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STRATIGRAPHIC RELATIONS OF THE SHAKOPEE DOLOMITE AND THE ST. PETER SANDSTONE IN SOUTHWESTERN WISCONSIN

By

Arthur E[merson]. Flint 1913

Prepared in cooperation with the Wisconsin Geological and Natural History Survey

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INTRODUCTION

This paper is concerned with the origin and geologic history of the boundary that separates the widespread St. Peter sandstone from the underlying Shakopee dolomite. That interformational surface is highly undulatory, and most contemporary geologists who have examined it believe that the contact irregularities result from pre-St. Peter subaerial erosion of the upper Shakopee surface. Some earlier investigators do not entirely concur.

This report is a by-product of work done for the U. S. Geological Survey during an investigation of the lead-zinc resources of Wisconsin by the U. S. Geological Survey in cooperation with the Wisconsin Geological and Natural History Survey. Attention was focused on the problem by stratigraphic studies of the Prairie du Chien formations, particularly of the Shakopee dolomite, in which structural and lithologic characters observed in the carbonate sediments seemed to be incompatible with the widely accepted erosional origin of the upper Shakopee surface. It was decided, in 1950, to explore the whole problem of the Shakopee-St. Peter relations by detailed outcrop examinations, supplemented by subsurface and other studies that might contribute to a better understanding of the genetic relationships involved. The area of the investigation was restricted to three counties in southwestern Wisconsin and closely adjacent areas in Iowa (fig. 1), differing in this respect from the broader and more general studies that previously have tended to be the rule.

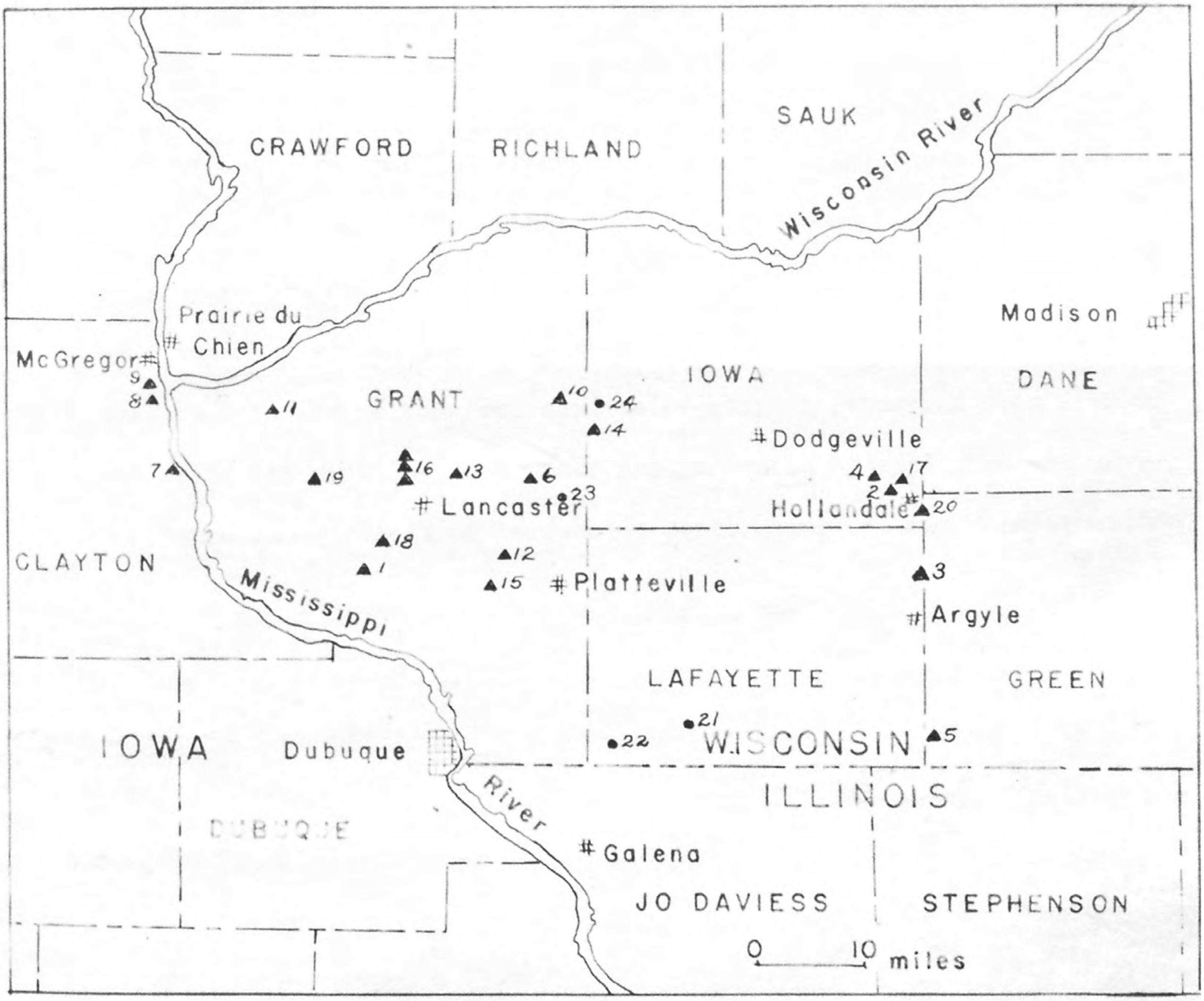


Figure 1: Index map of southwestern Wisconsin and adjacent parts of Illinois and Iowa. Locations of critical exposures and of drill holes from which subsurface data were acquired are indicated.

▲ = exposure • = drill hole(s)

1. Beetown road cut
2. Ryan quarry
3. Saw Mill Creek exposures
4. Cleary quarry
5. Dill railroad cut
6. Anaton exposures
7. Clayton sand pit
8. Sand Cave ravine
9. Miller ravine
10. Castle Rock exposure
11. Patch Grove road cuts
12. Ellenboro road cut
13. U. S. Highway 61 road cut
14. Blue River road cut
15. Big Platte River exposure
16. Grant County K road cuts
17. Iowa County K road cut
18. Wisconsin Highway 35 road cut and borrow pit
19. Bloomington sand pit
20. Olson quarry

21. James Mine diamond drill hole
22. Kennedy Mine churn drill hole
23. Crow Branch diamond drill hole
24. Highland (Steil) churn drill holes

Of the more than 100 exposures examined during the progress of this study eleven that together contain all the critical elements bearing on the problem are described in detail in this paper. Ten additional outcrops, less critical, are located and described. Subsurface data are mainly from studies of samples recovered from diamond and solid bit drilling, but these are augmented by published and unpublished descriptions of bore holes penetrating the two formations.

REVIEW OF LITERATURE

The irregular surface that separates the St. Peter sandstone and the subjacent Shakopee dolomite is mentioned in many places in geologic literature. Early investigators reported no unconformity at the contact in question. Neither McGee (1891) in northeastern Iowa, nor Percival (1855) in Wisconsin found evidence of pre-St. Peter erosion of the Shakopee surface. Hall and Whitney (1858) in Iowa and (1862) in Wisconsin seemed to have regarded the contact in question as conformable. Calvin (1894) in northeastern Iowa mentioned no irregularity at the contact, and Leonard (1905) in Clayton County, Iowa, found that the St. Peter rested conformably on the Shakopee but noted a varying thickness of the St. Peter, which ranged from 40 to 85 feet.

Chamberlin (1877, pp. 268-290, 1883, pp. 138-140) was the first of the early investigators to place in the literature a detailed and significant description of St. Peter-Shakopee contact relations. He reported thicknesses of the Prairie du Chien group, of which the Shakopee is the uppermost formation (see Stratigraphy), to range from 65 to 250 feet, and observed that the varying thickness was due to the irregularity of its upper surface, which is characterized, in his words, by "petrous billows" that he found to vary from gentle swells to "elliptical domes rising a hundred feet above their bases." He described a typical domal structure as having the superficial strata dipping in every direction from the center, most steeply at the sides, less so at the extremities. He thought the superficial beds appeared to have been laid down as a mantle with no unusual evidence of fracture or disturbance. The interior of these domes, where observed, he found to be a brecciated mass of carbonate fragments "cemented by calcareous material that appeared to be a mud derived from abrasion of the rocks themselves." In Chamberlin's interpretation of the genesis of these domes he outlined a history that includes a period of uplift and erosion during Prairie du Chien time followed by a readvance of the sea, which broke up the superficial beds and piled comminuted material into "shoals, bars and reefs." These deposits subsequently became covered with calcareous debris and lay below wave base. The ensuing deposition "covered the irregularities of the bottom like an undulatory blanket." Chamberlin mentions submarine erosion of the sides of these domes but nowhere describes subaerial erosion of the upper Shakopee surface or unconformable relations between that formation and the overlying St. Peter sandstone.

Irving (1877) in central Wisconsin and Strong (1877) in the lead region of Wisconsin both ascribe the irregularities they found on the upper surface of the Prairie du Chien strata to pre-St. Peter, presumably subaerial, erosion.

Sardeson (1916, pp. 1-2) described the upper surface of the Shakopee formation as being unequal, which he thought was due, in part, to original reeflike structures and, in part, to alteration. The domes he described are much smaller than those pictured by Chamberlin. He believed, however, that some subaerial erosion had occurred on the Shakopee in parts of Wisconsin, but implied that it was generally insignificant. Later (1926, p. 27) he concluded that, after a proper stratigraphic delimitation of the Shakopee formation had been made "the supposed unconformity" between it and the St. Peter sandstone would all but disappear. He accounted for the irregular contact between the two formations by a combination of factors that include algal reefs and "rock billows" caused by recent leaching, brecciation, and slumping, in the Shakopee formation, and by the formation of cone-dome structures. The cone-domes he believed were the counterpart of Chamberlin's "elliptical domes" and concluded that their origin was more or less analogous to salt or oil dome structures.

