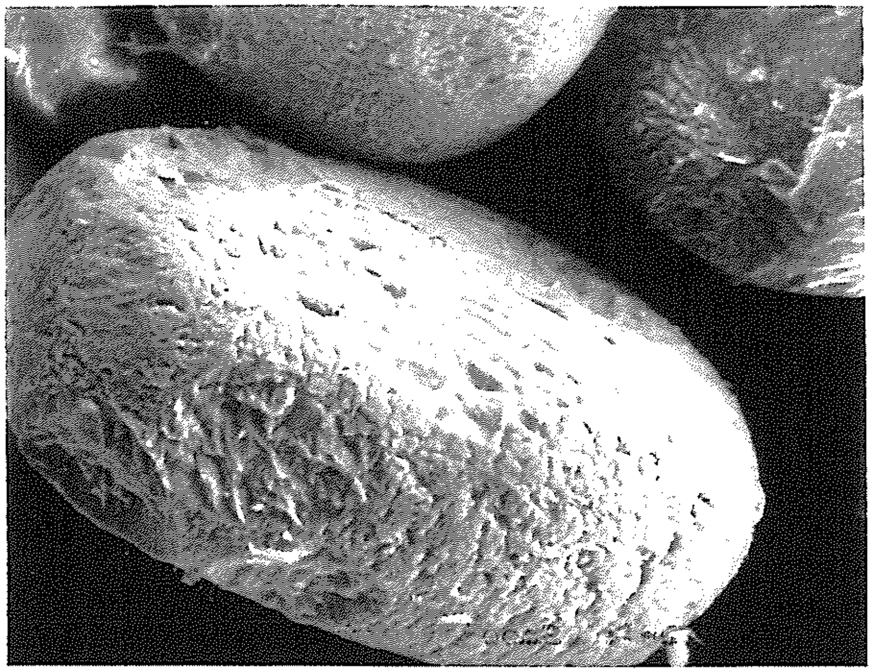


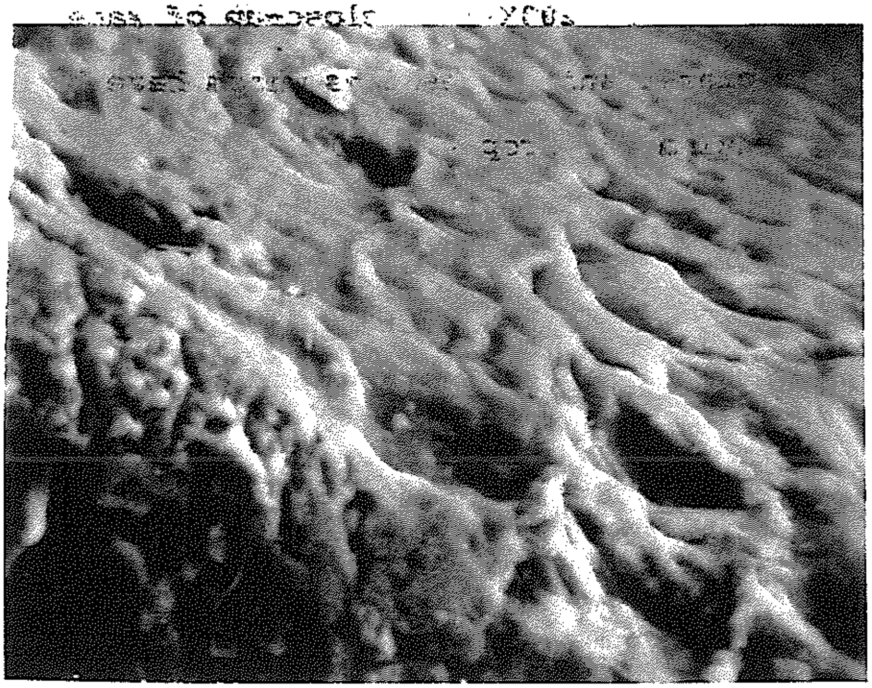
FIGURE B-3: Euhedral overgrowths on marine grains (outcrop #46, 300X).

FIGURE B-4: Smooth surface produced by precipitation and dissolution: a) eolian grain; notice rounding of cleavage plates (200X); b) close-up of same grain; notice rounded plates and depressions which have been filled by precipitation (outcrop #14, 700X).

A.



B.



