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# PREFACE

The St. Peter Formation is an important aquifer as well as a source of high-purity silica sand in southern and eastern Wisconsin. This report summarizes the first of a series of studies planned to investigate the stratigraphy and geometry of the Cambrian and Ordovician rocks in the subsurface of Wisconsin. These rocks are the source of much of the water supply for the urban and rural communities of southeast Wisconsin, and the abundance of samples collected during construction of private and municipal wells makes such studies possible. An understanding of the thickness, depth, variability and composition of these water-bearing formations is essential to protect and manage our deep groundwater resource.

Dr. Meredith E. Ostrom
Director and State Geologist

# A Subsurface Study of the St. Peter Sandstone In Southern and Eastern Wisconsin

by

Huazhao Mai[1] and R. H. Dott, Jr.[2]

## ABSTRACT

A subsurface study of the St. Peter Sandstone in southern and eastern Wisconsin has been undertaken using water well samples and sample logs and one core. A thickness map of the St. Peter Sandstone, a structure contour map of the pre-St. Peter surface, and a paleogeologic map of the pre-St. Peter surface have been constructed. Regional distribution and thickness patterns, source of sand, tectonic implications as well as sedimentation of the St. Peter Sandstone are discussed in the text. This investigation provides a more complete picture of the subsurface geology of the St. Peter Sandstone in Wisconsin than has ever been shown before. The information therefore should be helpful to government agencies, industry, educators and the general public, especially because the St. Peter is a potential aquifer and source of pure silica sand. It also is important as a possible avenue for the migration of toxic wastes.

The St. Peter Sandstone (or Formation) was deposited upon an extensive erosion surface developed on older Ordovician, Cambrian, and (locally) even Precambrian rocks. Drainage patterns can be recognized from the structure contour map. The purity and texture of the sandstone attest to a long history of abrasion and sorting prior to deposition. There is little doubt that much of its character was inherited by recycling of Cambrian sandstones during the pre-St. Peter erosional episode. Sedimentological studies have shown that much of the St. Peter in Wisconsin was deposited by eolian processes, but marine transgression from the southwest also produced a marine facies, which is best developed in western Wisconsin and at the top of the formation farther eastward. Both the paleo-drainage and paleogeologic patterns indicate that the so-called Wisconsin arch was not influential at this time. Instead a pre-St. Peter domal area lay beneath eastern Wisconsin and pre-St. Peter drainage was entirely eastward.

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## INTRODUCTION

In Wisconsin the St. Peter Sandstone or Formation crops out along the flanks of the Wisconsin arch in an arcuate belt (Fig. 1). Along the west flank, the sandstone is more dissected, forming a belt of outliers, which includes isolated examples in northwestern Wisconsin (St. Croix and Pierce Counties) that were not studied. The St. Peter Sandstone is found in the subsurface throughout eastern and southern Wisconsin. The subsurface extent occupies more than three-fourths of the total area of distribution of the St. Peter in the state. Therefore a subsurface analysis of the Sandstone was undertaken primarily to establish: a) thickness variations, b) configuration of the basal unconformity, and c) paleogeology beneath the unconformity. A fuller knowledge of these aspects should complement recent detailed sedimentologic studies of surface exposures (e.g. Mazzullo and Ehrlich, 1983, Winfree, 1983; Winfree and Dott, 1983) to provide an understanding of the genesis of one of the world's most famous sandstones. Such knowledge also should have considerable economic importance.

The Middle Ordovician St. Peter Sandstone is a classic cratonic supermature quartz arenite composed of remarkably uniform and very pure, rounded, well-sorted, coarse- to fine-grained sand. The sandstone constitu-

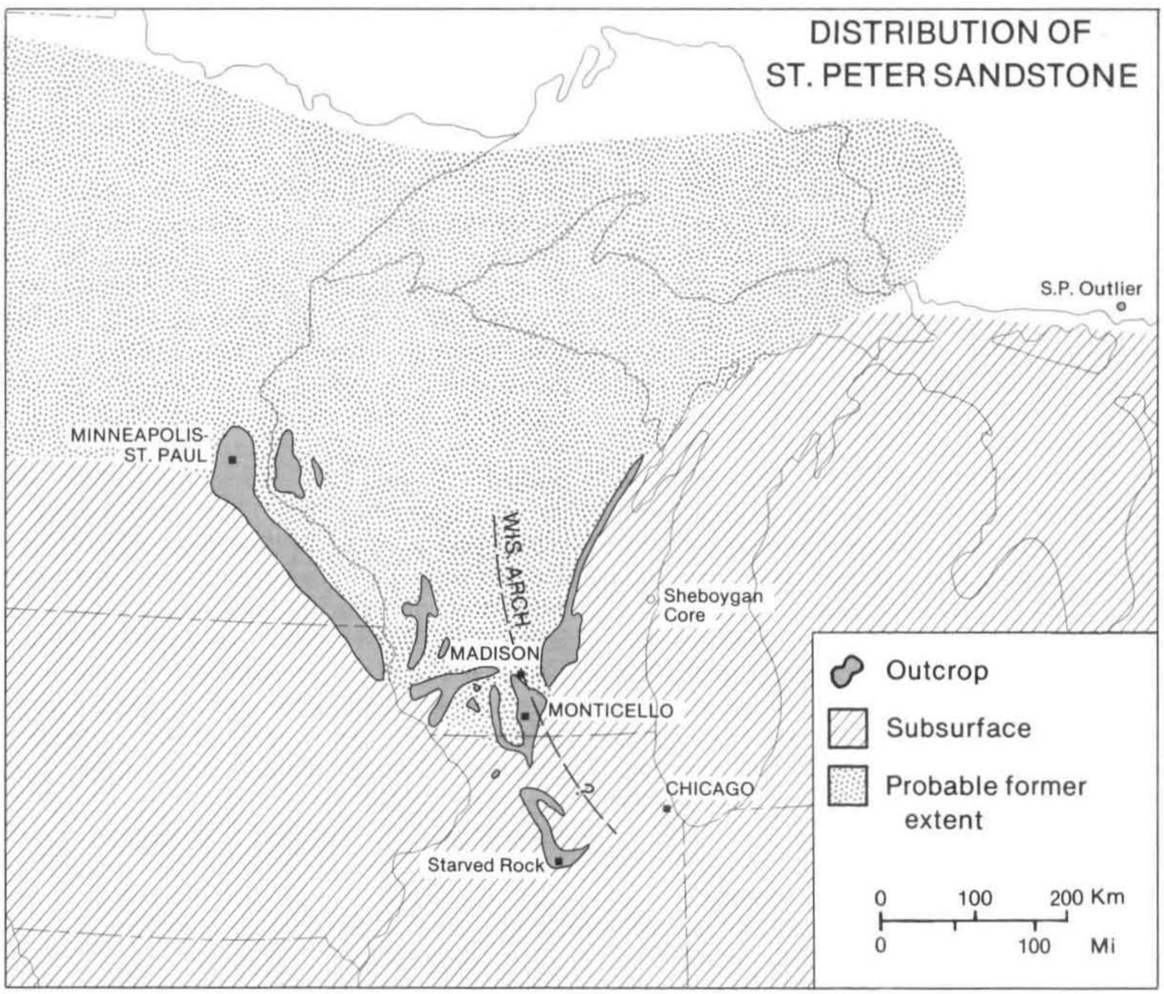


Figure 1. Distribution of the St. Peter Sandstone

tes an extensive and continuous sheet of clastic rocks overlying a widespread unconformity and occupying much of the central part of the United States (Fig. 1). The exceptionally widespread sub-St. Peter unconformity defines the base of the Tippecanoe stratigraphic sequence of Sloss (1963). Although the St. Peter Sandstone has long been studied in Wisconsin, few geologists have availed themselves of subsurface information available from many graphic logs prepared from detailed study of water well drill cuttings contained in the files of the Wisconsin Geological and Natural History Survey. The synthesis of this vast data bank would provide much information on subsurface stratigraphy and structure as well as the tectonic history of Wisconsin and adjacent states.

The purity of the St. Peter Sandstone makes it a sand resource for glass manufacture, abrasives, and foundry molding. Its porosity and permeability make it a potential ground water and petroleum reservoir. The St. Peter is quarried extensively for silica sand and is a major aquifer in Illinois (Willman et al., 1975, pp. 62-63); it has been similarly exploited to a lesser degree in Iowa, Minnesota and Wisconsin. The St. Peter could be important to toxic waste movement in the subsurfaces.

## METHODS OF STUDY

The major sources of data were three types of logs. These were primarily water well sample logs, some water well drillers' logs, and one core. Cuttings from selected wells were studied to gain understanding of the general lithology, especially variations of grain size. Any apparent anomalies of formation identification on the logs were checked by examining cuttings. A single core of the entire formation from near Sheboygan in east-central Wisconsin provided lithologic data comparable to that available in outcrops. It is unfortunate that no other cores were available. Some outcrops were studied to correlate the surface and subsurface information. A search of the literature (including a few gamma ray logs for the Michigan Basin) provided additional data. Plates 1 and 2 are the principal results of the subsurface analysis.

## STRATIGRAPHY

### Name and Age

St. Peter is the name applied by Owen (1847, p. 170) to the sandstone exposed in Minneapolis and St. Paul, Minnesota, along the "St. Peter River", which is now called "Minnesota River". The type section is in a bluff where the Minnesota joins the Mississippi River at Fort Snelling in Minneapolis.