Trowbridge (1917b, pp. 177-182) was the first to investigate specifically and report on the contact relations of the St. Peter sandstone and the underlying Prairie du Chien group in Iowa. He concluded, on the basis of four lines of evidence, that the irregular contact was due to subaerial erosion of the Shakopee formation: (1) The contact between the St. Peter and the Prairie du Chien group is irregular, having a relief of as much as 200 feet; (2) the thickness of each formation varies greatly, but the combined thicknesses of the two units is practically constant; (3) the sum of the average thickness of the two units, in Iowa, is about the same as the average combined thickness of the two units; (4) the basal St. Peter sandstone contains chert derived from rock of the underlying Prairie du Chien group (one locality, near Church, Iowa, is cited). Trowbridge found two phases of St. Peter sandstone in Iowa, a valley phase of soft friable and varicolored sandstone that was deposited in subaerially eroded valleys, and an upland phase of gray massive indurated sandstone deposited on the Shakopee formation where it was more or less undissected. He computed the time interval of the uplift-erosion episode that preceded St. Peter deposition to be almost a half a million years and concluded the Cambro-Ordovician boundary should be drawn at the top, not the base, of the Prairie du Chien group.

Dake (1921) dealt generally with the St. Peter sandstone throughout its areal occurrence in fifteen states. He concluded that the base of the St. Peter is virtually everywhere marked by a vast erosional unconformity.

Thwaites (1923, p. 541), from subsurface investigations in Wisconsin, reported, "Study of well records leaves no doubt that there is an unconformity of great magnitude at the base of the St. Peter." In northern Illinois he concluded (1927), also, that the irregularity at the contact of the Prairie du Chien group and the St. Peter sandstone resulted partly from pre-St. Peter erosion. He noted, however, that upper Prairie du Chien strata dip parallel to the irregular contact, and that truncation of those strata had not been observed. He believed that in places the whole of the Prairie du Chien group has been removed by pre-St. Peter erosion.

Lamar (1928, p. 29) found in north-central Illinois that the Shakopee surface onto which the sand of the St. Peter was deposited had undergone uplift and a long period of erosion, that streams dissected deep valleys, and that in places thick residual clays accumulated on narrow divides. He suggested that solution was an important factor in shaping the pre-St. Peter land mass.

Stauffer and Thiel (1941) found in southeastern Minnesota that some of the variation in the Shakopee formation thickness is due to partial removal of its upper beds by pre-St. Peter erosion.

Willman and Templeton (1951) in north central Illinois found the Shakopee separated from the overlying St. Peter sandstone by a major unconformity that in places permitted the St. Peter to rest directly on the Upper Cambrian Trempealeau formation. Workman and Bell (1948), also in Illinois, concur in these findings.

As a general statement, of the geologists who have recorded their conclusions that account for the very irregular lower boundary of the St. Peter sandstone, those who found an erosional unconformity based their interpretation mainly on larger features of the two formations--gross thicknesses, the magnitude of the relief at the contact, and subsurface data from deep wells. On the other hand, those who found no marked evidence of erosional unconformity at the St. Peter-Shakopee boundary, Chamberlin and Sardeson particularly, concerned themselves with evidence observed in exposures of the contact and below it in the Shakopee formation. None of the investigators recorded a specific location of erosionally truncated Shakopee beds, and only Lamar (1928, p. 20-21) located and described an unquestioned thin conglomerate that might be basal to the St. Peter formation.

STRATIGRAPHY

The stratigraphic sequence of rock units mentioned in this paper is shown in the table below.

Classification of rock units

System	Series	Group	Formation
Ordovician	Middle		Platteville limestone
			St. Peter sandstone
	Lower	Prairie du Chien	Shakopee dolomite
			New Richmond sandstone
			Oneota dolomite
Cambrian	Upper		Trempealeau formation

In much of the older literature, the Prairie du Chien group is referred to as the Lower Magnesian limestone, a name introduced by Owen (1852). The older name is not used in this paper, and at places in the text where earlier literature that uses the name Lower Magnesian is cited, the term Prairie du Chien, except in direct quotations, is substituted to avoid the confusion of dual nomenclature.

The lowest formation of the Prairie du Chien group is the Oneota dolomite, named by McGee (1891) from the exposures along the Oneota River (the modern Upper Iowa River) in northeastern Iowa. In the area of this study it commonly is a hard, massive to thick-bedded, fine- to medium-grained crystalline dolomite that contains common to abundant chert in the upper half of the formation. Algal structures are present locally throughout the formation. Local quartz sandstone, shale, and glauconite also occur.

Overlying the Oneota is the New Richmond sandstone, named by Wooster (1882) for exposures along the Willow River near New Richmond, Wisconsin. Along the western border of the investigated area the New Richmond is a thin but well-defined quartz sandstone interbedded with dolomitic sandstone and dolomite. The sand is fine- to medium-grained, and the quartz grains commonly have crystal overgrowths. However, where these overgrowths are not present the sandstone is lithologically very similar to sandstone of the Trempealeau formation that underlies the Prairie du Chien group, to sand in stringers and lenses in the Shakopee dolomite next above the New Richmond, and to the St. Peter sandstone that is above the Shakopee. In most of southwestern Wisconsin, the New Richmond formation is a poorly defined zone of quartz sandstone, dolomite, and shale, so similar to zones in the overlying Shakopee dolomite that commonly the formation is not certainly identified in either outcrop or subsurface studies. For this reason the three formations that compose the Prairie du Chien group are differentiated only in a general way throughout most of the area of this study.

Above the New Richmond, the Shakopee dolomite may be massive and cherty, similar, particularly in its lower strata, to the Oneota. The upper half of the formation, however, is commonly thin-bedded fine-grained dolomite or dolomitic limestone interbedded with white quartz sandstone and shale. The dolomite, commonly impure, contains sparse to abundant clay- and silt-size material and floating quartz sand grains. Varying amounts of chert, much of which is oolitic, occur in the Shakopee. Near the upper Shakopee contact, separating the impure dolomite and dolomitic limestone from the overlying St. Peter sandstone, is a zone which ranges greatly in thickness from less than 2 feet to more than 100 feet of intercalated shale, sandstone, and admixtures of these, locally cemented by dolomitic material. This interval is considered by some geologists as a basal phase of the St. Peter sandstone, but others have interpreted it as a weathered residuum of the upper Shakopee surface. Commonly the juncture of the contact zone and the overlying typical St. Peter sandstone is moderately abrupt, but the contact zone is gradational into the underlying Shakopee dolomite and dolomitic limestone.

It is believed, for reasons stated later, that the uppermost beds of the Prairie du Chien group, immediately underlying the St. Peter sandstone in all the exposures observed during this study, are of the Shakopee formation and are so referred in the text.

The sandstone of the St. Peter is composed of white to buff, fine- to medium-grained, well-rounded quartz sand grains, the larger ones of which are commonly frosted. The typical St. Peter sandstone is nearly everywhere very pure except for local areas of infiltrated iron that coats the grains and locally cements them.

The Shakopee dolomite and the St. Peter sandstone are the two formations of primary concern in this study, for principally in these two units must be found the evidence of the process or processes that caused the highly irregular surface separating them; this evidence, in turn, will permit reconstruction of the geologic history of late Prairie du Chien and early St. Peter time.

DEFINITIONS OF TERMS

To preclude misunderstanding and to make entirely clear the meaning intended, some of the terms used to describe outcrop and subsurface features or stratigraphic zones are defined below:

Shakopee "domes" are upswelled areas that may vary from 3 or 4 feet to perhaps more than 100 feet. They are irregular in areal extent, but the larger ones appear to be elongate. They are characterized by centrifugally dipping stratification that is steepest in the dome walls, most gentle over the dome summits and in interdome areas.

"Typical St. Peter sandstone" refers to the well-sorted well-rounded fine- to medium-grained clean quartz sand. Individual grains may be frosted. The phrase is employed to differentiate this sandstone from an underlying finer-grained very impure sandstone, interbedded with shale.

The "contact zone" is a convenient designation for the vertical interval of mixed lithology that lies below typical sandstone of the St. Peter and above the typical dolomitic limestone and (or) dolomite of the Shakopee. The zone is composed of impure, commonly very fine quartz sandstone, interbedded and intermixed with green, gray, maroon, buff, or purple clay or shale and may also contain dolomite as cement or as thin soft laminae. It may range in thickness from 2 to 110 feet or more, and derives its name from the fact that the St. Peter-Shakopee contact necessarily must lie within or at one of the extremities of the interval. For consistency, the term is employed in a few places to define shaly zones, a part of which necessarily must lie below the contact.

Inclined beds of the Shakopee are described in many places as "steeply dipping." The term is used relatively. In the platform sediments that extend across and beyond the area of study, stratification dips greater than 3° to 4° are uncommon, and dips greater than 12°, except in Prairie du Chien strata, are virtually nonexistent. Hence, strata in the Shakopee or Oneota formations that dip from 15° to more than 35° are very "steeply dipping" as compared to gently tilted or flat lying strata in formations above and below.

Bretz (1950, p. 799) has introduced the term "slickolites", which he defined as follows:

> Slickolites are essentially slickensides, but are not abrasional in origin. They are made by differential solution along minor fault planes in calcareous rock and repeatedly are accompanied by other evidence of displacement. They consist of alternating grooves and ridges or half columns which fit into ridges and grooves opposite them, the series on one face being the exact reverse of the marking on the opposite face. Ends of columns are engaged by sockets in the termini of grooves, and the column-socket relationship on one face is the opposite of that in the other. Thus the relative movement is recorded. Beyond any doubt they are pressure-solution phenomena.

Slickolites as a descriptive and genetic term has been used repeatedly in this paper.

The term "bioherm" or "reef" is used in the sense agreed by Cloud (1952, p. 2146) to be proper for structures similar to those described in this paper. He notes that it is permissible to retain the name "bioherm" for structures similar to Upper Cambrian masses of stromatolitic limestone that show "filamentous structures strongly suggestive of the calcium-precipitating and sediment-binding blue green algae."

SURFACE EXPOSURES

Most of this study has been directed toward detailed examinations of outcrops in the stratigraphic interval that includes basal St. Peter sandstone, the shaly arenaceous strata of the contact zone, and the upper dolomite and dolomitic limestone beds of the Shakopee formation. This approach to the problem was adopted because most of the evidence on which present interpretations of Shakopee-St. Peter relations are based has come from subsurface data and from the general topographic relations of the two formations in adjacent exposures. Details of the strata just above and below the contact generally have been neglected, owing mainly to the fact that the friable sandstone of the St. Peter, except in a very few exposures, has fallen down over and veneered the contact interval, obscuring it completely. Removal of this surficial sand was necessarily the first step in most outcrop examination.