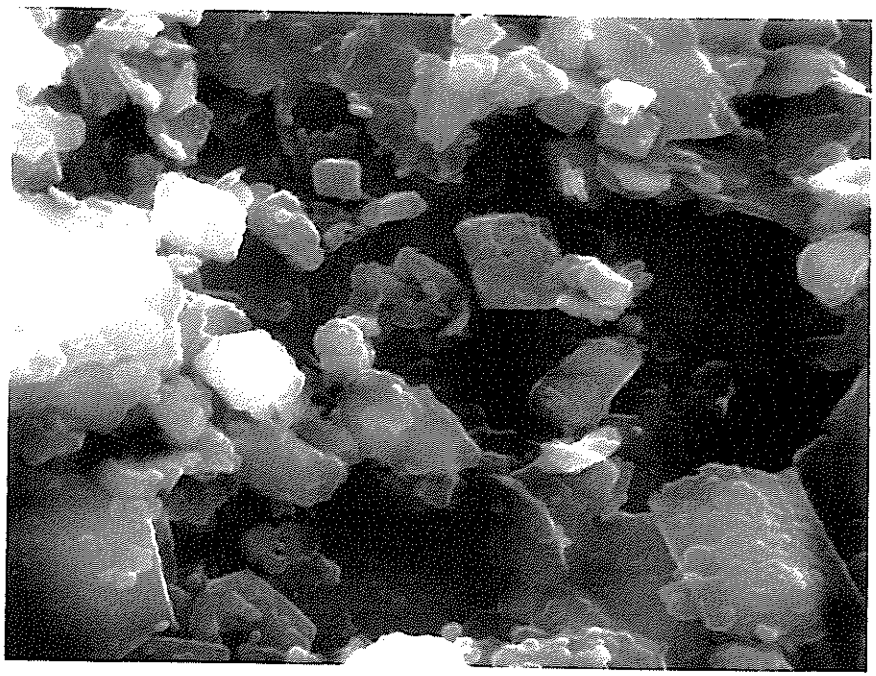


FIGURE B-5: Very small particles which cover most grains. Rhombohedral forms are probably feldspar or carbonate. Flat, hexagonally-shaped forms in lower left are probably layered silicates (outcrop #46, 7000X).

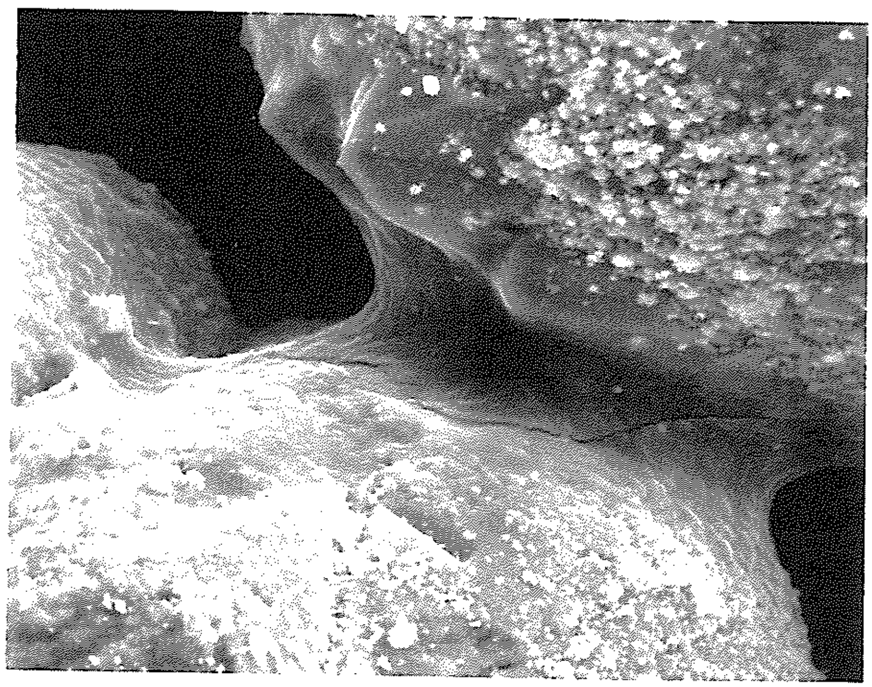


FIGURE B-6: Meniscus cement between two marine grains. Crack in cement is a dissolution feature (outcrop #61, 700X).

solution textures are abundant. The rounded plates of Figure B-4b show the effects of dissolution. Krinsley and Doornkamp (1973) postulate that dissolution occurs on the plates, and that precipitation fills in the depressions. Irregular pits and elongate, oriented, irregular grooves are also the result of dissolution (B-7). The latter probably represent the coalescence of individual pits along planes of weakness in the grain. V-shaped depressions formed by dissolution were also found, but they are rare (Fig. B-8). These may be distinguished from similar pits formed by abrasion because the dissolution pits have a consistent orientation.