Generally the St. Peter is non-fossiliferous, except for local "worm borings" (Skolithos) in western Wisconsin and throughout southeastern Minnesota and northern Illinois (Fig. 2). Sardeson (1896, pp. 70-79) described a few species of fossils, including pelecypods, gastropods, cephalopods, brachiopods, bryozoans and sponges, from several horizons below the top of the formation at St. Paul, Minnesota. He also reported fossils from the top of the St. Peter (probably the Glenwood Member) at Dodgeville, Wisconsin. Fossils have also been found in sandstone considered to be St. Peter at Kentland, Indiana (Shrock and Mallot, 1933, p. 351). Middle Ordovician Chazyan conodonts are reported from shales in cores at St. Paul, northwestern Iowa, and eastern Nebraska (Witzke, 1980) and Blackriveran ones from the Glenwood Member in southwestern Wisconsin

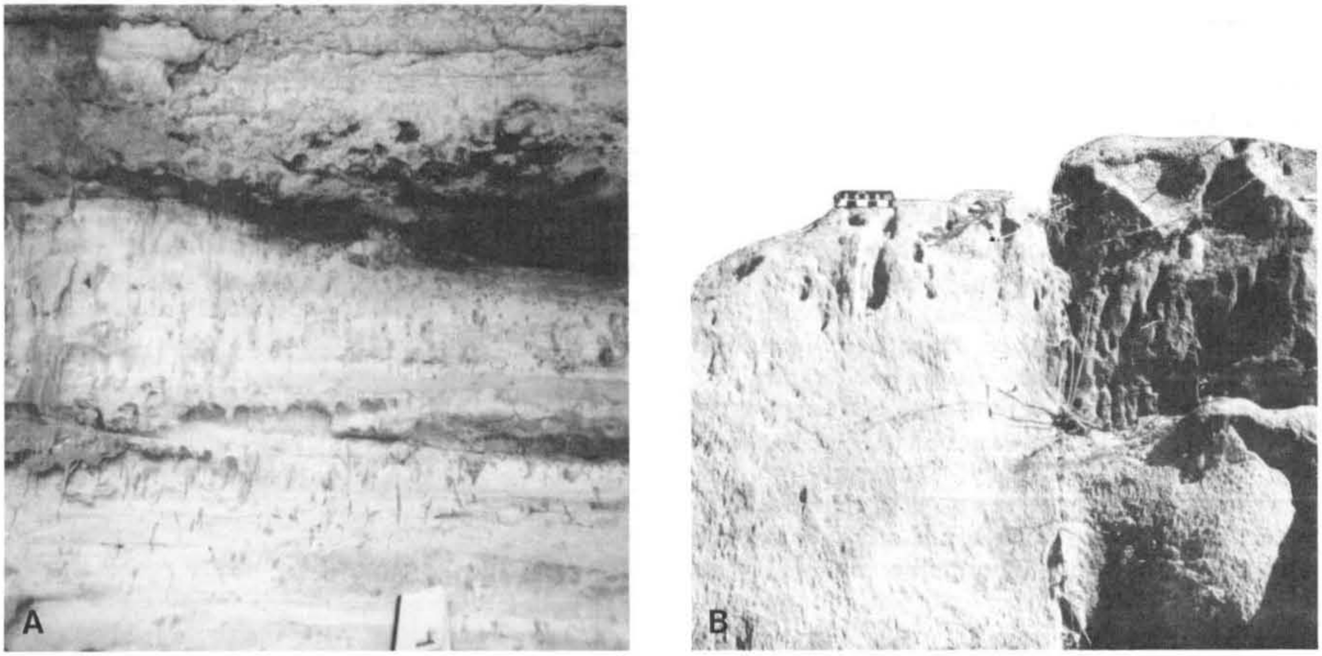


Figure 2. Examples of Skolithos trace fossils in the St. Peter Sandstone. A. Clear Skolithos tubes at many levels at the eastern end of Starved Rock State Park, Illinois. B. Subtle weathered tubes in a roadcut 1.2 miles north of Pine Bluff, Wisconsin on County Highway P approximately 12 miles west of Madison.

(Clark, 1971). In Iowa and Nebraska, brachiopods have also been found in dark shales (Witzke, 1980). The exact age span of the St. Peter Sandstone is unclear, but the span of the Simpson Group of Oklahoma, at least part of which is considered correlative with the St. Peter, ranges from possible Early Ordovician (Beekmantownian) through Middle Ordovician (Blackriveran) and is alleged to become progressively younger northward (Dapples, 1955, p. 445). But the McLish Formation in the Simpson Group, which is considered by some to be the principle equivalent of the St. Peter, is only Chazyan. Therefore, Witzke (1980) has suggested that the St. Peter is mostly Chazyan and (at the top) Blackriveran in the upper midwest.

## Stratigraphic Subdivisions

In Wisconsin the St. Peter Sandstone or Formation consists of a conglomeratic mixture of chert, shale and sandstone at the base, a clean, friable sandstone in the middle, and a shaly and dolomitic sandstone and shale at the top. The basal conglomerate was assigned the name Kress Member by Buschbach (1964, p. 51). Because the type section of the Kress Member is represented only by samples from a well in northern Illinois rather than from an outcrop, Ostrom (1967) renamed the basal conglomerate the Readstown Member for exposures in the vicinity of Readstown, Wisconsin (Fig. 3). The Readstown Member is very irregular in occurrence, but is easily identified in well cuttings as well as outcrops. It may rest unconformably upon any of the underlying older formations (Pl. 1-Cross Section AA', BB', CC', DD'; Pl. 2). Thickness of the Readstown Member can vary greatly, depending upon position along the irregular pre-St. Peter erosion surface. Its maximum thickness is 275 feet in well Iw-11 in Iowa County, where the entire formation is

| System | Series | Group | Formation | Member | |
|---|---|---|---|---|---|
| Ordovician | Cincinnatian | | Neda<br>Maquoketa | | |
| | Champlainian | Sinnipee | Galena | | |
| | | | Decorah | | |
| | | | Platteville | | |
| | | Ancell Group in Illinois | St. Peter | Glenwood | Hennepin |
| | | | | | Harmony Hill |
| | | | | | Nokomis |
| | | | | Tonti | |
| | | | | Readstown | |
| | Canadian | Prairie du Chien | Shakopee | Willow River | |
| | | | | New Richmond | |
| | | | Oneota | | |
| Cambrian | St. Croixan | Trempealeau | Jordan | Coon Valley | |
| | | | | Sunset Point | |
| | | | | Van Oser | |
| | | | | Norwalk | |
| | | | St. Lawrence | Lodi | Black Earth |
| | | Tunnel City | Lone Rock | Reno | |
| | | | Mazomanie | Tomah | |
| | | | | Birkmose | |
| | | Elk Mound | Wonewoc | Ironton | |
| | | | | Galesville | |
| | | | Bonneterre | | |
| | | | Eau Claire | | |
| | | | Mt. Simon | | |

Figure 3. Generalized stratigraphic column of Paleozoic rocks in Wisconsin (modified after Ostrom, 1978).

abnormally thick (Pl. 1-Cross Section CC'). The Readstown Member consists of white to red sandstone, conglomerate (consisting of fragments of shale, chert, sandstone and dolomite), brown to red shale, or any combination, all in a matrix of fine to coarse sand or clay.

Pure, fine-to-coarse quartz sandstone in the middle was named the Tonti Formation by Templeton and Willman (1963, p. 45), but was designated a member of the St. Peter Formation in Wisconsin by Ostrom (1967). The Tonti Member conformably overlies the Readstown Member, but, where the latter is absent, sandstones of the Tonti overlap it to rest directly upon any of the underlying older formations (Pl. 1-Cross Section AA', CC'). In Wisconsin the Tonti generally forms the greater part or the entirety of the St. Peter Sandstone. The Tonti is commonly 100-150 feet thick, but locally exceeds 260 feet. The Tonti Member is chiefly fine-to medium-grained, well-sorted sandstone, commonly with frosted grains, poorly cemented by dolomite, and is white, red or yellow in color. Commonly the Tonti Member contains thin layers of pale green shale.

The Tonti is overlain by the Glenwood Member, which consists of dolomitic poorly sorted sandstone, blue green shale or a sandy dolomite, gray to light gray in color. The name Glenwood was introduced by Calvin (1906, pp. 60-61) for a 15 foot-thick section of shale and sandstone exposed in Glenwood Township, Winneshiek County, northeastern Iowa. The Glenwood was designated a separate formation by Templeton and Willman (1963, p. 48), but it is considered by the Wisconsin Geological and Natural History Survey to be a member of the St. Peter. It was subdivided into the Nokomis, Harmony Hill and Hennepin (Fig. 3) (Templeton and Willman, 1963; Ostrom, 1967), but these were not distinguished in the present study. The Glenwood is absent in some areas, such as over the Wisconsin arch, but is distinguishable in most wells in other areas. It may be the only unit present in northeastern Wisconsin, where it occurs as a very sandy dolomite (Pl. 1-Cross Section BB').

Templeton and Willman (1963, p. 29) proposed the name "Ancell Group" to replace "St. Peter Sandstone". The name was taken from Ancell in southeastern Missouri, where quartz sandstone is intimately associated with argillaceous and sandy carbonate rocks (Dutchtown and Joachim Formations), which overlie the Everton Dolomite and underlie the Platteville Group. In northern Illinois the Ancell Group includes all strata previously referred to the St. Peter and Glenwood. The new group name apparently was proposed to encompass significant regional facies variations, which pose serious stratigraphic problems in the subsurface of Indiana, Illinois and Iowa. In the upper midwest, however, the name Ancell offers no advantage, so the original name St. Peter has persisted and is used in this study.

### Regional Distribution and Thickness Patterns

Areal distribution and stratigraphic relationships of the St. Peter Sandstone indicate that it consists of an extensive and continuous sheet of clastic sediment covering large areas in Wisconsin, Minnesota, Illinois, Iowa, Missouri, and Arkansas (Fig. 1). Except for local thickening in Wisconsin (Pl. 2 ) and Illinois, the St. Peter Sandstone is very uniform and shows no regular changes in thickness in the upper midwest, where it averages 100-200 feet. But the thickness of the clastic sheet increases progressively into southern Oklahoma (the equivalent Simpson Sandstone). Apparently the eastern depositional edge of sandstone passes through central Michigan, Indiana and Kentucky, where sandy facies grade eastward to carbonate ones (Fig. 1) (Dapples, 1955; Sloss and others, 1960, pp. 6-7; Droste and others, 1982, p. 6; Bricker and others, 1983, pp. 6-9). The stratigraphically equivalent Simpson Sandstone of Oklahoma grades southward into shaly sandstone, shale and sandy limestone (Dapples, 1955, p. 446). The St. Peter's western margin, which is erosional, is found in Nebraska, Kansas, and Minnesota (Fig. 1), but similar Ordovician pure quartz sandstones also occur widely on the western side of the transcontinental arch from Colorado to Manitoba (e.g. Harding, Winnipeg, etc.; summarized in Witzke, 1980). The northern margin also has been completely modified by erosion, but there are a few outliers of fossiliferous Middle Ordovician quartz sandstone in the southern Canadian shield (Fig. 1).