Another problem, that of making representative dip-and-strike measurements on the nearly continuous small-scale undulations of the beds in much of the Shakopee, was resolved by selecting a segment of one bed that seemed to be, in inclination and orientation, about average for the beds in the immediate area.

Virtually all of the exposures found and examined during the course of this investigation contained dipping beds at the contact. The Beetown road cut, the first of the surface exposures to be described, is one of the few exceptions.

Beetown road cut.--The Shakopee-St. Peter contact is exposed 1.4 miles southeast of Beetown, Wisconsin (near the center, W½ sec. 32, T. 4 N., R. 4 W., Lancaster quadrangle), where roadway excavation on the northeast side of Grant County Highway U has truncated a southwesterly trending spur, exposing typical St. Peter sandstone and, below it, 4.6 feet of argillaceous and dolomitic sandstone, shale, and chert. Strata above and below the contact are horizontal.

A section measured in July 1952 is described below:

	Thickness (feet)
St. Peter sandstone:	
Sandstone, quartz, fine- to medium-grained, rounded, larger grains frosted, much ferruginous staining, friable.	24+
Shakopee dolomite (contact zone):	
Sandstone, mainly fine- to very fine-grained, cemented in part by silica; the few medium grains are frosted; clay- and silt-size material common throughout; sparse gray and green shale near base; local areas of buff dolomitic and argillaceous cement occur in the sandstone.	1.5
Sandstone, white, mainly fine-grained, partly argillaceous.	0.4-0.8
Sandstone, dolomitic, buff.	0.2-0.4
Chert, light-gray, oolitic, arenaceous, partly leached to a white soft "cottonrock".	0.0-0.1

	Thickness (feet)
Shakopee dolomite (contact zone), contd.	
Sandstone, dolomitic, buff, leached.	0.6
Chert, gray, partly leached to white.	0.2
Shale, gray and green (in gutter).	0.6+

Most of the lower units have been nearly obscured by a veneer of fallen sand, which was removed to expose the complete thickness described above. The lowest green and gray shale is in the gutter more than a foot below road level, and a few fragments of gray-buff dolomite were dug up from below the shale.

Recurring throughout this investigation has been the problem of locating in the section the exact position of the Shakopee-St. Peter contact. It has been placed by most previous investigators at the top of the uppermost dolomite below the St. Peter. Consequently, the shale, argillaceous sandstone, and the chert, which has been interpreted as a basal conglomerate in both surface and subsurface descriptions, have been considered the basal phase of the St. Peter sandstone.

Three lines of evidence appearing in this outcrop bear on the contact problem. (1) The change from the ferruginous, well-sorted and rounded, clay-free sandstone, to the underlying, mainly fine, more poorly sorted, argillaceous, and locally dolomitic, sandstone is well defined and particularly well marked in this outcrop because of the color change (PLATE I). (2) Local areas of quartz sandstone in the contact zone are cemented by dolomite or by a dolomitic clay paste. These small lenticular areas appear to be remnants of much larger zones cemented by carbonate that has been removed by leaching. (3) The presence in a quartz sandstone of an oolitic chert bed as a primary or replacement feature is unexpected. Silica in solution percolating through a quartz sand reasonably might be expected to precipitate either as an overgrowth on the sand grains or as a clear silica cement, but not as chert.

Based on the above, the contact at this exposure is placed at the top of the shaly white sandstone of the contact zone. It is reasoned that the presence of dolomitic cement and oolitic chert, common in the dolomite beds of the Shakopee, and the inclusion of green clay, ever-present in Shakopee dolomite beds, are sufficient criteria to assign these strata to that formation. The much finer quartz sand in the contact zone is not of the type that would be expected in the basal beds of a sandstone formation, unless the contact is gradational and no break in sedimentation occurred.

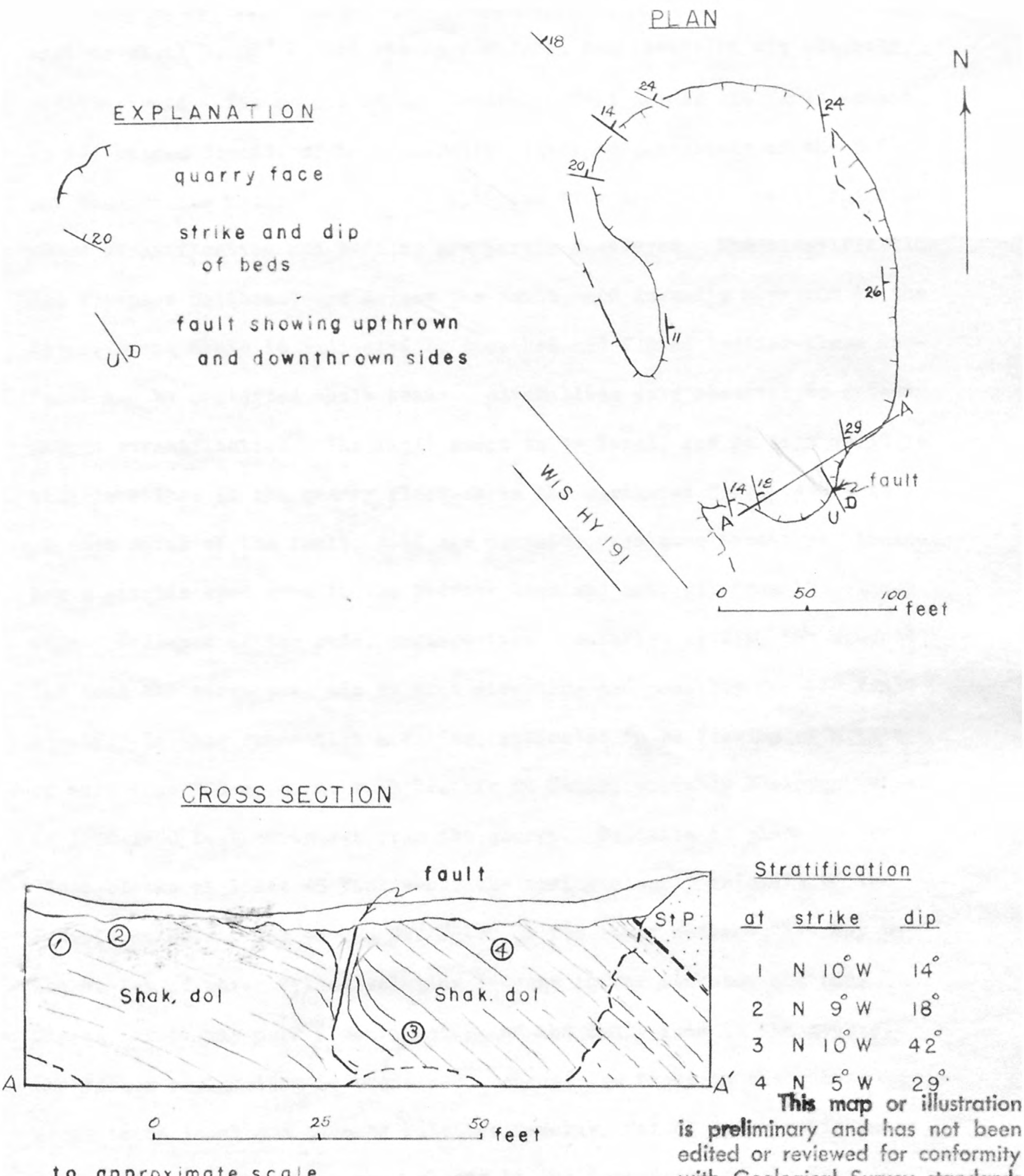
The punky, leached dolomite below the contact zone, the dolomitic material in it, and the leached chert, if considered together, suggest that the entire zone may have been impure, arenaceous dolomite or dolomitic sandstone before leaching and removal of the carbonate. If the leaching occurred in post-St. Peter time, an explanation is offered for the sharp boundary at the base of the iron-stained sandstone. The contact zone sandstone, although clayey and silty, is at present both porous and permeable, and if the iron were infiltrating into the St. Peter presently, it would also penetrate downward into the contact zone sediments. If, however, the contact zone sediments were cemented by dolomite, it is reasonable to suppose that they also would be essentially impermeable. Such a condition, if present when the iron infiltration occurred, would block the incursion downward of the iron-ladened waters, leaving an abrupt change from ferruginous to nonferruginous strata, which is the situation existing in this road cut at present.

The basal ferruginous sandstone, here as elsewhere, is homogeneous in grain size and composition, and no suggestion of a basal conglomerate occurs in it.

Another road cut about 1500 feet north on the opposite side of the highway contains 10 to 12 feet of Shakopee dolomite beds and the overlying contact zone below the typical sandstone of the St. Peter. The contact zone in this road cut, 34 feet topographically higher than in the cut first described, has more green clay but is otherwise very similar. The exposure, however, is relatively poor.

__Ryan quarry__.--This excavation, 1.7 miles northwest of Hollandale, Wisconsin (near the center, NE¼ sec. 24, T. 5 N., R. 4 E., Blanchardville quadrangle), on the northeast side of Wisconsin State Highway 191, exposes the Shakopee dolomite, including the contact zone, and locally the basal St. Peter sandstone. The quarry, in the northeast valley wall of the Dodge Branch of the Pecatonica River, is about 250 feet long by 145 feet wide, and the top of the highest quarry face is 30 or more feet above the floor.

In contrast to the Beetown road cut, here steeply dipping Shakopee beds (PLATE II, B; Fig. 2) at and below the contact, compose three faces of the quarry. Near the top of the northeast face the contact zone crops out, and overlying it is the St. Peter sandstone, much of which, however, has been removed as overburden, leaving a bench above the quarry face. The sandstone is exposed in the floor of the bench. The map of the quarry and vicinity (Fig. 2) shows that both the dip and strike of the beds in the quarry area vary substantially. The steepest dips are in the lowest exposed beds in the northeast face. In the upper face a dip of 25° was measured; about 25 feet lower a dip of 42° was measured. Outside the quarry about 30 feet northwest from the entrance the most gentle dips were measured. The beds in the northwest part of the quarry strike from N. 43° W. to N. 70° W., whereas the beds in the northeast and southeast faces strike N. 5°-10° W. The centrifugal nature of the stratification dip suggests that the quarry site is in the northeast part of a Shakopee dome. Presumably the summit of that structure, if it were present, would lie in the Dodge Branch valley.