There are no obvious qualitative differences between the eolian and marine grain surface textures, and grain shape and rounding are identical, to my eyes (Fig. B-9a, B-9b). Extensive overgrowths are more common on the marine grains, but this probably represents a sampling bias. The "dish-shaped concavities" appear to be more abundant on the eolian grains, and quantitative study of many samples might show a significant difference. The similarity of the grains from both facies is consistent with reworking of eolian deposits in a marine environment. The diagenetic features are expected for a sandstone as old as this one, and they probably represent several episodes of cementation and dissolution. My observations are

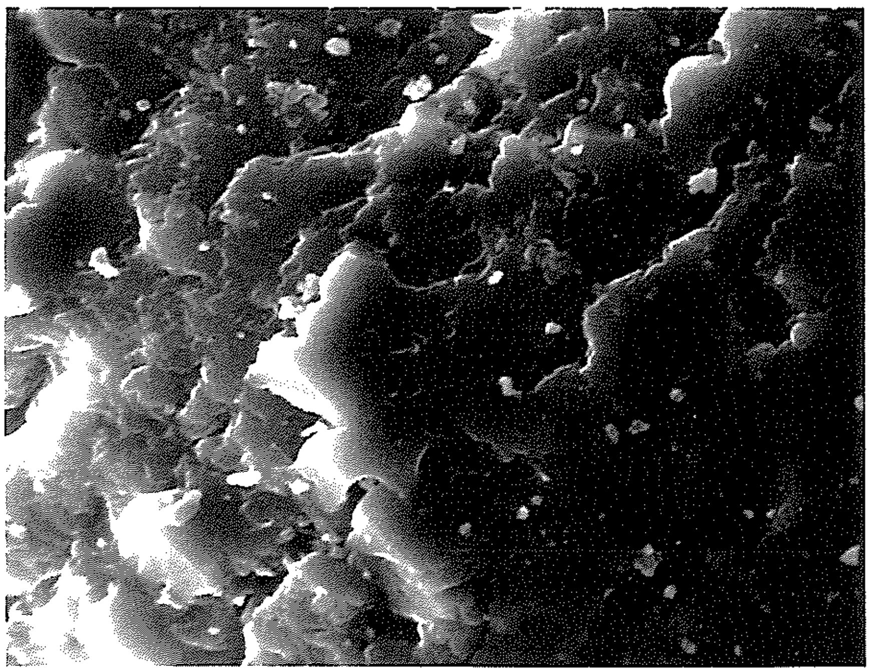
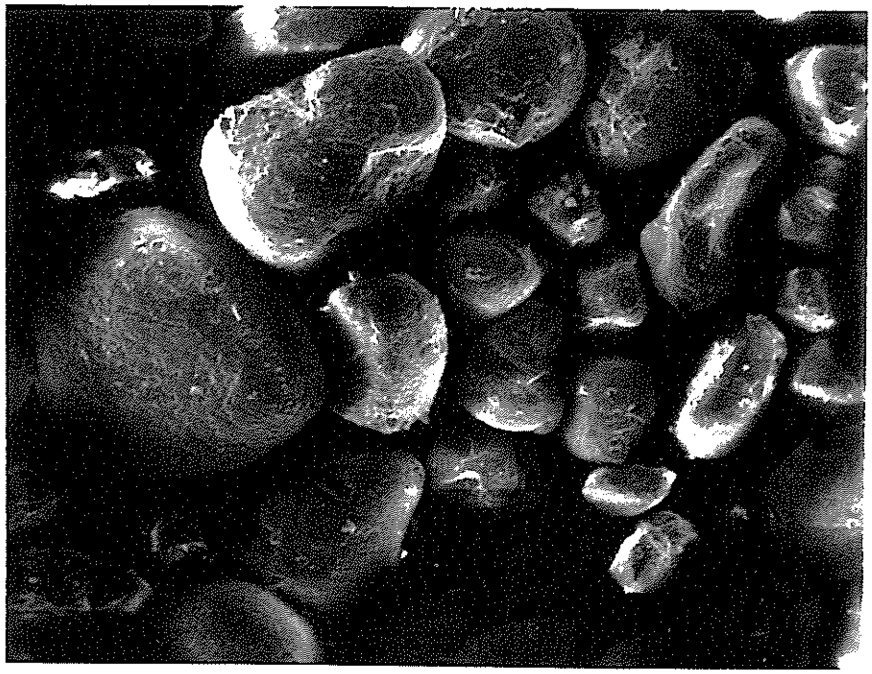
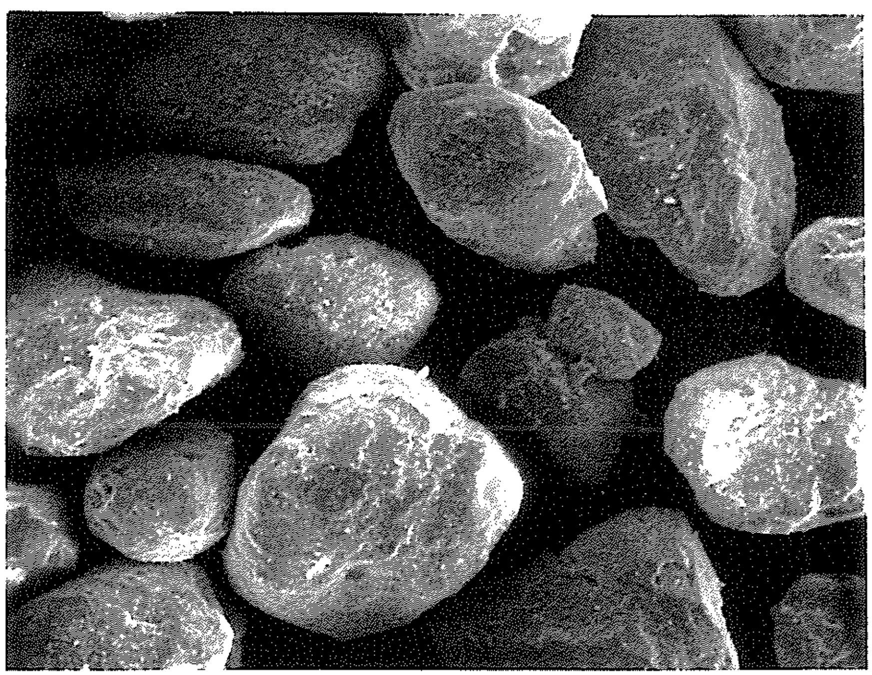