The St. Peter must have once extended many miles farther toward the north and west according to the characteristics of the formation as seen in the most northern outcrops of Wisconsin and Minnesota (Thiel, 1935, p. 352) as well as along its western subsurface limit. Thus even the impressive preserved extent of the St. Peter and its correlative sandstones understates the original vastness of this exceptional clastic formation.

## STRATIGRAPHIC PATTERNS WITHIN WISCONSIN

### Overlying and Underlying Strata

The St. Peter Sandstone is overlain conformably by carbonate rocks of the Sinnipee Group, specifically limestone or dolomite of the Platteville Formation. The St. Peter - Platteville contact is sharp both in outcrops and in the subsurface. In southwestern Wisconsin - as in adjacent Iowa and

Illinois - the Glenwood tends to comprise several feet of green shale with variable proportions of quartz sand. Farther east it is characterized by intensely bioturbated calcareous sandstone and sandy dolomite. Its thickness varies from 0 to 60 feet, but no obvious pattern of variation is evident (Pl. 1-cross sections).

The famous basal unconformity everywhere separates St. Peter strata from older ones. In much of the area studied, the St. Peter overlies the Lower Ordovician Prairie du Chien Group, which is dominated by cherty dolomite (Pl. 1, 2). In many areas, however, pre-St. Peter solution and/or erosion removed Prairie du Chien strata to expose various Cambrian and, locally, even Precambrian rocks (Pl. 1, 2).

## The Unconformity Surface

The thickness of the St. Peter Sandstone ranges from 0 to about 400 feet in Wisconsin (Pl. 2). The top of the St. Peter Sandstone is so flat that the variation of more than 200 feet in thickness in less than 1 mile clearly reflects the very irregular pre-St. Peter erosional surface (Pl. 1, 2).

On the regional scale of the entire study area, the maximum relief of the pre-St. Peter surface is 1700 feet in eastern Wisconsin and 900 feet in southern Wisconsin. The surface presently dips toward the east about 25 feet per mile in eastern Wisconsin and toward the south or southwest about 18-20 feet per mile in southern Wisconsin. On the scale of a few townships, the maximum relief is 300-400 feet (Pl. 1). Variation is appreciable even on a local scale. For example in the Pine Bluff area 10 miles west of Madison, maximum relief is 120 feet within only 1.3 miles horizontally and the total thickness varies from 20 feet to 140 feet within a distance of only 1,000 feet.

The morphology of the pre-St. Peter surface (Pl. 1, 2) suggests that both stream drainage patterns and karst topography were developed. As both Buschbach (1961) and Thwaites (1961) have argued, the surface could not be the result simply of post-depositional solution and compaction as was suggested by Flint (1956).

Comparison of the 3 maps and the cross sections shows that in the vicinity of Beaver Dam, Watertown, and Dodgeville cities, abnormally thick sections of 150-400 feet of St. Peter Sandstone can be traced among several wells as continuous channel fillings (Pl. 2). They coincide well with the pre-St. Peter topography (Pl. 1) as well as the occurrence of older rocks exposed by erosion on the pre-St. Peter surface (Pl. 2). In Beaver Dam, such an ancient channel lies directly along the northwest flank of a paleotopographic high of Precambrian rock (Pl. 1, 2). The channel gradient is from southwest to northeast. The bottom of the channel reaches Upper Cambrian Trempealeauan strata (Pl. 1, 2). In Watertown and Milwaukee, a valley descends in a southeasterly direction. It has been complicated by post-St. Peter faulting (Pl. 1, 2). Southwest of Dodgeville, a channel reaches Tunnel City strata and contains the thickest section of St. Peter in the entire map area. It flowed toward the south and can be traced into northern Illinois as a tributary to a more easterly-trending channel with over 300 feet of St. Peter (Fig. 4). Also another tributary of this valley seems to underlie the Mississippi River in southwestern Wisconsin (Pl. 1). Contours also indicate smaller, somewhat branching channel patterns in the southeastern corner of Wisconsin (Pl. 1).

Karst topography is strongly suggested on parts of the pre-St. Peter

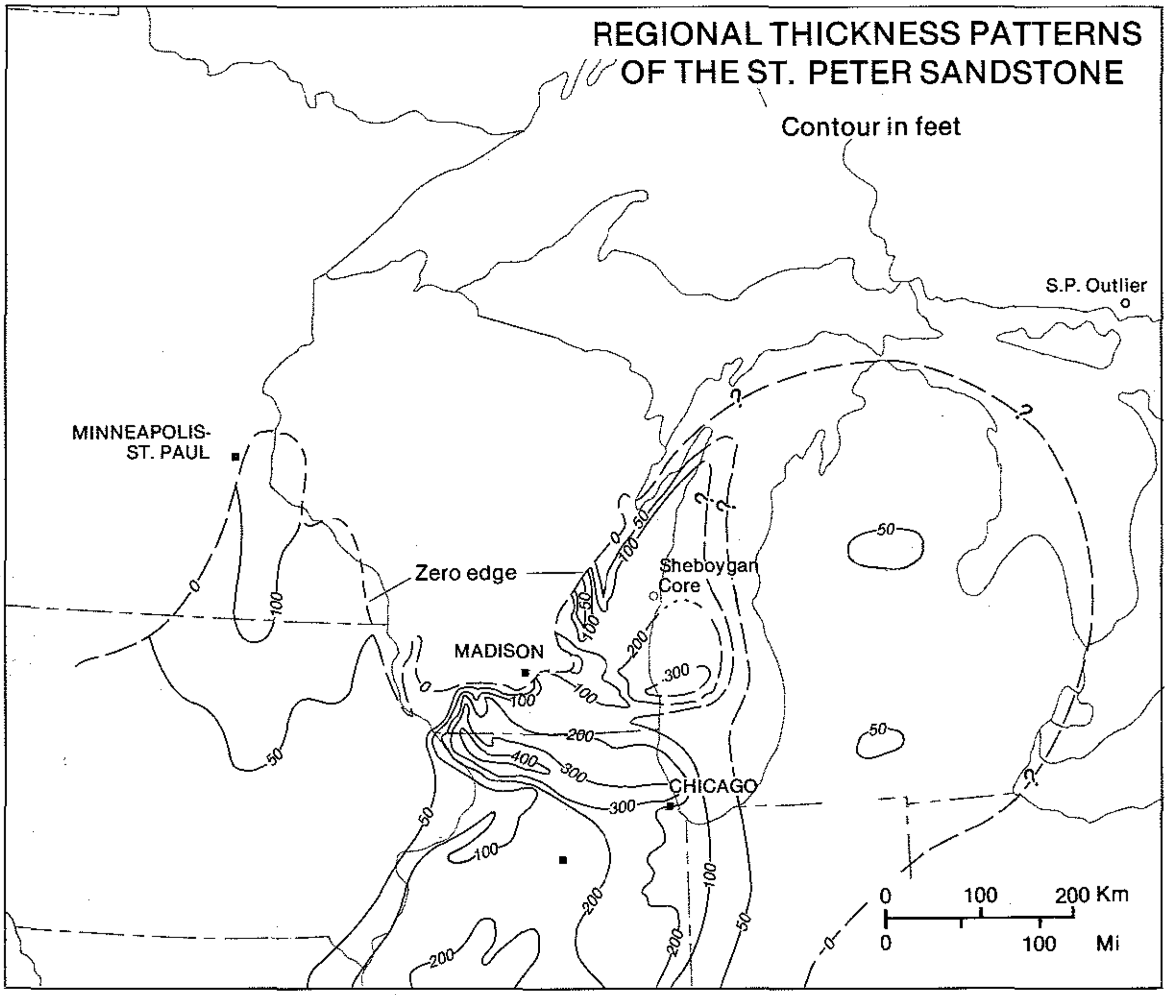


Figure 4. Thickness of the Ancell Group (including St. Peter Sandstone) in the northern midwest region. Thicknesses outside of Wisconsin are modified after Dapples, 1955; Willman and others, 1975; Droste and others, 1982; and Bricker and others, 1983.

surface by isolated circular areas with anomalous thickness. Examples occur in Dodgeville, Monroe and southeast of Darlington, and northwest of Green Bay (Pl. 1, 2), which are constrained by closely spaced wells. Probably many more exist than could be detected. Prairie du Chien carbonate rocks generally underlie the St. Peter Sandstone along the flank of the Wisconsin arch. Apparently these carbonate rocks were subject to solution by ground water in a humid, tropical Ordovician climate, which would also account for the clays of the Readstown Member with chert and dolomitic fragments. Buschbach (1961) recognized probable pre-St. Peter karst topography on carbonate rocks in the subsurface of northern Illinois. Where the St. Peter overlies Cambrian clastic rocks, however, he inferred stream-channel topography. A similar dual origin for the pre-St. Peter surface is indicated in Wisconsin.