This map or illustration is preliminary and has not been edited or reviewed for conformity with Geological Survey standards and nomenclature.

Figure 2: Outline map of Ryan quarry and cross section of Shakopee and St. Peter strata exposed in it, 1.6 miles northwest of Hollandale, Wisconsin. Shak = Shakopee; St P = St. Peter.

A fault (PLATE II, A) exposed in the southeast end of the quarry, strikes about N. 35° W. and the narrow fault zone seems to dip slightly southwestward. The amount of the bedding offset across the fault cannot be determined because of the generally disturbed conditions of the beds and because the upper beds on the upthrown side are in the weathered zone where stratification and bedding are partly destroyed. The stratification dip steepens northeastward across the fault, and down-dip movement in the dolomite and shale is indicated by smoothed and fluted bedding-plane surfaces and by contorted shale seams. Slickolites were observed to extend across stratification. The fault seems to be local, for no sign of it is visible either in the quarry floor or in the northwest face. About 15 to 20 feet north of the fault, cold air emanates from open fractures, indicating a sizable open area in the bedrock back and down dip from the quarry face. Collapse of the beds, perhaps into a solution cavity, may account for both the steepening dip in that direction and possibly for the fault itself. In this connection a spring, estimated to be flowing at a rate of more than 300 g. p. m. from Prairie du Chien, probably Shakopee, strata, is 1500-1600 feet northwest from the quarry. Dolomite in place and as float blocks at least 40 feet above the spring clearly relate it to the Prairie du Chien, not to the St. Peter or its lower contact. It may be the outlet of water-filled solution caverns in the Shakopee and (or) Oneota, or it may mark a continuation of the fault zone in the quarry. The former explanation is preferred, because the fault in the quarry seems to be local and because solution caverns, formed by phreatic water circulation, are known in many places in the formations of the Prairie du Chien group (Martin 1916, pp. 77-78).

No reflection of the tilted Shakopee strata in the stratigraphically higher Platteville, Decorah, or Galena beds could be found in the general area of the Ryan quarry, although outcrops of these beds occur short distances northeast, north, and northwest of the quarry, and across the valley from it, south of Dodge Branch. Also, the upper beds of the St. Peter sandstone, cropping out less than 600 feet northwest of the quarry, are flat-lying.

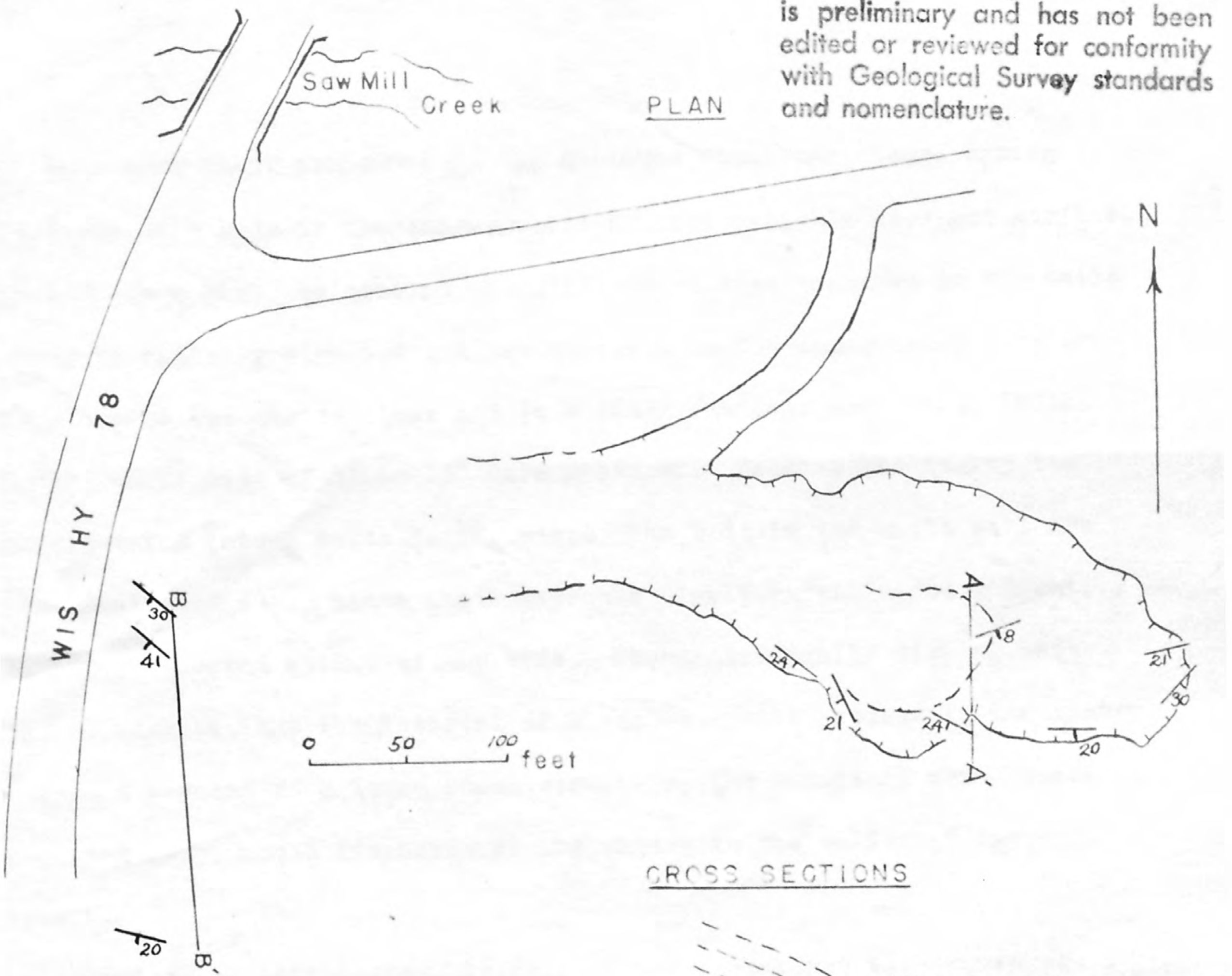
The highest exposed unit at the quarry site is the St. Peter sandstone. It crops out in the floor of the bench northeast of the quarry, and farther east about 120 feet from the northeast face it is exposed as a much weathered ferruginous sandstone. At the latter place the stratification is partly crossbedded, but the true bedding appears to have a general eastward dip. Values from 2° to 20° were measured. The dips may or may not be a reflection of the underlying Shakopee structure. A detailed search of the St. Peter sandstone found no hint of a basal conglomerate, and the basal sandstone in the limited exposures at the approximate contact contains no evidence of unconformity.

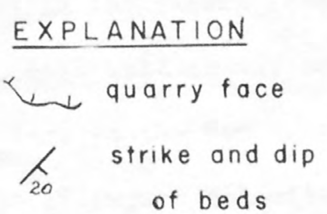
A stratigraphic section measured in the northeast face (Section 1) shows the contact zone to comprise green, maroon, and purple shale interbedded with buff and white, mainly fine-grained sandstone, lying under typical rounded and frosted fine- to medium-grained St. Peter sandstone. In about the middle of the zone is a bed 0.1-foot thick of white leached chert. Stratification is contorted throughout the interval, and compaction and slumping has disturbed the chert bed, fracturing the nodules. The chert band follows stratification above and below it in the zone, and individual nodules that compose it have been leached, but not rounded by abrasion; the chert is not a basal conglomerate of the St. Peter.

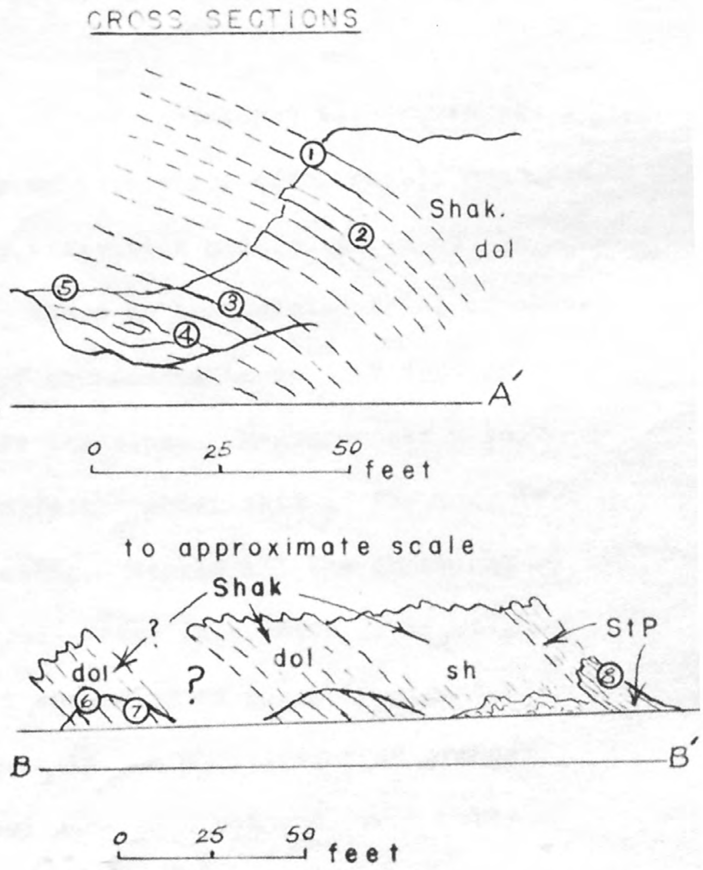
Below the contact zone in the quarry face cryptozoan structures cause the dolomite beds to pinch and swell. The floor of the quarry is continuously rolling and irregular because of the algal nature of the beds.

It is concluded from the variety of evidence observed in the quarry and its immediate vicinity that the steep dip of the exposed beds is primarily a product of compaction before and after interstratal solution over a less compressible mass, probably of algal origin, but the dip may be due partly to collapse or subsidence into subterranean solution cavities. The St. Peter seems to overlie the Shakopee conformably, and the relief at the contact, which may be considerable if the dip of the exposed beds is maintained at depth, is unrelated to pre-St. Peter erosion of the upper Shakopee surface. The contact zone is believed to be uppermost Shakopee, and the white-buff sandstone, clay, and decomposed chert just below the typical St. Peter sandstone are thought to be mainly residual products of leaching by waters from the overlying porous aquifer.