FIGURE B-7: Individual pits and irregular grooves formed by dissolution (compare with Fig. 18, p. 38, Krinsley and Doornkamp, 1973; outcrop #14, 2000X).

FIGURE B-8: V-shaped depressions formed by dissolution. Notice parallelism of depression in center with larger depression on the right margin and very small depression in the lower right reflecting crystallographic structure (outcrop #14, 2000X).

FIGURE B-9: a) eolian grains (outcrop #14, 70X); b) marine grains (outcrop #61, 100X).





basically compatible with those of Mazzullo and Ehrlich (1983), although I am not convinced that their evidence for pre-depositional dissolution (their Fig. 4, p. 110) is conclusive.

APPENDIX C

GRAIN SIZE ANALYSIS

Samples of eolian and marine sandstone were disaggerated for mechanical sieve analysis of grain size. The test hypothesis states that there are no significant differences between the two sets of samples with respect to mean grain size and standard deviation. Fourteen samples were collected from four marine outcrops and six eolian samples were taken from two localities. The results are expressed in the cumulative frequency diagram of Figure C1. The two sets overlap greatly, but the marine samples appear to show more spread and there may be a slight difference in the shapes of the envelopes.

The great overlap made quantitative tests necessary so I Followed Till's (1974, p. 108-110) outline of one-way analysis of variance using both the graphic mean grain size and standard deviation of the samples (Folk,1968, p.45). The average eolian sample mean is 0.022 millimeters and the corresponding marine value is 0.026 millimeters. The results of these two tests are summarized in Table 1.