The paleogeologic or subcrop map of the pre-St. Peter surface in Wisconsin (Pl. 2) shows an eroded domal feature in the vicinity of Milwaukee, which has

TABLE 1. Composition of selected samples of the St. Peter Sandstone (volume percent).

| | Thin Section No. | Mono-crystalline quartz | Other quartz | Other grains | Quartz over-growths | $CO_3$ cement | Other cement | Pores | Total % (No. grains) |
|---|---|---|---|---|---|---|---|---|---|
| Sheboygan Core | SP1219 | 78.8 | 0.6 | --- | 1.2 | 2.3 | 0.2 (iron) | 16.9 | 100 (n=485) |
| | SP1222 | 86 | 1.8 | 0.5 | --- | 0.2 | --- | 11.4 | 99.9 (n=437) |
| | SP1287 | 77.8 | 0.2 | --- | 0.9 | 0.9 | 0.2 (iron) | 19.9 | 99.9 (n=423) |
| Pine Bluff Area | 84-1SP | 83.9 | --- | --- | --- | --- | --- | 16.2 | 100.1 (n=421) |
| | 84-2SP | 82.5 | 0.4 | --- | --- | --- | --- | 17.1 | 100 (n=468) |
| | 84-3SP | 74 | --- | --- | --- | --- | --- | 26 | 100 (n=416 |
| | P-75P | 69.1 | --- | --- | 2.1 | --- | 1.5 (iron) | 27.4 | 100.1 (n=475) |
| | P-9SP | 70.1 | 0.6 | --- | 1.3 | 13.2 | --- | 14.7 | 99.9 (n=469) |
| | SP-30 | 78.5 | --- | --- | 0.5 | — | --- | 21 | 100 (n=442) |
| | SP-3L | 70.3 | --- | --- | 0.2 | --- | 3.3 (clay mineral) | 26.1 | 99.9 (n=421) |
| | SP-5 | 73.8 | --- | --- | 0.2 | --- | 8.8 (iron) | 17.1 | 99.9 (n=432) |
| Monticello | 82-2ASP | 78 | --- | --- | 0.9 | --- | 2.4 (feldspar) | 18.6 | 99.9 (n=424) |
| Argyle | 84-5SP | 75.2 | 0.7 | --- | 4.6 | --- | --- | 19.5 | 100 (n=415) |

TABLE 2. Grain size data for selected samples of the St. Peter Sandstone. (See Table I for locations)

| Thin section No. | Mean size (mm) | Median size (mm) | Sorting ($\phi$) ($\pm$s) |
|---|---|---|---|
| SP1219 | 0.38 | 0.41 | 0.53 |
| SP1222 | 0.28 | 0.27 | 0.71 |
| SP1287 | 0.28 | 0.28 | 0.6 |
| 84-1SP | 0.26 | 0.25 | 0.49 |
| 84-2SP | 0.22 | 0.25 | 0.50 |
| 84-3SP | 0.27 | 0.25 | 0.6 |
| P-7-SP | 0.21 | 0.21 | 0.47 |
| P-9-SP | 0.23 | 0.23 | 0.57 |
| SP-30 | 0.41 | 0.44 | 0.67 |
| SP-3L | 0.35 | 0.34 | 0.71 |
| SP-5 | 0.33 | 0.31 | 0.63 |
| 82-2ASP | 0.26 | 0.25 | 0.6 |
| 84-5SP | 0.55 | 0.57 | 0.61 |

been noted before by Ostrom (1970, p. 32). This dome-like feature shows oldest Cambrian strata (Mt. Simon Formation) in its center with younger Cambrian formations concentrically distributed around the core in a westward direction. The eastern side of the dome is unknown because it lies beneath Lake Michigan. The dome was eroded extensively during pre-St. Peter time because the St. Peter directly overlies the much older Mt. Simon Formation at its center. A curious oval-shaped area of Precambrian quartzite and granite were exposed on the northwest flank of the dome rather than at its center. Apparently this is merely one of several irregularly distributed hills of Precambrian rocks whose distribution bears little relation to early Paleozoic structural features. Other patterns on the paleogeologic map more directly reflect the topography of the unconformity surface with areas of Cambrian rocks simply occupying the deepest ancient valley floors (as in southwestern Wisconsin especially).

# SEDIMENTATION OF THE ST. PETER SANDSTONE

## Composition

The St. Peter is a remarkably pure and supermature quartz arenite containing 99 per cent quartz sand grains with the majority of the remaining volume being cements (Table 1). The heavy mineral suite of the St. Peter Sandstone makes up less than 1 per cent of the total grains with zircon, tourmaline, ilmenite and leucoxene dominant, and rutile, garnet, anatase, apatite, staurolite, ceylonite, and pyrite occurring as traces (Tyler, 1936, p. 55).

The St. Peter is generally very poorly cemented by authigenic cementing materials. Quartz overgrowths ("cement") are widespread and carbonate cements are locally abundant. Feldspar occurs especially at the base of the St. Peter, and has been considered to be syngenetic sanidine (Woodard, 1972) or simply diagenetic K-feldspar (Odom, 1974; Odom and others, 1979). Iron cements are locally abundant, and have produced bright red, yellow and brown colors. The origin and timing of these latter cements are not clear, but some probably represent oxidized pyrite or marcasite because these sulphides are known to occur in the subsurface. Clay and feldspar cements are present but rare.

## Texture

The size of St. Peter sands is generally characterized in most of the literature as fine sand, but there is a lot of medium and even some coarse sand in the formation, especially in Wisconsin (Table 2). The overall average size in Wisconsin falls near the fine/medium boundary (i.e. about 0.25-0.35 mm). Winfree (1983) found a statistically significant difference between the mean sizes for 19 samples each of eolian (0.22 mm) and marine (0.26 mm) sandstones. Coarse sand occurs both as: 1. scattered grains making a bimodal texture, 2. very thin laminae, and 3. in small ripple lenses.

Dapples (1955, pp. 456-459) showed no trends in regional size distribution and stated that the mean size of the St. Peter and Simpson sands range from coarse to fine. He indicated that the sands are coarser in Illinois, northern Missouri and most parts of Kansas. We believe that he showed the sands in Wisconsin as "too fine" (0.125-0.25 mm).

Shale is almost, but not quite, completely lacking in the St. Peter Sandstone, but increases to the southwest into the Simpson Group (in Oklahoma) as though currents winnowed and carried most clay to the southern edge of the craton (Dapples, 1955).

The St. Peter Sandstone is well to very well sorted (Table 2 & Fig. 5). The standard deviations of size distributions in Wisconsin are generally about 0.60 (Table 2). Dapples (1965, pp. 456-459) showed no significant trend in sorting in the St. Peter, and supposed that the sorting is uniformly good throughout. Winfree (1983, pp. 104-107) found no difference between the eolian and marine sets of standard deviations. Indeed, size-distribution statistics have proven undiagnostic for determining process or environment in either the St. Peter or similar older Cambrian sandstones.

The St. Peter is noted for its grain roundness (Fig. 5). In general, rounding decreases with decreasing grain size, as is to be expected (Table 3), but even the finer sand grains tend to be better rounded in the St. Peter than in most sandstones (Fig. 6).

Porosity for the samples analyzed in this study varies from 11% to 27%

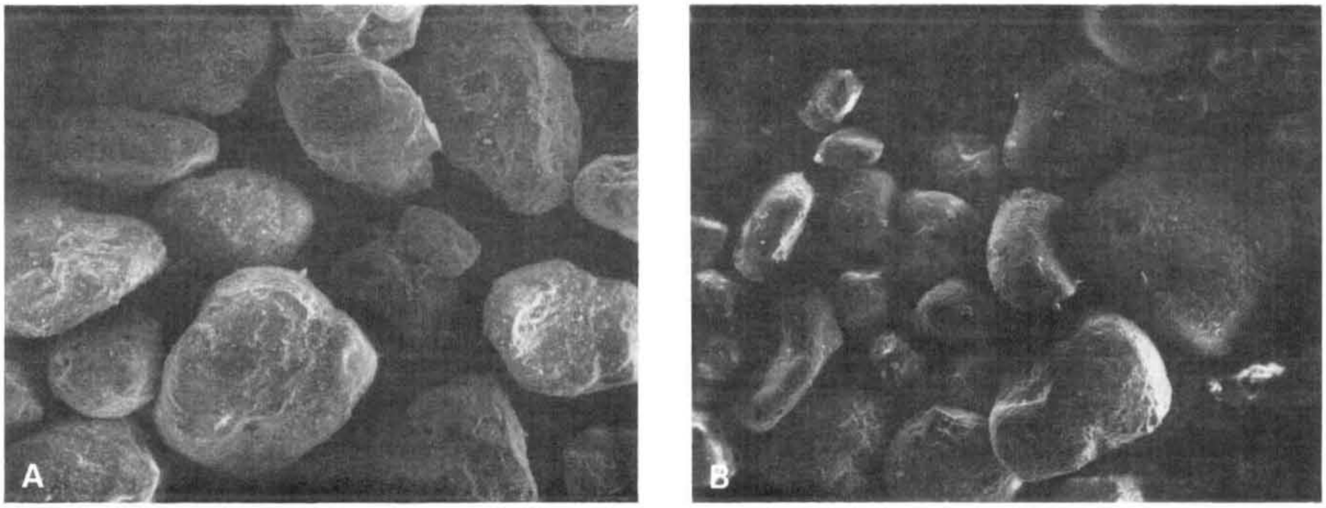


Figure 5. Scanning electron microphotograph of well-rounded St. Peter Sandstone quartz grains. A. Marine grains (100x); B. Eolian grains (70x). Note that there is no obvious difference of rounding. (From Winfree, 1983).

(Table 1). A more extensive study by Hoholick and others (1984) shows that porosity in the St. Peter varies from nearly 40% at the surface to nearly zero percent at a depth of 8,000 feet in the Illinois Basin.

## Grain-Surface Textures and Overgrowths

Most of the grains of the St. Peter are frosted, which was noted long ago and attributed to wind abrasion. Now the frosting of sand is generally considered to be the result of chemical etching (Shepard and Young, 1961, pp. 196-214; Kuenen, 1960, pp. 94-113; Kuenen and Perdok, 1962, pp. 648-658).

With the scanning electron microscope Mazzullo and Ehrlich (1983) and also Winfree (1983, pp. 87-103) found upturned or broken cleavage plates and dish-shaped concavities to be abundant on some grains that they regard as eolian (Fig. 7). They also found extensive diagenetic overgrowths, which inhibit the interpretation of origin from grain-surface textures (Fig. 8). In general, Winfree concluded that grain-surface textures do not differ significantly for the eolian and aqueous strata (as established independently by sedimentary structures and trace fossils). The only exception may be a slightly greater abundance of dish-shaped concavities on eolian grains (Fig. 7).