Saw Mill Creek exposures.--Two significant exposures, one a quarry the other a road cut, are 4.5 miles north of Argyle, Wisconsin (NE$\frac{1}{4}$NE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 2, T. 3 N., R. 5 E., Blanchardville quadrangle), along Wisconsin State Highway 78. The road cut on the east side of the highway, about 250-440 feet south of Saw Mill Creek, exposes both Shakopee and St. Peter strata; but the quarry, 300-600 feet east of Highway 78 along a township road, exposes only Shakopee and perhaps upper Oneota beds. Figure 3 shows the relative locations of Saw Mill Creek, the road cut, and the quarry and includes the outline and orientation of the latter.







Stratification

at	strike	dip
1	N 73° W	24°
2	N 85° W	28°
3	N 76° E	18°
4	N 72° E	13°
5	N 70° E	8°
6	N 50° W	30°
7	N 50° W	41°
8	N 75° W	20°

Figure 3: Outline map of Saw Mill Creek quarry and vicinity, and cross sections of Shakopee and St. Peter rocks exposed, 4.5 miles north of Argyle, Wisconsin. Shak = Shakopee; St P = St. Peter

Like many other exposures of the Shakopee formation viewed during this study, the beds in the quarry walls exhibit variable dips and strikes. Figure 3 shows that, in general, stratification dips measured in the walls tend to be radially directed and are steepest in the upper beds; they are less steep at the quarry floor and in a small subfloor excavation (PLATE III, A), where dips of 8° to 13° were measured. Because the quarry has been excavated into a north-facing slope, the beds in the north wall are in the weathered zone, hence their dips are highly variable and indicative only of the slumped nature of the beds. The centrifugally dipping beds (Fig. 3) suggest that the interval of Shakopee strata exposed in the quarry composes a segment of a large domal structure, the summit of which, were it not eroded away, would lie north of the quarry in the valley of Saw Mill Creek.

A variety of lithologies, typical of upper Shakopee strata, is exhibited in the quarry face. A stratigraphic section (Section 2), measured in the east wall of the small subfloor excavation and continued up the south face to the top of the exposure, shows an accumulated total of about 32 feet of impure dolomite, 4.8 feet of arenaceous shale, 1.7 feet of decomposed chert, and 1.2 feet of white sandstone. Measurements were made normal to bedding. The most notable characteristic of the rock is the great amount of alteration by leaching. Nearly all the chert has abundant small round or ellipsoidal brown areas in a white or light-gray crystalline quartz matrix, which are interpreted as possible structures of algal origin that have been preserved in the chertification process. In a few chert boulders the brown areas have been removed, presumably by leaching, leaving a vesicular rock of mainly very fine grained crystalline quartz.

The dolomite, as well as the chert, bears evidence of substantial leaching. Slickolites (PLATE III, B), particularly in the more massive beds, are common. The relatively thick-bedded dolomite in the east wall of the subfloor excavation exhibits one such occurrence. Here the grooves are on surfaces oriented nearly normal to stratification and distinctly record a very slow differential movement of these surfaces.

In general, interstratal solution has progressed farther in the thin-bedded less homogeneous dolomite in the middle and upper quarry face. Virtually all the chert is leached, and much of it is so decomposed that it can be crushed between the fingers. If the relatively insoluble chert has been so attacked, what quantities of the more soluble carbonate must also have been leached and removed? Clearly the question of the origin of the shale exposed in the quarry face must be considered with the leached chert in mind. A reasonable supposition is that much, and perhaps all, of the fine clastics is a residue from an argillaceous, silty, and arenaceous carbonate rock, and none, or very little, of it represents an unaltered, primary sediment.

Abundant evidence of down-dip movement is recorded in the quarry beds. For example, a chert band in the south quarry wall has been fractured and drag folded by down-dip movement of overlying beds. Fractures that are continuous through the leached and unleached areas indicate that at least some of the movement involving the chert fragments occurred after lithification and partial decomposition of the rock. Differential movement is evidenced, also, by structures in the thin sandstone beds in the quarry face. These beds have crenulated upper and lower surfaces that appear not unlike ripple marks except that in each place where they occur the orientation of the ridges and troughs coincide with the strike of the adjacent dipping beds, hence are better explained as a result of drag on the upper surface of the sandstone by the overlying dolomite bed. A cross-section view of the crenulations, normal to their strike, shows the characteristic asymmetric configuration of a drag fold. A similar feature is present on the upper surfaces of many of the shale layers except that the relative amplitudes of the crenulations are very small. Their strike parallels the strike of the adjacent beds, and they are asymmetric in the down-dip direction.

The area south of the quarry, although part of the overburden has been removed, is so heavily overgrown that no information could be gained in the examination of it. However, 125 to 150 feet south of the south quarry face a gully, oriented parallel with the general strike of the quarry strata, is believed to mark the location of the soft, more easily eroded sand and shale of the contact zone just below the typical St. Peter sandstone.

The road cut along Highway 71 is about 350 feet west of the center of the quarry (Fig. 3). When first examined (1950), the contact zone was moderately well exposed, but within two years that zone has been nearly covered with a veneer of sand and sandstone blocks, and it is overgrown with vegetation. The dipping Shakopee dolomite beds and the fractured and sheared St. Peter sandstone, however, can remain exposed indefinitely.

Shakopee dolomite crops out intermittently through a distance of about 100 feet in the northern part of the road cut. Its beds dip southwestward more than 28° and strike about N. 45° W. The appearance of the road cut suggests that the covered areas which intervene the resistant dolomite outcrops represent zones of shaly and sandy, less indurated, strata.

South of the dolomite exposure, beyond a covered interval, is a thick zone of arenaceous shale, which is predominantly maroon but contains interbedded green shale seams and also white leached chert. When the exposure was fresh the surface of the shale zone was littered with fragments of strongly slickened shale. Weathering, however, has reduced most of these fragments to incoherent clay. A few pieces of grooved and quartzitized sandstone, which attest to the magnitude of the deforming forces, are preserved. The shale differs in several respects from that observed at the same stratigraphic position in other exposures. The deep maroon color, for example, is not similar to the multicoloration of purples, reds, and browns, exhibited at the Clayton sand pit (discussed later) or at the Ryan quarry. In addition, the shale is markedly thicker here than observed in exposures elsewhere, although its maximum thickness is not determinable from outcrop examination. The horizontal thickness of the exposed shale is more than 20 feet. Between it and the nearest dolomite outcrop is a zone of friable sand, fallen from the thick sandy soil and residuum above, that has obscured the bedrock. A hand auger was used to explore this covered interval, and in the several places investigated maroon shale was penetrated below 2-3 feet of loose sand. Presumably, therefore, the covered interval marks the north part of the shale zone, and the total horizontal thickness of that zone is 40-45 feet or, allowing for an average dip of 25°, its thickness measured normal to stratification is 17-18 feet.

The advanced stage of decomposition of the chert contained in the shale is significant. Although much of the shale includes silt- and sand-size clastics, it is semi-impervious to percolation of water through it. It is thought, therefore, that most of the leaching occurred while the chert was enclosed in a more porous and permeable rock. No evidence in the outcrop, however, suggests that the chert has been transported to its present position. Many of the completely leached chert fragments have been elongated, in some places to thin laminae, by movement within the shale, and their original outlines cannot be observed. A few larger fragments whose surfaces are distinctly angular were found, and if they have been abraded, the leaching obscured it. These fragments appear to be identical to chert at other exposures of the same stratigraphic zone, for example at Ryan quarry, where it distinctly was not the product of water transportation and accumulation as a conglomerate.

It is proposed that this chert was enclosed in an impure dolomite or limestone through which ground water percolated to leach it, at the same time dissolving and removing the carbonate. Thus, most of the fine clastic material, as well as the chert, that occupies the interval between the dolomite and the sandstone is believed to be a residuum from that carbonate rock.

The shale's maroon color and the deep red ferruginous staining of the overlying St. Peter sandstone at this and other exposures in road cuts both north and south along Highway 78 have a clear genetic relationship. If the ferruginous staining of the sandstone and the subjacent shale resulted from different episodes of infiltration of iron, such would be an astonishing coincidence, and certainly at this exposure highly improbable. The iron was introduced probably by infiltration as suggested by Dake (1921, pp. 191-192) for the origin of most of the iron in the St. Peter sandstone. It is important to note that the iron was introduced after St. Peter deposition, for the dark-red or maroon coloration caused Norton (1912, pp. 79-80) to suggest that a similar shale penetrated below typical St. Peter sandstone in a deep well at Maquoketa, Iowa, is a basinal filling of continental sediments. In this exposure, at least, the color was acquired post-deposition, and the sediment need not have been maroon when it was deposited.

The St. Peter sandstone lies against the shale zone on the south and is separated from it by a poorly defined boundary. The St. Peter extends upon and partly over the shale zone, and fallen sand has obscured the contact relations. The very platy, less-weathered sandstone here has been fractured and sheared, so much so that to recognize which are fracture or shear planes and which are stratification is, in itself, a problem. Perhaps some of the structures record down-dip movement along stratification planes. In any event, the planes--shear, fracture, or bedding--dip southward. The dip is steepest high in the exposure adjacent to the shale contact, becoming more gentle southward along the road cut. The traces of these surfaces in a vertical plane thus are concave upward. The attitude of the fractures and shears indicate that the sandstone has subsided, moving down and southward; the fracturing, of course, requires that the subsidence took place after the sandstone was lithified. A detailed examination of the typical St. Peter sandstone disclosed no suggestion of a basal conglomerate.

A summary of the facts bearing on the origin of the irregularities at the St. Peter-Shakopee boundary in these exposures show:

1. Shakopee beds dip steeply, but dip directions are centrifugal, and, therefore the beds probably were not folded by lateral compressive forces.

2. The Shakopee and the St. Peter beds seem to be conformable.

3. Much evidence of interstratal solution and down-dip movement of the Shakopee beds is present.

4. The abundant maroon shale acquired its color after deposition.

In the general vicinity of this quarry the lower 20-40 feet of the St. Peter sandstone strata, for the most part, are ferruginous and platy and dip irregularly in many directions within limited areas. Where the upper, commonly massive beds are exposed, however, they are flat-lying or dipping negligibly. In several exposures the beds are seen to change progressively upward through the sandstone interval from steeply dipping to flat-lying positions, undoubted evidence that the Shakopee large-scale domal features did not originate as tectonic features unless the deformation occurred wholly within and long before the end of St. Peter time.