The sedimentologic significance of the difference in mean size and the homogeneity of standard deviations reported in Table 1 is not clear so I offer these speculations. Local variations in the grain size of the source sandstones probably accounts for the variation of the St. Peter's mean size. The Jordan sandstone and sandstones in the Prarie du Chien and Tunnel City Groups were exposed by erosion before the St. Peter was deposited so each

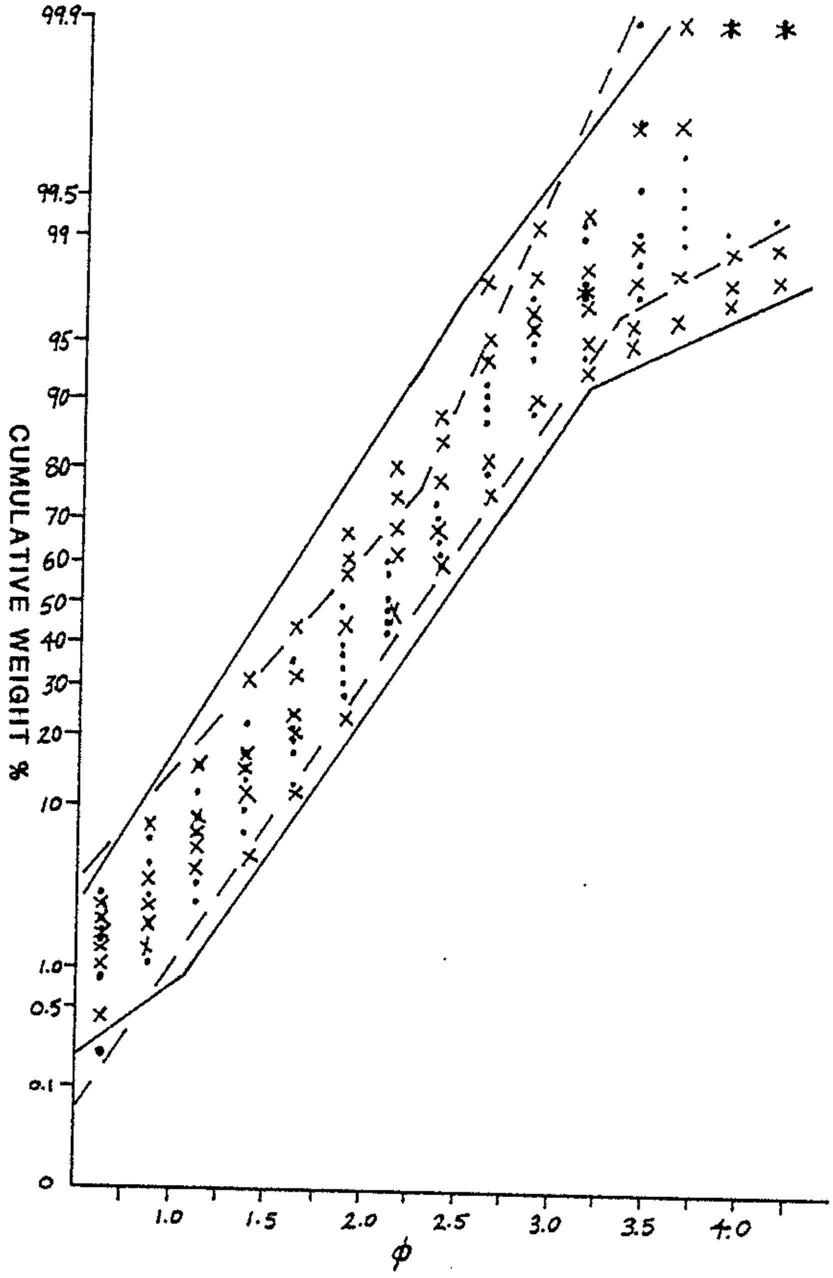


Figure C1: Cumulative weight % vs. grain size for eolian samples (marked with ...) and marine samples (xxxx). Dashed lines= eolian field; solid lines= marine field.

TESTED HYPOTHESES: H1 = There is no difference between the eolian and the marine sets of mean grain sizes.

H2 = There is no difference between the eolian and marine sets of standard deviations.

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARE	F	DECISION
MEAN GRAIN SIZE:					
between groups	1	0.22	0.22	11	REJECT H1
within groups	18	0.37	0.02		
STANDARD DEVIATION:					
between groups	1	0.0006	0.0006	0.077	ACCEPT H2
within groups	18	0.1388	0.0077		

F(0.05, 1, 18) = 4.41. 4.41 less than 11 so reject H1.

4.41 greater than 0.077 so accept H2.

Table 1: Summary of one-way analysis of variance tests of mean grain size and standard deviation of eolian and marine samples. Units are

could produce local variations. The lack of difference in standard deviation seems more puzzling especially in light of the apparent lower sorting of the marine samples (Fig. C1). This homogeneity may indicate that the source sandstones were each too well-sorted to develop a St. Peter environmental signature. These results, therefore, could suggest a source for the St. Peter which consisted of well-sorted sandstones of slightly different mean grain sizes.