## Diagenesis

The St. Peter Sandstone has had a complex diagenetic history characterized by several episodes of cementation and dissolution. Quartz overgrowths tend to be earliest, followed by carbonate and iron cements. Quartz cement occurs at all depths, chert and chalcedony are present locally near the surface, calcite predominates at intermediate depths, and dolomite and local anhydrite occur in the deepest part of the Illinois basin (Hoholick and others, 1984). In the silts and clay-size fractions, K-feldspar, illite, smectite and chlorite are present; kaolinite has also formed where fresh water has invaded (Odom, and others, 1979). Primary porosity is said to predominate down to a depth of 4,000 feet; it

TABLE 3. Grain roundness estimates using the Rho scale (0-6) - percentage of grains in each Rho class. (See Table I for locations).

| Thin section No. | Sub-angular (2-3) | Sub-rounded (3-4) | Rounded (4-5) | Well-rounded (5-6) | Total % (No. grains) | Mean size (mm) |
|---|---|---|---|---|---|---|
| SP1219 | 2.3 | 26.9 | 43.5 | 27.3 | 100 (n=216) | 0.38 |
| SP1222 | 21.8 | 42.7 | 27.7 | 7.8 | 100 (n=206) | 0.28 |
| SP1287 | --- | 19.4 | 46.3 | 34.4 | 100.1 (n=227) | 0.28 |
| 84-1SP | 0.3 | 13.5 | 42.6 | 43.6 | 100 (n=289) | 0.26 |
| 84-2SP | 0.9 | 16.7 | 45.1 | 37.2 | 99.9 (n=215) | 0.22 |
| 84-3SP | 0.5 | 9.3 | 55.6 | 34.6 | 100 (n=214) | 0.27 |
| P-7SP | 3.0 | 39.1 | 49.8 | 8.1 | 100 (n=235) | 0.21 |
| P-9SP | 4.7 | 45.6 | 47.4 | 2.3 | 100 (n=215) | 0.23 |
| SP-30 | --- | 3.9 | 41.1 | 55 | 100 (n=231) | 0.41 |
| SP-3L | --- | 4.1 | 40.7 | 55.2 | 100 (n=221) | 0.35 |
| SP-5 | 0.5 | 5.5 | 57.1 | 36.9 | 100 (n=217) | 0.33 |
| 82-2ASP | --- | 15.6 | 59 | 25.4 | 100 (n=205) | 0.26 |
| 84-5SP | --- | --- | 15.1 | 84.9 | 100 (n-212) | 0.55 |

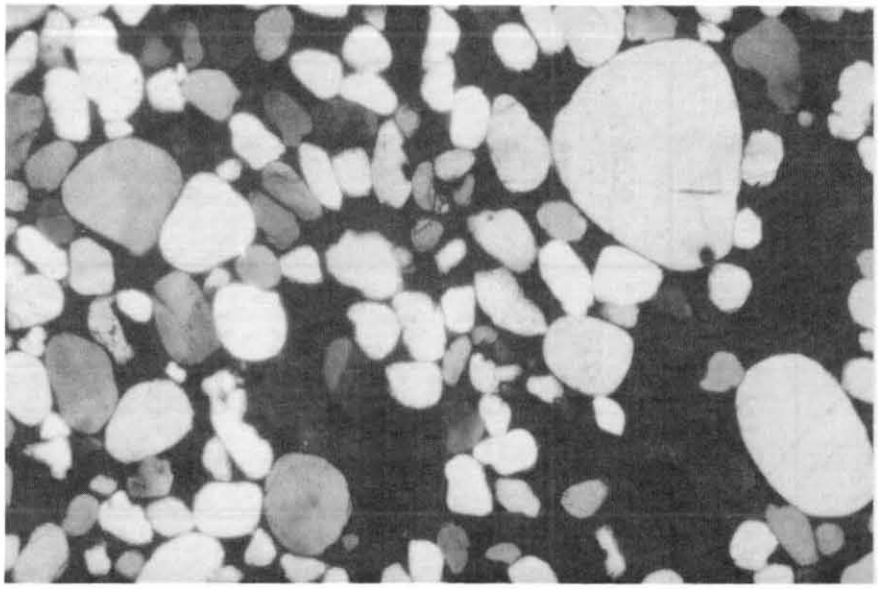

Figure 6. Microphotograph of a thin section of the St. Peter Sandstone from Pine Bluff (12 miles west of Madison) showing a bimodal size distribution (Crossed Nicols; 10x).

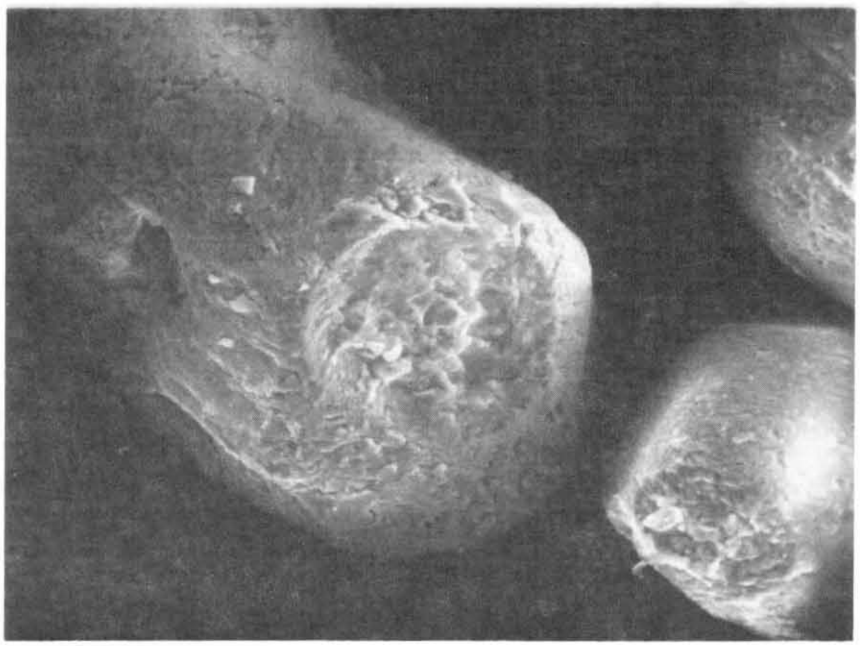

Figure 7. SEM photograph of an eolian quartz grain with a dish-shaped concavity with broken cleavage plates to the left (200x). (From Winfree, 1983).

ranges from 10 to 40%. Much of this, however, is probably due to solution of cements, especially carbonate, so would not be strictly primary. Winfree recognized meniscus cements with the SEM, which would have formed in the vadose zone. Secondary porosity dominates from depths of 4,000 to 8,000 feet but is mostly less than 10%; it has resulted from the leaching of both grains and cements (Hoholick, and others, 1984).

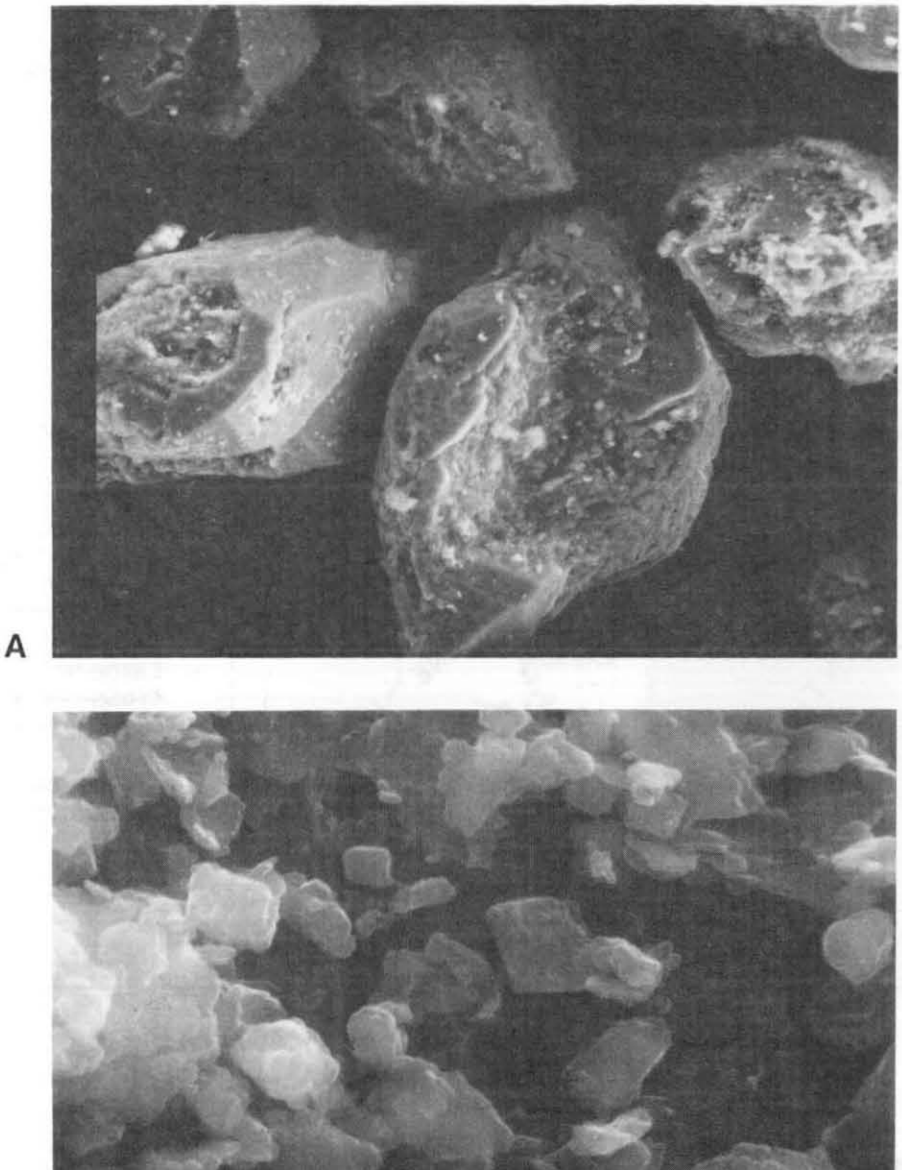

Figure 8. SEM photographs of quartz grains with diagenetic coatings. A. Euhedral syntaxial quartz overgrowth (300x). B. Rhombic carbonate and hexagonal platy layered silicate (lower left) (7000x). (Both from Winfree, 1983).