Several outcrops that expose much of the St. Peter formation occur along Highway 78 and along adjacent township roads, and in these the progressive upward change from dipping to flat-lying beds is exposed. Similar bedding conditions in the St. Peter were noted elsewhere in the studied area, but the iron cement in the sandstone of the Argyle-Hollandale, Wisconsin, area has preserved the stratification, whereas elsewhere those features are nearly lost in the friable, poorly cemented sandstone.

The conclusion that the dipping beds in the lower St. Peter reflect the differential compaction of the lime muds of the Shakopee below under the accumulating weight of the sandstone seems justified.

Cleary quarry.--This excavation is about 4.0 miles northwest of Hollandale, Wisconsin (SE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 14, T. 5 N., R. 4 E., Mineral Point quadrangle), on the Cleary property and lies just northeast of Wisconsin Highway 191. Only Shakopee and (or) Oneota strata are present in the quarry walls, presumably 20-40 feet below the St. Peter sandstone.

Two similar and significant features, however, are present in these strata. In the northeast wall is exposed (PLATE IV, A) a lenticular mass of brecciated, dense, very hard, buff and gray dolomite that shows no visible stratification except in its peripheral areas. The unstratified zone, which vertically is more than 15 feet thick, contains local faint algal structures, common slickolites, and several subspherical solution vugs 2-4 feet in diameter. Rising steeply onto the central mass are well-stratified shaly dolomite beds which, as they approach it, thin rapidly over the summit or finally wedge out in the brecciated zone. Some, however, can be traced into the disturbed zone for several feet, precluding the possibility that the feature is an erosional remnant over which the stratified Shakopee beds were deposited. A well-defined very undulating chert band that is visible around the quarry walls sags under the brecciated dolomite mass, and the highest exposed beds seem to be continuous over its upper poorly defined surface.

A larger but otherwise nearly identical lens is in the southeast quarry face (PLATE IV, B). The brecciated dolomite, slickolites, solution vugs, and faint algal structures are all of the same nature as those in the northeast face, but here, included in the basal part, is a zone of extremely brecciated chalcedonic partly leached chert. The brecciated dolomite and chert interval is more than 18 feet thick, and the beds on the northeast rise upon it or thin into it. On the southwest, however, some of the beds continue to rise irregularly as though approaching a similar but topographically higher upswelling, which, if once present, has been eroded away.

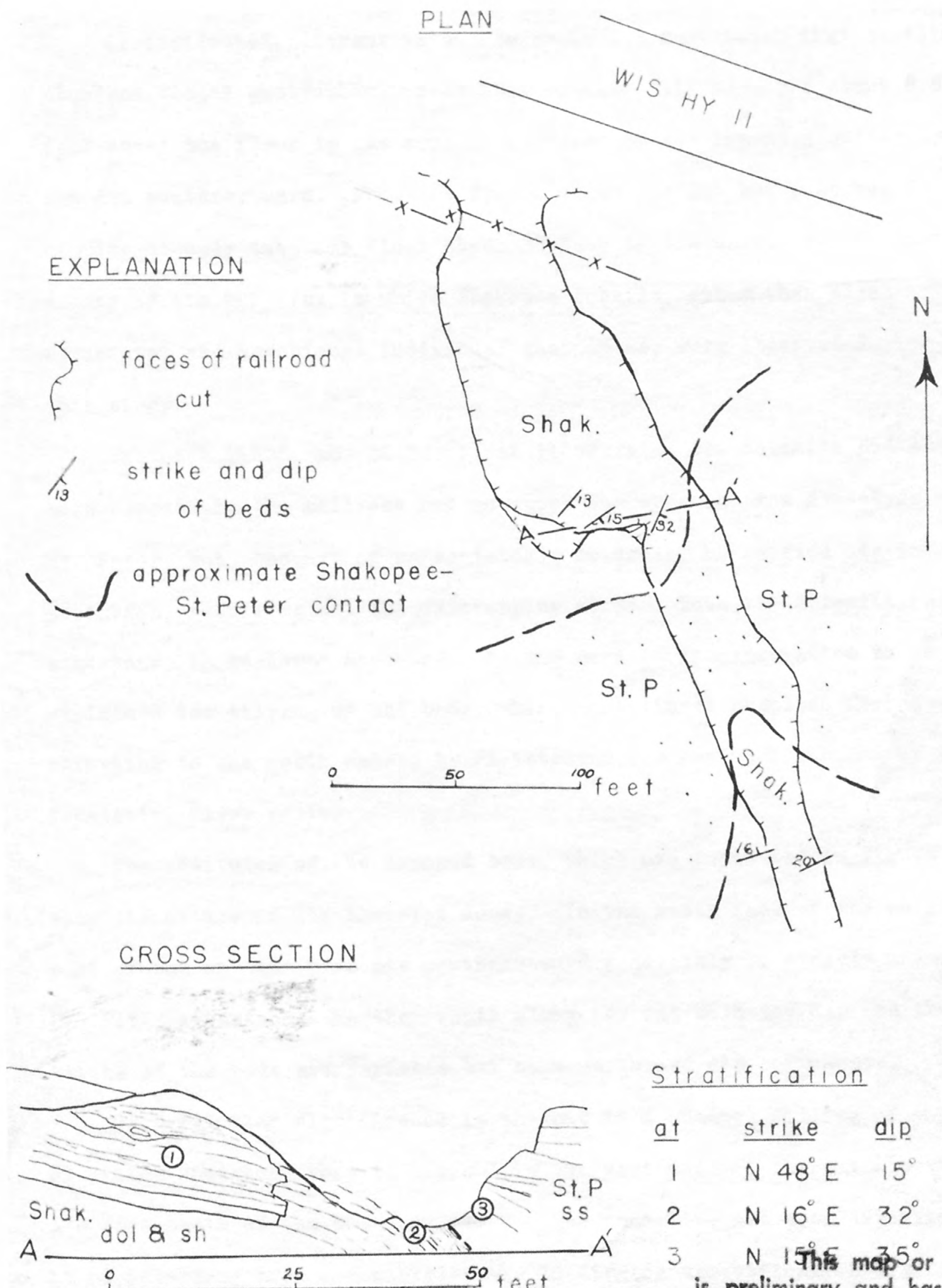
No evidence of submarine wave erosion was observed on the sides of these brecciated masses.

These masses are interpreted as reef cores and the dipping strata on both sides as sediments, compacted over them. The brecciation seems to have been caused by several processes, but there is no suggestion that lateral compressive force is one of them. The pressure-solution criteria, particularly the slickolites, which are on nearly vertical surfaces, and such offsetting of the buff dolomite fragments as can be seen in the gray dolomite matrix, seems to require the deforming forces to have been directed vertically downward. One evident fact is that the brecciated dolomite, although compacted somewhat, is, relative to the adjacent and overlying bedded sediments, notably incompressible.

Although the suspected biohermal cores were seen in other quarries, these are the only ones, and they are relatively small, viewed during this study that are completely exposed. If these are isolated bioherms, and not integral parts of a larger reef, they account for relief on beds compacted over them of no more than 15 feet.

Dill railroad cut.--An exposure of upper Shakopee beds in a railroad cut is located and described by Sardeson (1926, pp. 32-33) at Dill, Wisconsin, and for that reason the name is retained here although Dill, which was little more than a railroad depot at an intersection of the railroads, no longer exists. The railroad cut is 3.2 miles east of South Wayne, Wisconsin (NE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 6, T. 1 N., R. 6 E., South Wayne quadrangle), along an abandoned branch of the Illinois Central Railroad, and extends 350-400 feet south from U. S. Highway 11. Figure 4 shows the outline, size, and orientation of the exposure.

The railroad excavation was made through parts of two irregular domes of stratified Shakopee dolomite, exposing, also, the contact-zone shale and sand and the overlying St. Peter sandstone that fills the interdome areas. The floor at both sides of the north end of the cut exposes Shakopee dolomite. In the east wall, beginning 108 feet south of the highway boundary fence, however, St. Peter is exposed at the floor for a distance of 90 feet. Farther south is a covered horizontal interval of about 35 feet, beyond which the Shakopee beds rise and continue in outcrop to the end of the cut. On the west side the St. Peter occurs at the floor about 125 feet south of the boundary fence and continues so exposed for about 55 feet southward, where a covered interval of about 45 feet occurs before the Shakopee beds rise above the floor and continue intermittently exposed to the south end of the cut. The upper Shakopee green shale contact zone crops out only on the west and south sides of the northern expanded part of the cut, although fragments of the shale were noted in the unconsolidated debris farther south in the cut. Elsewhere it is covered or has been removed. Local relief on the upper dolomite beds is more than 15 feet.



Stratification

at	strike	dip
1	N 48° E	15°
2	N 16° E	32°
3	N 15° E	35°

Figure [illegible]: Outline map of Dill railroad cut, and cross section of Shakopee and St. Peter rocks exposed in it, 3.2 miles east of South Wayne, Wisconsin. Shak = Shakopee; St. P = St. Peter

Of incidental interest is a zone about 1.8 feet thick that contains abundant fossil gastropods. Beds that compose this zone are about 8.5 feet above the floor in the southwest corner of the expanded cut area, and dip southeastward. They are truncated by the cut but reappear dipping steeply into the floor about 20 feet to the east. This exposure is one of the very few in which Shakopee fossils, other than algal structures and occasional individual gastropods, were observed during this study.

Sardeson (1926, pp. 32-33) first interpreted the dolomite and shale beds exposed in the railroad cut as upper Shakopee and the sandstone as St. Peter, but, because of paleontologic evidence, he revised his interpretation, requiring all the outcropping strata, both the dolomite and sandstone, to be lower Shakopee. In the revised interpretation he also explained the tilting of the beds, which he believed resulted from overthrusting to the north caused by Pleistocene ice moving northward up the Pecatonica River valley.

The attitudes of the exposed beds, which are indicated in Figure 4, show the nature of the Shakopee domes. In the south face of the enlarged part of the cut the beds dip southeastward moderately to steeply under St. Peter sandstone. Farther south along the cut both the dip and the strike of the beds are variable but have northward dip components.