REFERENCES CITED

Allen, J. R. L., 1980, Sand waves: a model of origin and internal structure: Sedimentary Geol., v. 26, p. 281-328.

Amaral, E. J., and Pryor, W. A., 1977, Depositional environment of the St. Peter Sandstone deduced by textural analysis: Jour. Sed. Petrology, v. 47, p. 32-52.

Bagnold, R. A., 1941, The Physics of Blown Sand and Desert Dunes: London, Methuen and Co., 265 p.

Berkey, C. P., 1906, Paleogeography of Saint Peter time: Geol. Soc. Am. Bull., v. 17, p. 229-250.

Bourgeois, J., 1980, A transgressive shelf sequence exhibiting hummocky stratification: The Cape Sebastian Sandstone (Upper Cretaceous), southwestern Oregon: Jour. Sed. Petrology, v. 50, p. 681-702.

Brookfield, M. E., 1977, The origin of bounding surfaces in ancient aeolian sandstones: Sedimentology, v. 24, p. 303-332.

Buschbach, T. C., 1961, The morphology of the sub-St. Peter surface of northeastern Illinois: Ill. Acad. Sci. Trans., v. 54, p. 83-89.

Buschbach, T. C., 1964, Cambrian and Ordovician strata of northern Illinois: Ill. State Geol. Survey Report of Inv. 218, p. 47-53.

Cady, G. H., 1920, The structure of the LaSalle anticline: Ill. State Geol. Survey Bull., no. 36, p. 85-179.

Chamberlin, T. C., 1883, Geology of Wisconsin, Survey of 1873-1879, v. 1: Commissioners of Public Printing, p. 145-150.

Clifton, H. E., Hunter, R. E., and Phillips, R. L., 1971, Depositional structures and processes in the non-barred high-energy nearshore: Jour. Sed. Petrology, v. 41, p. 651-670.

Dake, C. L., 1921, The problem of the St. Peter Sandstone: Missouri School of Mines and Metallurgy, Univ. Missouri Bulletin, v. 6, no. 1, 228 p.

Dalrymple, R. W., 1980, Internal structures of shallow-marine tidal sand waves: Am. Assoc. Petrol. Geologists Abs. for Annual Meeting, p. 43.

Dapples, E. C., 1955, General lithofacies relationship of St. Peter Sandstone and Simpson Group: Am. Assoc. Petroleum Geologists Bull., v. 39, p. 444-467.

Dott, R. H., Jr., 1974, Cambrian tropical storm waves in Wisconsin: Geology, v. , p. 243-246.

Dott, R. H., Jr., 1978, Sedimentology of Upper Cambrian cross-bedded sandstone facies as exemplified by the Van Oser sandstone: Wisconsin Geol. and Nt. Hist. Survey, Field Trip Guidebook #3, p. 52-66.

Dott, R. H., Jr., and Batten, R. L., 1976, Evolution of the Earth: New York, McGraw-Hill, 504 p.

Dott, R. H., Jr., and Byers, C. W., 1980, Field trip guidebook for the S.E.P.M. research conference on modern shelf and ancient cratonic sedimentation: Soc. Econ. Paleontologists and Mineralogists, p. 26-27.

Dott, R. H., Jr., and Roshardt, M. A., 1972, Analysis of cross-stratification orientation in the St. Peter Sandstone in southwestern Wisconsin: Geol. Soc. Am. Bull., v. 83, p. 2589-2596.

Field, M. E., Nelson, C. H., Cacchione, D. A., and Drake, D. E., 1981, Sand waves on an epicontinental shelf: Northern Bering Sea: Marine Geol., v. 42, p. 233-258.

Flint, A. E., 1956, Stratigraphic relations of the Shakopee Dolomite and the St. Peter Sandstone in southwestern Wisconsin: Jour. Geol., v. 64, p. 396-421.

Folk, R. L., 1968, Petrology of Sedimentary Rocks: Austin, TX, Hemphill's Book Store, 170 p.

Fraser, G. S., 1976, Sedimentology of a Middle Ordovician quartz arenite-carbonate transition in the upper Mississippi Valley: Geol. Soc. Am. Bull., v. 86, p. 833-845.

Freeman, L. B., 1949, Regional aspects of Cambrian and Ordovician subsurface stratigraphy in Kentucky: Am. Assoc. Petroleum Geologists Bull., v. 33, p. 1655-1681.