## Source of Sand

Tyler (1936) stated that the ultimate source of the St. Peter sands was largely a plutonic (granitic) terrane, based upon inclusions in quartz. The immediate source was a sedimentary terrane, however. Apparently St. Peter sand was recycled from Cambrian sandstones during pre-St. Peter erosion,

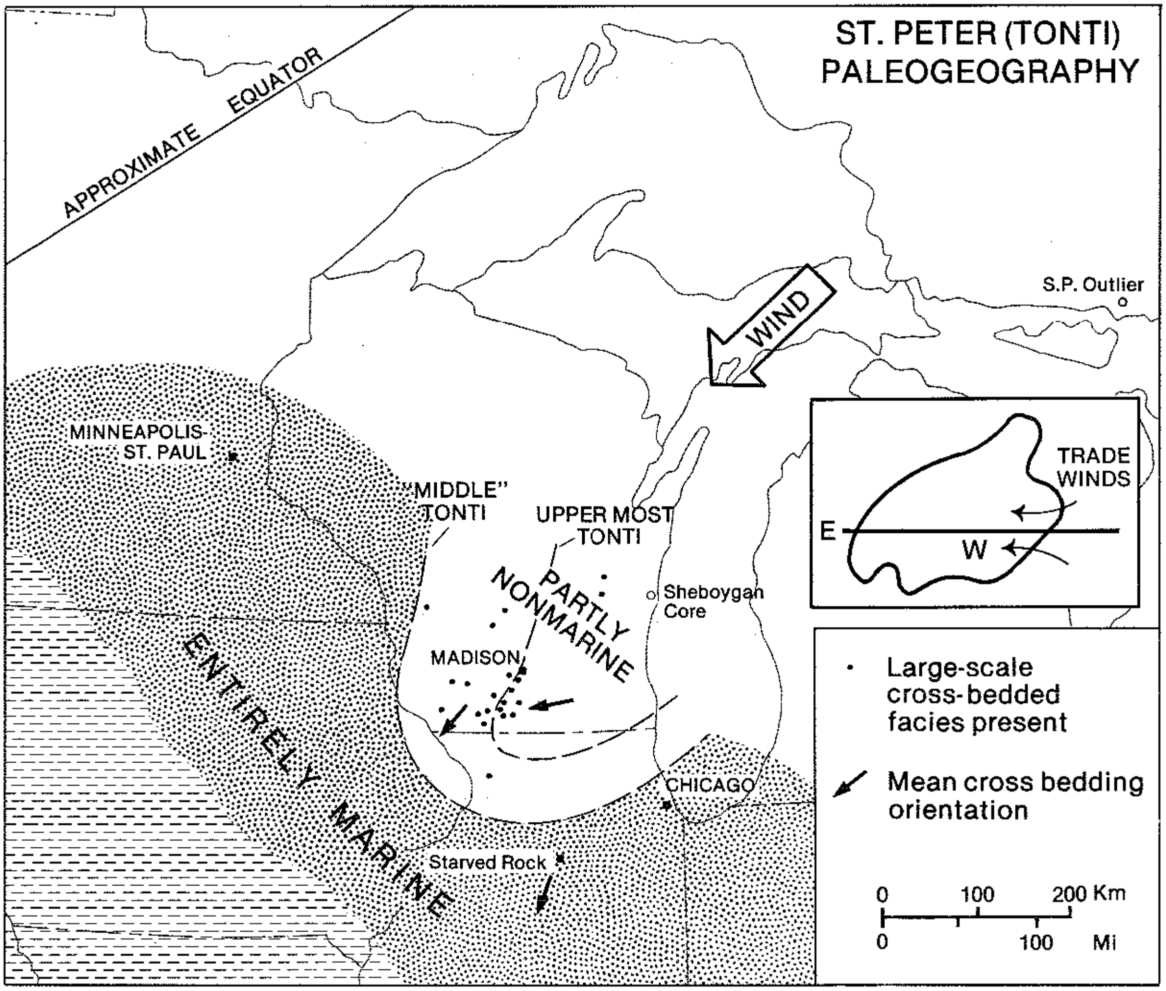


Figure 9. Facies and paleogeography for Tonti deposition in the upper midwest (modified after Dapples, 1955). Inset map: E is the Ordovician equator and W locates Wisconsin.

for most of the sands of the Wonewoc and Jordan Formations are as mature as those of the St. Peter.

Dapples (1955) postulated northeast to southwest dispersal on the basis of regional facies (i.e. more shaly to the southwest in Oklahoma where the Simpson Group is located). The gradation to marine carbonate facies toward the east precludes a source in that direction. Potter and Pryor (1961) reported a mean cross bedding dip direction toward the southwest in Illinois, and Dott and Roshardt (1972) showed dispersal toward the west from cross bedding orientations in dominantly eolian facies in southwestern Wisconsin. Seemingly the source of sand lay somewhere to the north of southern Wisconsin (Fig. 9).

## Depositional Processes and Environments

The problem of deposition of the St. Peter Sandstone has been debated for more than a hundred years. Early in the present century, authors favored an eolian environment by noting the dominant fine grain size, excellent sorting, rounding and frosting as well as its craton-wide extent (e.g. Berkey, 1906; Grabau, 1913), while other authors argued for a marine origin based upon reports of fossils and burrows (e.g. Dake, 1921; Dapples, 1955). Many workers have envisioned the sand as fluvial and eolian originally with final reworking by transgressive marine processes. Dake emphasized that textural features could be inherited from one cycle to another. This seems clearly to be the case for the exceptional rounding of medium and coarse grains in both the St. Peter and underlying Cambrian sandstones. A long history of wind abrasion (Kuenen, 1960) is implied even for some of those sandstones that contain marine fossils.

Large cross-beds in sets as much as 30 feet thick were found in the St. Peter Sandstone in Wisconsin by Pryor and Amaral (1971). They, and also Dott and Roshardt (1972), interpreted these as marine and probably of tidal origin. Such large-scale cross bedding is more typical of eolian dunes, however, and adhesion structures (Reineck, 1959; Hunter, 1973) were discovered near Madison by Dott and Byers in 1980. In 1981 Dott found them also in the very large-scale cross sets at Monticello, which were illustrated by Pryor and Amaral as well as Dott and Roshardt. Subsequently Winfree (1983) discovered several other localities with adhesion pseudo-cross lamination and other types of stratification suggestive of eolian deposition for some of the St. Peter southwest of Madison. Meanwhile, trace fossils, chiefly Skolithos, also were recognized by Dott, Byers and Winfree in other places. Winfree (1983) found them widely from Starved Rock, Illinois, throughout western Wisconsin, to southeast Minnesota (Fig. 2). In Ordovician strata, these are taken as proof of a marine origin for sandstones containing them. Meanwhile, Mazzullo and Ehrlich (1983) proposed both aqueous and eolian contributions in Minnesota based upon microscopic studies of grain shape and surface textures. It is an interesting bit of irony that the St. Peter Sandstone is now seen to be both eolian and marine. Winfree (1983) and Winfree and Dott (1983) described both an eolian and a marine facies in southwestern Wisconsin, and indicated that part of the eolian facies was reworked during the Tippecanoe transgression - as several earlier workers proposed but could not actually prove.

Hunter's (1977, pp. 361-387) stratification types together with adhesion structures (Reineck, 1959; Hunter,

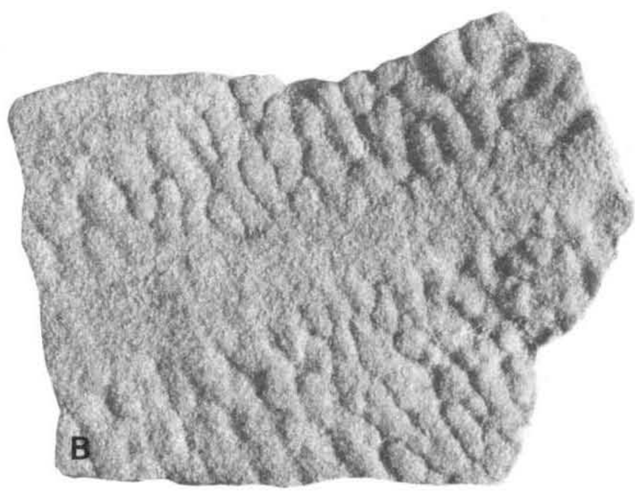

**Figure 10. Adhesian-ripple structures in the St. Peter Sandstone; A. Oblique view showing pseudo-crosslaminae dipping toward the right (roadcut on County Highway J, 1.8 miles southeast of Pine Bluff, Wisconsin); B. Plan view showing characteristic irregularly rippled surface (locality uncertain; specimen is 12 cm long). Wind was from the left in both cases.**

1973) are the most convincing evidence for an eolian origin. Adhesion pseudo-cross lamination is formed by deposition of saltating dry sands, which adhere to a water-saturated sandy surface. The adhesion ripples so formed aggrade and migrate up wind if the sand supply persists. This produces a distinctive sort of cross lamination (Fig. 10). Eolian climbing translatent laminae are formed by the migration and climbing of wind ripples during tractional deposition. The laminae are very thin because eolian ripples are so low in profile (Fig. 11). Grainflow deposits are formed by non-cohesive sands avalanching intermittently down dune slipfaces. Grain fall laminae are formed by grainfall deposition related to flow separation at a dune crest, resulting in short transport in suspension.

Besides the area southwest of Madison (Winfree, 1983), we think most of the St. Peter in the Sheboygan core is eolian because of identifiable translatent laminae and a lack of trace fossils (Fig. 12). In eastern Wisconsin, impressive large cross-bed, climbing translatent laminae as well as grain fall laminae are well exposed in the St. Peter Sandstone along a road cut west of a quarry at Ripon, Winnebago County. Those structures can also be found in another quarry east of Berlin, Winnebago County.

## Paleogeographic Setting

The regional geometry of the St. Peter and supermaturity of its grains imply a very stable, cratonic landscape with low relief. Moreover, no significant land vegetation is known for pre-Devonian times.

Probably a eustatic fall of sea level led to formation of the basal unconformity. The variation of relief carved on the pre-St. Peter strata indicates that, after deposition of the carbonate strata of the Prairie du Chien Group, the Early Ordovician epeiric sea withdrew and recently-deposited rocks were eroded throughout the area. More than 400 feet of strata were removed in some locations to expose units as old as the Mt. Simon and even Precambrian rocks (Pl. 1, 2). The magnitude of the relief suggests that the duration of the erosion was considerable. During erosion, streams cut deep valleys to form stream drainage patterns as noted above. At the same time, solution by ground water apparently formed caves and sinkholes in carbonate rocks, and finally developed a mature karst landscape. The St. Peter sea advanced over this landscape, drowning many valleys but irregularly submerging other areas. Sand derived from exposed Cambrian sandstones in Wisconsin, northern Michigan, Ontario, and probably also northern Minnesota was transported southwestward (present coordinates) by eolian and braided fluvial processes (Fig. 9). The Readstown Member apparently was deposited during the development of the valleys and sinkholes by erosion and solution, but the Tonti sands were deposited long afterward; they simply filled and leveled the irregular land surface. Finally, the eolian and fluvial deposits were reworked and/or buried by the advancing sea. Either medium-scale trough cross bedding or a complete lack of discernible stratification and presence of some recognizable *Skolithos* traces characterize the marine facies.