Of particular significance in the cut is a channel filling of St. Peter sandstone that is exposed in the west wall of the cut about 175 feet south of the boundary fence. The sandstone has been deposited in an interdome area and exhibits the in-dipping stratification typical of channel filling. Significant also are the dipping sandstone beds in the east wall of the cut about 115 feet south of the highway right-of-way. Dips measured on stratification range from 5° to 35°, the steepest dips being in the lowest exposed strata. The structures described are clearly primary sedimentary features in both places, and no evidence of superficial movement by ice shove could be found anywhere in the railroad cut. The dip of the stratified sandstone in both the channel filling and in the lowest southeastward-dipping beds conforms in direction and approximate magnitude to the dip observed in subjacent Shakopee beds, which, although not exposed directly under the sandstone, crop out close by. Nothing observed in the exposure suggests that the channel into which the sandstone was deposited is a product of subaerial erosion. On the contrary, the conformably dipping beds and the absence of truncated Shakopee strata seem to establish beyond a doubt that the upswelling beds of the Shakopee form pre-St. Peter features.

Sardeson's revised interpretation is not acceptable. The upper sandstone has all the characteristics of typical St. Peter; the contact relations are similar to exposures of them observed in many other outcrops; and no evidence of any deformation other than compaction of the sediments could be found. His first stratigraphic interpretation seems to be correct.

The railroad cut is the only exposure examined that showed a distinct primary irregularity of the upper Shakopee surface, although such initial irregularity is strongly suspected to have been present at many other outcrops. Original sedimentary features, however, in the St. Peter sandstone commonly are obscure, and no absolute evidence of such irregularity could be found elsewhere.

Anaton exposures.--One of the best examples of the domal nature of beds in the Shakopee formation appears in exposures west and southwest of Anaton (also spelled Annaton), Wisconsin (east edge of sec. 13, T. 5 N., R. 2 W., and west edge of sec. 18, T. 5 N., R. 1 W., Lancaster quadrangle), in the Platte River valley walls both north and south of Grant County Highway E. The significant exposures are identified on the map (Fig. 5, I-IV).

In this area of a little less than a quarter of a square mile, Shakopee beds dip from 6° to 54° and strike in virtually all directions. Exposure I (Fig. 5) is a road cut on the north side of Highway E where nearly continuously exposed dipping Shakopee dolomite, shale, and sandstone beds crop out for a horizontal distance of about 200 feet. The thickness of the exposed strata, measured normal to the bedding, totals about 65 feet. Overlying the Shakopee, the friable ferruginous St. Peter sandstone crops out at road level in the western part of the exposure.

Figure 5 includes a field sketch of the road cut. The uppermost Shakopee strata near the west side of the outcrop dip 54° westward. Toward the central part of the exposure the beds become progressively less tilted and their strike rotates inconsistently toward a northwesterly direction. For about 100 feet east of the St. Peter-Shakopee contact, stratification is distinct, but farther east it becomes locally obscure or disappears. In the latter area two small-scale faults occur. The westerly one strikes N. 83° W. and is nearly vertical, the other strikes N. 85° W., dips northward 50°, and appears to be a reverse fault with the north side upthrown. Both faults have little displacement,

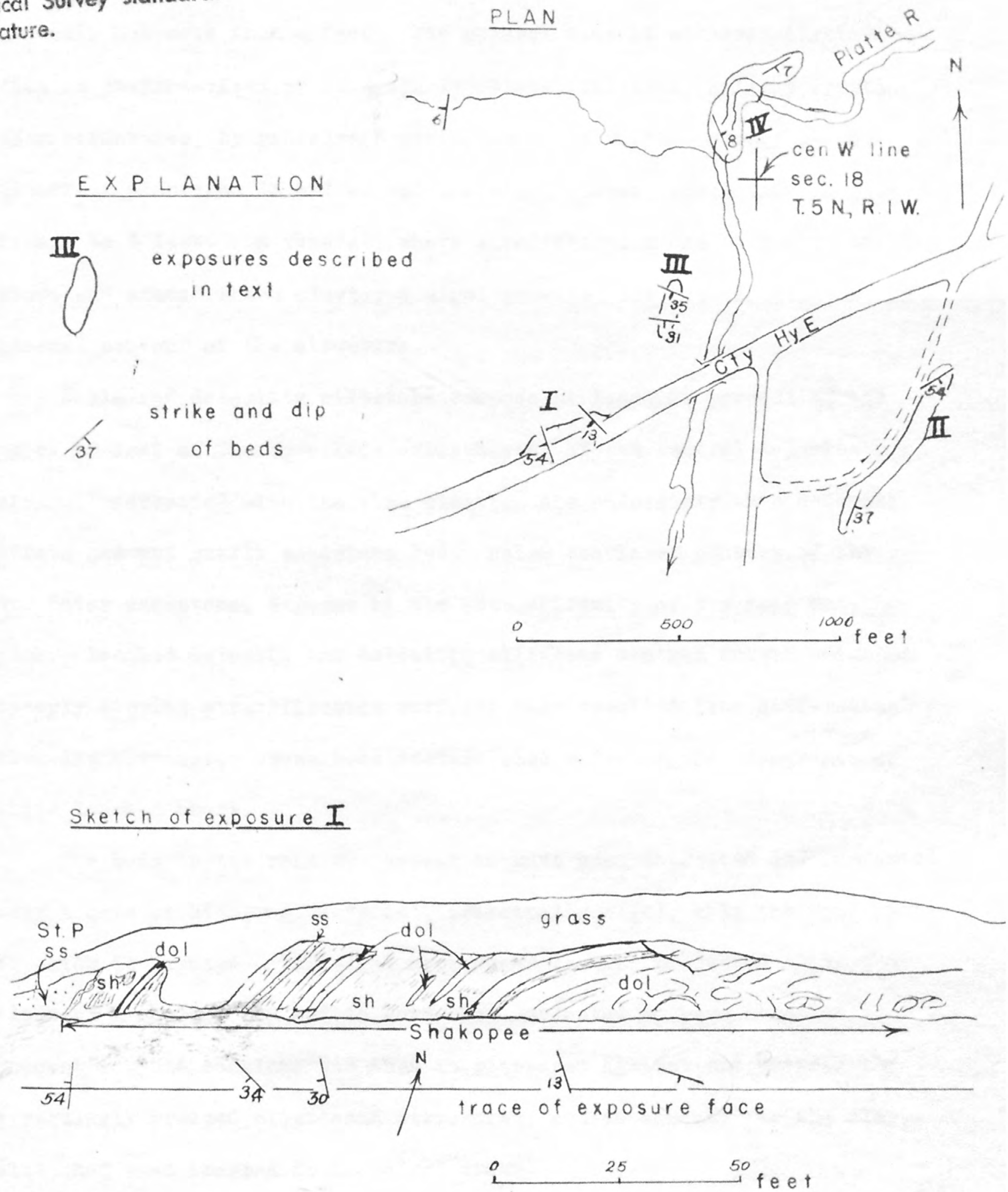


Figure 5: Map of area 0.5-1 mile southwest of Anaton, Wisconsin, and sketch of a road cut in that area. Critical exposures are indicated by roman numerals for ease of text reference. St P = St. Peter.

probably not more than a foot. The general zone of obscured stratification is characterized by irregularly oblate, foliated, crinkly cryptozoan structures, by rehealed breccia, and by a small--or pebble--conglomerate plastered in and around the algal masses, which vary in size from 2 to 4 feet. In general, where stratification can be recognized above and around these clustered algal growths, the beds follow the general contour of the structure.

Shale and dolomitic siltstone compose at least 70 percent of the upper 40 feet of Shakopee beds exposed west of the central dolomite area. Interbedded with the fine clastics are moderately thin dolomite strata and one quartz sandstone bed. Below the lower contact of the St. Peter sandstone, exposed at the west extremity of the road cut, punky, leached dolomite and dolomitic siltstone contain curved smoothed steeply dipping stratification surfaces that resulted from differential down-dip movement. These beds include also a few angular fragments of white leached chert.

The beds in the road cut appear to have been deposited and compacted over a core of biohermal material, principally algal, only the upper part of which is exposed. The algal mass seems to have projected above the floor of a shallow sea and to have been subjected to wave abrasion to account for the conglomerate that is plastered against and between the irregularly grouped cryptozoan structures, and to account for the clay, silt, and sand trapped in the algal areas.

The evident movement along stratification planes and the leached, punky dolomite and white chert in the uppermost Shakopee beds suggest the accentuation of bedding dips by interstratal solution and compaction, but considerably more evidence of differential movement in the strata is required to account for all, or even most, of the dip in the beds; hence, it is concluded that most of the dip is due to primary compaction.

Northeastward about 260 feet from the east end of the road cut is a natural exposure (Fig. 5, III) in the west valley wall of the Platte River that gives another view of this domal feature. The dolomite beds dip 31° to 35° southward and strike N. 60°-85° W. The vertical relief on a particular bed was determined to be 39 feet in a horizontal distance of about 70 feet. The dip becomes more gentle near the top of the outcrop, but the steep dip is maintained downward into the valley fill at the base of the exposure.

The St. Peter sandstone does not crop out here but occurs as friable sand in the soil well above the top of the exposure. The dolomite is thickbedded and contains sparse shale, which suggests that the strata are probably lower in the section than those in exposure I. Algal and associated material compose much of the exposure below the upper 7 feet (measured normal to stratification) of the bedded dolomite.

Upstream 600-700 feet in the stream bed (Fig. 5, IV) the dip and strike of stratification in the thin Shakopee beds change abruptly. The beds at one place strike N. 30° W. and dip 8° northeast; at another 100 feet upstream the beds strike N. 60° E. and dip 7° southeast. A rapids is formed at the latter place where the stream flows over the upturned Shakopee beds.

To complete as much of the picture on the west side of the Platte River as exposures permit, the somewhat poorly exposed Shakopee beds about 850 feet west of exposure IV in a ravine strike N. 10° E. and dip 6° west. Only a few feet beyond, the shale and sandstone of the contact zone, overlain by the St. Peter sandstone, crop out. In the intermittent exposures of Shakopee beds eastward from the contact zone, virtually all are characterized by rolling, gnarled algal structures, and measurement of representative strikes and dips on stratification cannot be made.