Frey, R. W., and Howard, J. D., 1969, A profile of biogenic sedimentary structures in a Holocene barrier island-salt marsh complex, Georgia: Gulf Coast Assoc. Geol. Socs. Trans., v. 19, p. 427-444.

Fryberger, S. G., and Schenk, C., 1981, Wind sedimentation tunnel experiments on the origins of aeolian strata: Sedimentology, v. 28, p. 805-821.

Glennie, K. W., 1972, Permian Rotliegendes of northwest Europe interpreted in light of modern desert sedimentation studies: Am. Assoc. Petrol. Geol. Bull., v. 56, p. 1048-1071.

Goldring, R., and Bridges, P., 1973, Sublittoral sheet sandstones: Jour. Sed. Petrology, v. 43, p. 736-747.

Goodwin, P. W., and Anderson, E. J., 1977, Specific habitat of the Skolithos community within lower Paleozoic tidal environments (abs.): Jour. Paleontology, v. 51, supplement to no. 2, p. 12.

Grether, W. J., and Clark, D. L., 1980, Conodonts and stratigraphic relationships of the Readstown Member of the St. Peter Sandstone in Wisconsin: Geoscience Wisconsin, v. 4, p. 1-29.

Horne, R. R., 1971, Aeolian cross-stratification in the Devonian of the Dingle Peninsula, County Kerry, Ireland: Geol. Magazine, v. 108, p. 151-158.

Howard, J. D., 1972, Trace fossils as criteria for recognizing shorelines in stratigraphic record: in Rigby, J. K., and Hamblin, W. K., eds., Recognition of Ancient Sedimentary Environments, Soc. Econ. Paleontologists and Mineralogists Spec. Pub. No. 16, p. 215-225.

Howard, J. D., 1975, The sedimentological significance of trace fossils in Frey, R. W., ed., The Study of Trace Fossils, Springer-Verlag, New York, p. 131-146.

Howard, J. D., and Reineck, H. E., 1972, Georgia coastal region, Sapelo Island, U.S.A.: Sedimentology and Biology. IV. Physical and biogenic sedimentary structures of the nearshore shelf: Senckenbergiana Marit., v. 4, p. 81-123.

Howard, J. D., and Reineck, H. E., 1981, Depositional facies of high-energy beach-to-offshore sequence: comparison with low energy sequence: Am. Assoc. Petrol. Geologists Bull., v. 65, p. 807-830.

Hunter, R. E., 1973, Pseudo-cross lamination formed by climbing adhesion ripples: Jour. Sed. Petrology, v. 43, p. 1125-1127.

Hunter, R. E., 1976, Comparison of eolian and subaqueous sand-flow cross-strata: Am. Assoc. of Petroleum Geologists Abs., v. 60, p. 683-684.

Hunter, R. E., 1977, Basic types of stratification in small eolian dunes: Sedimentology, v. 24, p. 361-387.

Kocurek, G., 1981, Significance of interdune deposits and bounding surfaces in aeolian dune sands: Sedimentology, v. 28, p. 753-780.

Kocurek, G., and Dott, R. H., Jr., 1981, Distinctions and uses of stratification types in the interpretation of eolian sand: Jour. Sed. Petrology, v. 51, p. 579-595.

Kocurek, G., and Fielder, G., 1982, Adhesion structures: Jour. Sed. Petrology, v. 52, p. 1229-1241.

Krinsley, D., and Doornkamp, J. C., 1973, Atlas of Quartz Sand Surface Features: Cambridge University Press, 91 p.

Lamar, J. E., 1928, Geology and economic resources of the St. Peter Sandstone of Illinois: Ill. State Geol. Survey Bull., no. 53, p. 14-62.

Mazzullo, J. M., and Ehrlich, R., 1980, A vertical pattern of variation in the St. Peter Sandstone, fourier grain shape and analysis: Jour. Sed. Petrology, v. 50, p. 63-70.

Mazzullo, J. M., and Ehrlich, R., 1983, Grain-shape variation in the St. Peter Sandstone: A record of eolian and fluvial sedimentation of an early cratonic sheet sand: Jour. Sed. Petrology, v. 53, p. 105-119.

McBride, E. F., and Hayes, M. O., 1962, Dune cross-bedding on Mustang Island, Texas: Am. Assoc. Petroleum Geologists Bull., v. 46, p. 546-551.

Merriam, D. F., and Atkinson, W. R., 1956, Simpson-filled sinkholes in eastern Kansas: Kansas State Geol. Survey Bull., v. 119, p. 61-80.