The sandstone of the Tonti Member grades upward into thin dolomitic, shaly sandstone and shale of the Glenwood Member (Pl. 1), reflecting a near-cessation of deposition as suggested by the abundance of shale and, in sandy phases, of intense bioturbation as well as some phosphatic nodules and glauconite pellets. Fraser (1976) postulated that the Glenwood formed in a large, relatively quiet lagoon behind a large sand barrier in northern Illinois. Transgression

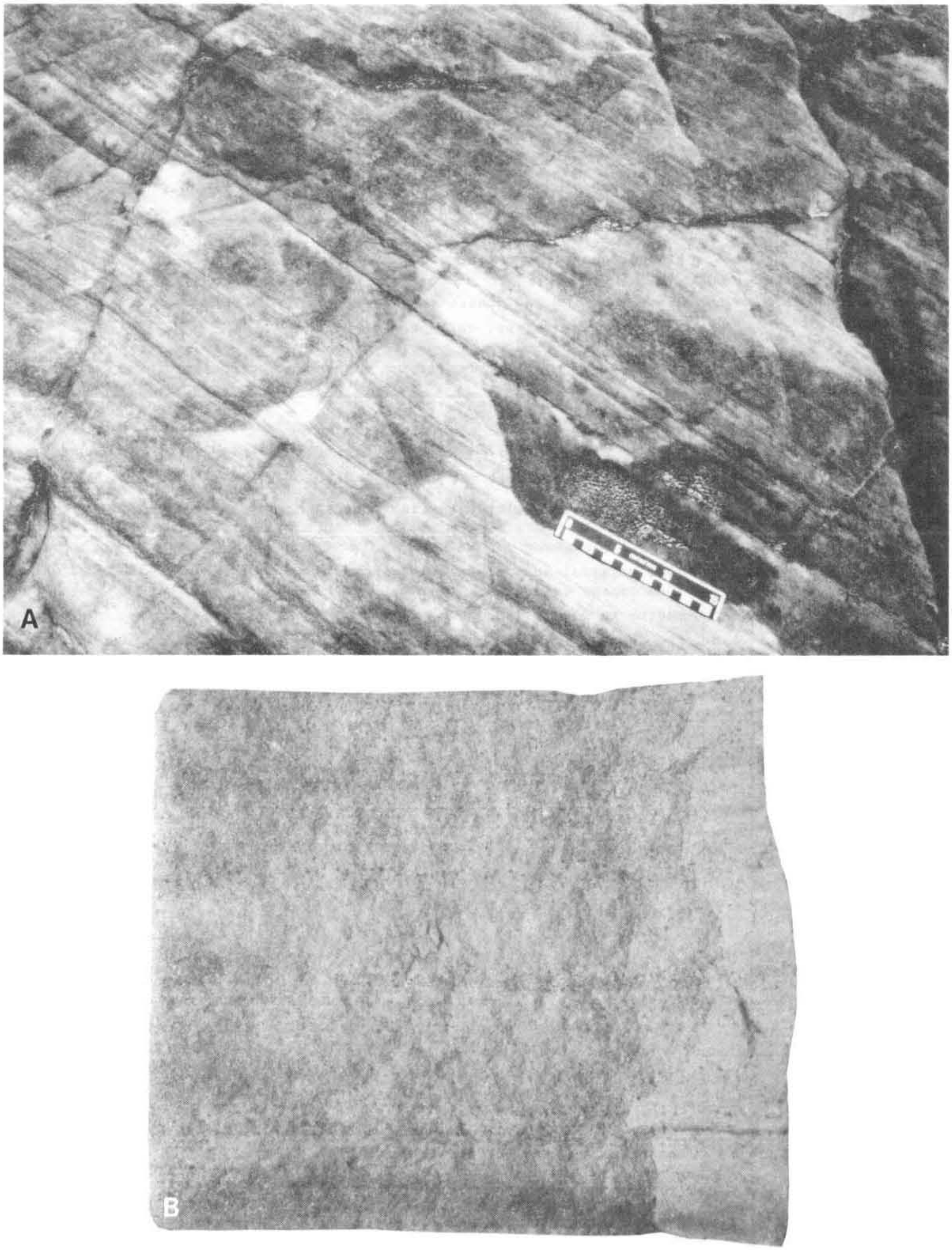


Figure 11. Climbing-ripple **translatent (eolian ripple) lamination** in the St. Peter Sandstone. A. Roadcut on U.S. Highway 15 near Blockhouse approximately 3 miles northeast of Dickeyville, Wisconsin. B. Core from Van Driest No. 1 well at Sheboygan, Wisconsin; width of core is 10 cm (Sec. 12, T. 13N, R. 22E.).

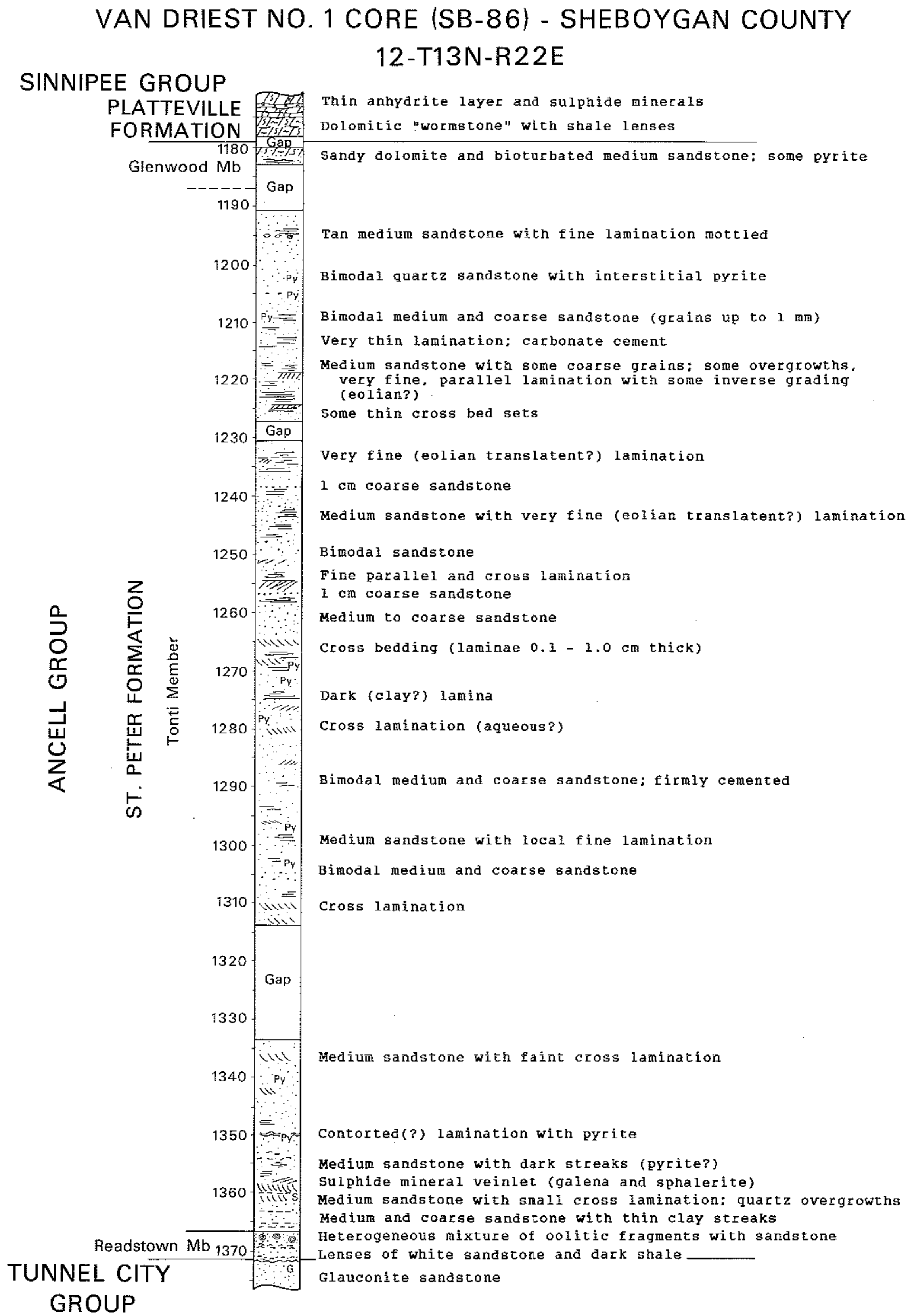


**Figure 12.** Lithologic log of the St. Peter Sandstone in the Van Driest No. 1, Sheboygan, Wisconsin. (Sec. 12 T. 13N., R. 22E.).

apparently had progressed sufficiently to stop the supply of sand to the midwest. After an interval of nondeposition there, deposition of the richly-fossiliferous Platteville carbonate sediments began as transgression continued to flood the craton. The carbonate facies spread over the craton from the southeast (Dapples, 1955). Except for local winnowing, there is no evidence of erosion between St. Peter and Platteville deposition in Wisconsin.

## TECTONIC IMPLICATIONS

Supermaturity and blanket geometry (thin but very widespread) of the St. Peter - Simpson - Harding - Winnipeg sandstones attest to a very stable craton. Stable cratons, however, do show evidence of broad arches and basins. Always there is a question of when such features formed. Was the Wisconsin arch, for example, already in existence during St. Peter time? Results from the present study bear upon this issue.

At present in Wisconsin, the St. Peter dips very slightly eastward and southward. A trial removal of present dip showed no significant change of direction, so Pl. 1 was not corrected for present dip.

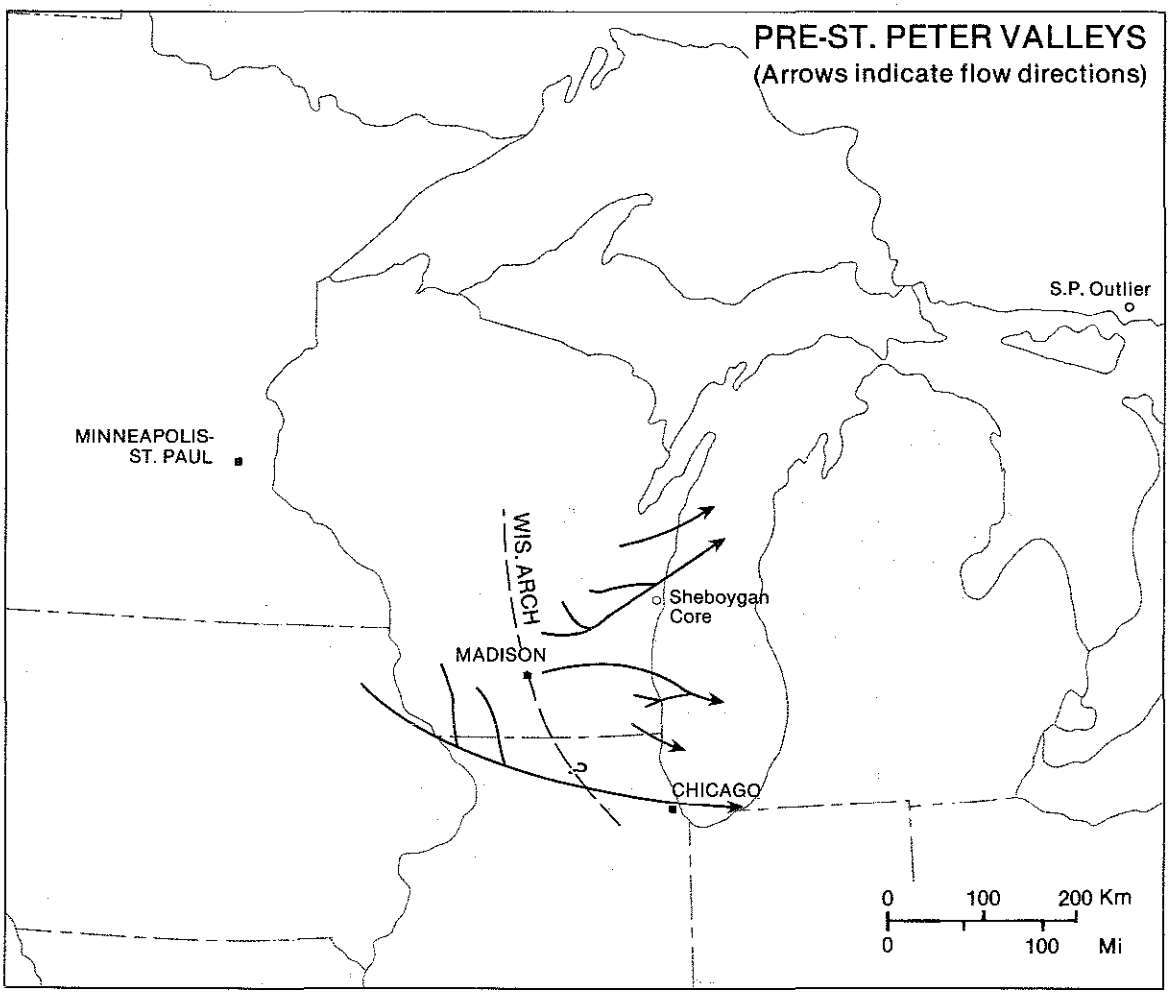


Figure 13. Drainage patterns on the pre-St. Peter unconformity surface inferred from plate 1 for Wisconsin and from Willman and others (1975) for northern Illinois.

The large channel in northern Illinois, tributaries of which are evident in the southwestern corner of Wisconsin, cuts directly across the extension of the arch into Illinois, indicating that there was no topographic divide there (Fig. 13). The paleogeologic map (Pl. 2 and Fig. 14) shows that the most deeply truncated ("domal") area beneath the St. Peter is not coincident with the Wisconsin arch, but lies to the east. Only the area of uppermost Cambrian rocks south of Madison gives any hint of the arch.

Facies and dispersal patterns also bear upon arch history. Nonmarine facies (Winfree, 1983) lie southwest of Madison, and the St. Peter in the Sheboygan core, Ripon road cut, and Berlin quarry appear nonmarine and a little coarser-grained than in western Wisconsin. Finally, the dispersal data suggests derivation of the sand from the north with spreading toward the southwest right across the Wisconsin arch (Fig. 9).

In summary, the Wisconsin arch seems not to have had any topographic influence during Middle Ordovician time. Either it is chiefly post-St. Peter in origin, or else it had a very spasmodic history prior to and after that time.

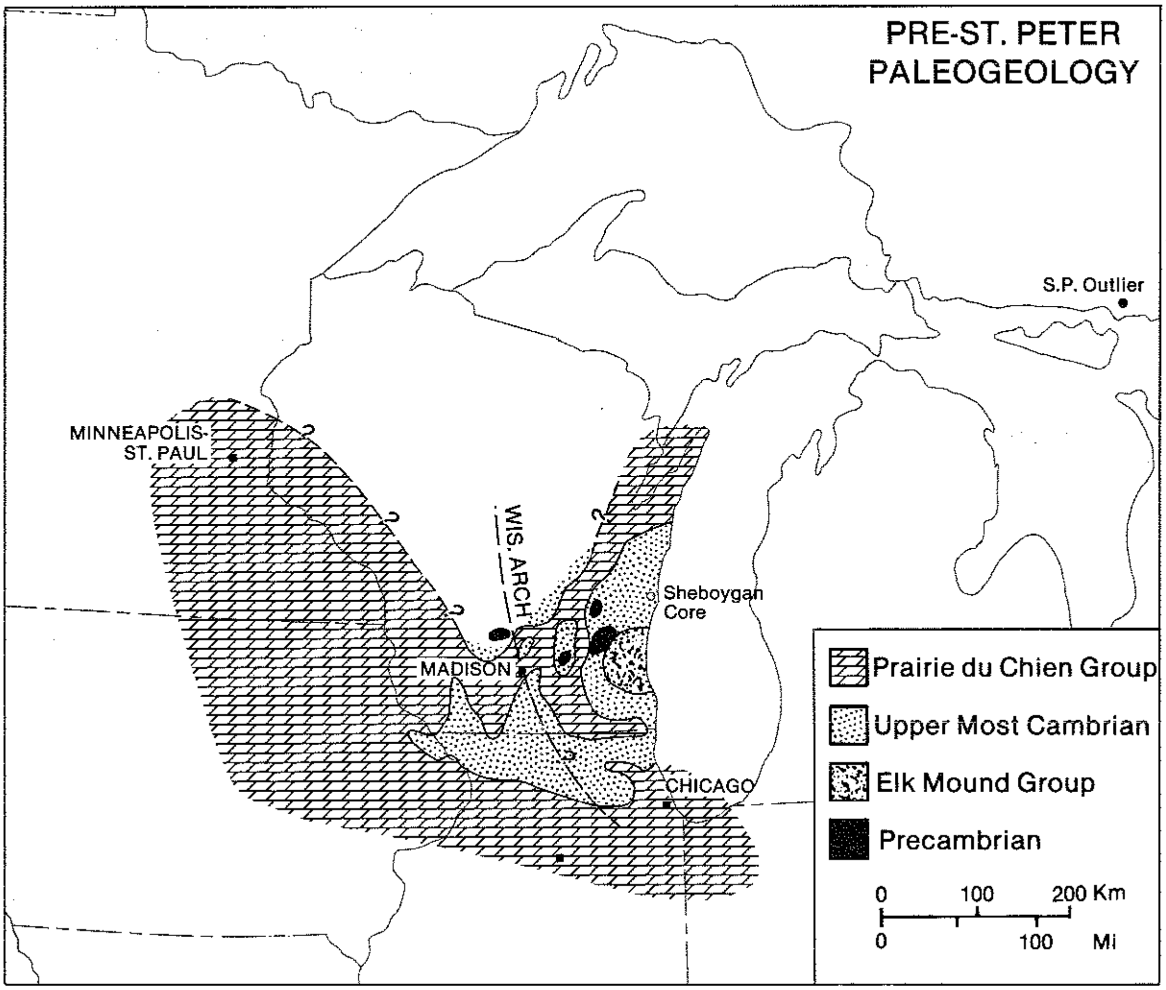


Figure 14. Regional sub-crop map of the pre-St. Peter unconformity. Adapted from Ostrom (1970), Buschbach (1961), Witzke (1980), and plate 2 of this study.

## SUMMARY

1. The morphology of the pre-St. Peter surface in Wisconsin reveals that normal stream erosion and karst development both acted to shape the very irregular pre-St. Peter surface.

2. The character of the pre-St. Peter surface was controlled mainly by underlying rock type. Erosional streams flowed on both Cambrian clastic and Prairie du Chien carbonate rocks, but karst evidence is confined to the latter.

3. Today the pre-St. Peter surface dips 29 feet per mile toward the east in eastern Wisconsin, and about 18-29 feet per mile toward the south or southwest in southern Wisconsin. The paleogeology and paleotopography of the basal unconformity surface, however, suggest that this tilting - and thus the Wisconsin arch - post-date the St. Peter Sandstone. By implication, it would also post-date the overlying Platteville-Galena strata because they are perfectly concordant with the upper St. Peter. If the arch originated before Middle Ordovician time, it must have been structurally inactive during the Middle Ordovician, for it did not produce a topographic divide.

4. The St. Peter was deposited in a variety of nonmarine and marine environments. Residual deposits of the Readstown Member probably formed more or less contemporaneously with erosion and karst formation. Sands of the Tonti Member were dispersed across the central craton by fluvial and eolian processes on a vegetation-free landscape; they filled valleys and sinkholes to level the landscape. Marine transgression reworked these sands to varying degrees - completely in western Wisconsin, and southeastern Minnesota, partially in south-central Wisconsin, and possibly not at all in eastern Wisconsin. The Glenwood Member represents an interval of near nondeposition and intense bioturbation of uppermost Tonti sands prior to Platteville carbonate deposition across the entire craton during the greatest epeiric sea flood in all of Phanerozoic time.


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