Ostrom, M. E., 1967, Paleozoic stratigraphic nomenclature for Wisconsin: Univ. Wis. Geol. and Nat. Hist. Survey Info. Circ. 8.

Ostrom, M. E., 1970, Stratigraphy and sedimentation of Cambrian and Ordovician rocks in western Wisconsin: Geol. and Nat. Hist. Survey, Univ. of Wis., Info. Circ. no. 11, p. 84.

Palmquist, R. C., 1969, The configuration of the Prairie du Chien-St. Peter contact in southwestern Wisconsin: Jour. Geol., v. 77, p. 694-702.

Pilkey, O. H., Ayers, M. W., Blackwelder, B. W., Howard, J. D., and Knebel, H. J., 1979, History of the Georgia Embayment sediment cover: Geol. Soc. Am. Abs. with Programs, SE section, p. 208.

Piper, D. J. W., 1970, Eolian sediments in the basal New Red Sandstone of Arran: Scott. Jour. Geol., v. 6, p. 295-308.

Pryor, W. E., and Amaral, E. J., 1971, Large-scale cross-stratification in the St. Peter Sandstone: Geol. Soc. Am. Bull., v. 82, p. 239-244.

Reineck, H. E., 1955, Haftrippeln und Haftwarzen, Ablagerungs Formen von Flugsand: Senckenbergiana Lethaea, v. 36, p. 347-357.

Reineck, H. E., and Singh, I. B., 1972, Genesis of laminated sands, and graded rhythmites in storm-sand layers of shelf muds: Sedimentology, v. 18, p. 123-128.

Rodolfo, K. S., Buss, B. A., and Pilkey, O. H., 1971, Suspended sediment increase due to Hurricane Gerda in continental shelf waters off Cape Lookout, North Carolina: Jour. Sed. Petrology, v. 41, p. 1121-1125.

Roshardt, M. A., 1964, Paleocurrent and textural analyses of the St. Peter sandstone in a portion of south central Wisconsin: unpub. M.S. thesis, Univ. Wisconsin-Madison, 40 p.

Sanders, J. E., and Kumar, N., 1975, Evidence of shoreface retreat and in-place "drowning" during Holocene submergence of barriers, shelf off Fire Island, New York: Geol. Soc. Am. Bull., v. 86, p. 65-76.

Sardeson, F. W., 1891, Fossils in the St. Peter Sandstone: Minn. Acad. Sci. Bull., v. 3, 1883-1891, p. 318-319.

Sardeson, F. W., 1892, The St. Peter Sandstone: Minn. Acad. Sci., Bull., v. 4, 1892-1910, p. 64-88.

Sharp, R. P., 1963, Wind ripples: Jour. Geol., v. 71, p. 617-636.

Sloss, L. L., 1963, Sequences in the Cratonic Interior of North America: Geol. Soc. Am. Bull., v. 74, p. 93-114.

Suter, M., Bergstrom, R. E., Smith, H. F., Emrich, G. H., Walton, W. C., and Larson, T. E., 1959, Preliminary report on ground-water resources of the Chicago region, Illinois: Ill. State Geol. Survey and State Water Survey Cooperative Ground-Water Report I, p. 21-31.

Templeton, J. S., and Willman, H. B., 1952, Guidebook for the sixteenth annual field conference of the Tri-State Geological Society, Central Northern Illinois: Ill. Geol. Survey, Guidebook no. 2.

Templeton, J. S., and Willman, H. B., 1963, Champlainian series (Middle Ordovician) in Illinois: Ill. State Geol. Survey Bull., v. 89, p. 39-47.

Thwaites, F. T., 1923, The paleozoic rocks found in deep wells in Wisconsin and northern Illinois: Jour. Geol., v. 31, p. 529-555.

Thwaites, F. T., 1961, The base of the St. Peter Sandstone in southwestern Wisconsin: Wis. Acad. Sci. Arts and Letters, v. 50, p. 203-219.

Till, R., 1974, Statistical Methods for the Earth Scientist; An Introduction: New York, Wiley, 154 p.

Trowbridge, A. C., 1917, The Prairie du Chien-St. Peter unconformity in Iowa: Iowa Acad. Sci. Proc., v. 24, p. 177-182.

Twenhofel, W. H., and Thwaites, F. T., 1919, The Paleozoic section of the Tomah and Sparta Quadrangles, Wisconsin: Jour. Geol., v. 27, p. 614-633.

Wilson, I. G., 1973, Ergs: Sedimentary Geology, v. 10, p. 77-106.