The remaining exposure of particular interest in the Anaton vicinity is either a natural outcrop or an old road cut south of Highway E in the east valley wall of the Platte River (Fig. 5, II) where Shakopee and (or) Oneota beds dip 37° to 54° southeast and strike N. 30°-60° E. The beds crop out for about 550 feet and are exposed vertically for about 30 feet. The general thickness of the beds and the sparse shale in this exposure suggest that the strata are stratigraphically lower than those at Exposure I. Much of the dolomite in the outcrop is brecciated and, through about a 3-foot interval in the central area of the exposure, much of the stratification is obscure. In this zone, plastered in and around blocks of dolomite, which are in part rounded, is a conglomerate of subangular to subround, dense tan dolomite pebbles that range in size from 0.05 to 0.2 feet. Surfaces of the larger dolomite blocks under the conglomerate appear water worn, suggesting a reef-type conglomerate that was produced by wave and current action.

From the exposures of Shakopee and St. Peter strata in the Anaton vicinity certain facts become apparent:

1. The steeply dipping nature of the Shakopee beds, which in one place shows 39 feet of relief in a horizontal distance of about 70 feet, emphasizes that a conformable Shakopee-St. Peter contact may carry considerable relief.

2. Where the contact is exposed the beds are not truncated, and no basal conglomerate is present.

3. The configuration of the upper Shakopee surface as reconstructed from the attitudes of the exposed beds is irregularly domal. The steepness of the dip decreases as the beds arch up and over a central mass.

4. Lateral compressive forces could not account, in any simple manner, for the structures exposed in the outcrop. Moreover, Platteville and Decorah beds that crop out in the surrounding upland area have dips no greater than 6° and most are nearly horizontal. If, therefore, the structures resulted from diastrophic forces, most of the disturbance must have occurred in pre-Platteville time.

5. The abundant clustered cryptozoan structures that underlie the bedded dolomite, dolomitic siltstone, and shale, as in Exposures I, II, and III, are bioherms that extended above the Shakopee sea floor far enough to undergo wave erosion. Their total size cannot be determined in these exposures, but if the interpretation is valid that the bedded sediments overlying the algal areas represent lime mud deposition compacted over these reefs, then the bioherms may be very sizable structures.

Clayton sand pit.—The most extensive exposure of the St. Peter-Shakopee contact observed during this study is in the Waterloo Concrete Materials Company sand pit that is about 1.5 miles southeast of Clayton, Iowa ($SW\frac{1}{4}SW\frac{1}{4}$ sec. 6, T. 93 N., R. 2 W., Elkader quadrangle), in the west bluff of the Mississippi River valley. Work in the pit has been discontinued in favor of mining the sandstone from an area just southeast of the pit, and a newly cut (1952) entrance into the mine is through the southeast face of the pit.

Figure 6 shows the size and orientation of the sand pit. From the present floor of the main excavation to the top of the face is about 150 feet. The sand pit walls throughout the exposed thickness of the St. Peter sandstone are nearly vertical, but in the Shakopee interval below, the walls slope steeply toward the center of the excavation. Except for a relatively few feet of exposure below the contact of the two formations, the Shakopee strata are covered with talus and loose quartz sand.

Beds of the Shakopee, St. Peter, and Platteville formations are exposed in the pit walls. The Shakopee, represented by a varying thickness of dolomite, shale, and quartz sandstone, is overlain by pure white St. Peter sandstone whose exposed thickness, owing to the irregular surface at its base, ranges from 85 to 140 feet. The Glenwood shale member of the Platteville formation overlies the St. Peter and joins it conformably at a nearly horizontal contact. The Glenwood, about 2 feet thick, is overlain by the basal massive to thick-bedded dolomite of the Pecatonica member of the Platteville formation.

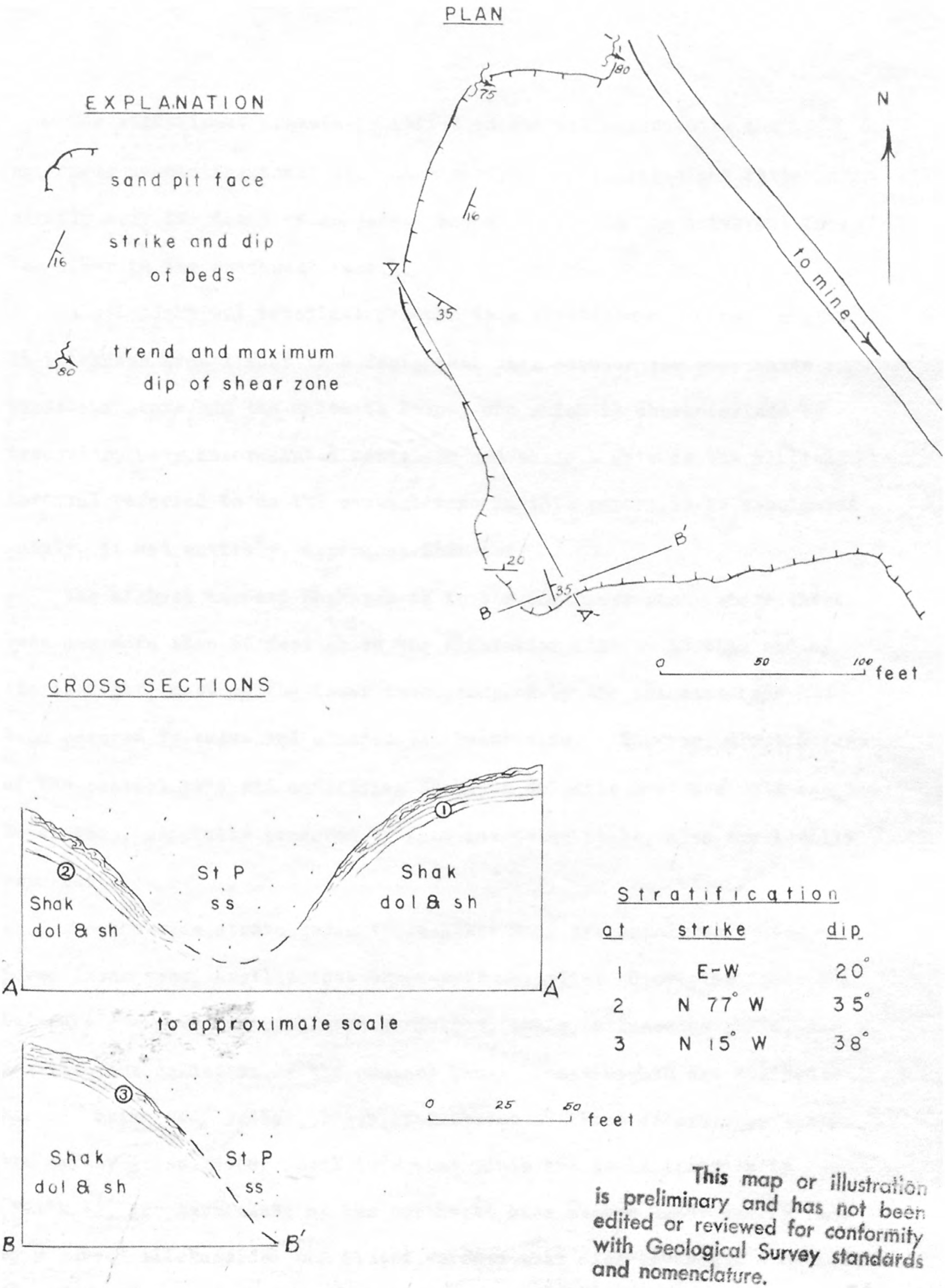


Figure 6: Outline map of Clayton sand pit, and cross section of Shakopee and St. Peter rocks exposed in it, 1.5 miles southeast of Clayton, Iowa. Shak = Shakopee; St P = St. Peter

The significant feature exhibited in the pit exposure is the extremely undulating basal St. Peter surface, which rises and falls steeply over two domes of subjacent Shakopee, one in the northwest face, the other in the southwest face.

A secondary but important feature is a stratigraphic zone, ranging in thickness from 1 foot to 4 feet, that lies between the pure white sandstone above and the dolomite below, and which is characterized by irregular, wavy intercalated sandstone and shale. This is the vertical interval referred to as the contact zone in this paper; it is considered mainly, if not entirely, uppermost Shakopee.

The highest exposed Shakopee is in the northwest face, where those beds are more than 56 feet above the excavation floor. At this end of the sand pit, most of the lower face occupied by the Shakopee beds has been covered by talus and slumped St. Peter sand. However, about 5 feet of the contact zone and underlying Shakopee dolomite beds are well exposed. Lower beds, generally veneered by sand and talus slabs, also are locally exposed.

The Shakopee strata below the contact zone are mainly soft, decomposed, arenaceous, argillaceous brown-buff dolomite. Overlying these beds are contorted intercalated sandstone, shale, arenaceous shale, and argillaceous sandstone of the contact zone. These strata are stained purple, brick-red, yellow, brown, and shades of these colors; the shales are mainly green. Individual beds that pinch and swell irregularly (PLATE V), are terminated at the northeast side of the upper quarry face by a curved slickensided and fluted surface that dips southeast a maximum of 75°. Grooves extending to depths of more than half an inch on the surface have been caused by retardation of the subsiding sandstone past the buttressing Shakopee rocks below. The slope beneath this exposure is strewn with slabs of fluted, slickensided, multicolored sandstone. The induration of the sandstone, most of which is due to quartzitization along movement surfaces, and the depth of the fluting indicate that the subsidence occurred under a heavy load and could not be a product of deformation contemporaneous with sedimentation.

A similar sheared and faulted zone is present 60 feet to the east, at the north entrance to the excavation 3-9 feet above road level, where several several parallel irregularly curved slickened surfaces (PLATE VI), wholly within the St. Peter sandstone, extend through a vertical distance of about 7 feet. The surfaces, which contain a white silica gouge, dip southeastward a maximum of 85°. At this place, the buttressing mass is back in the sand pit wall behind the faulted and sheared zone. If these faulted surfaces are interpreted correctly, they originated as fracture cleavage; continued pressure caused shearing, and finally faulting, along the irregular fracture surfaces. The record is one of continued very slow yielding in response to pressures directed essentially downward. The amount of total movement cannot be ascertained from the exposure. The Shakopee dolomite beds and the several feet of contact zone sediments are not continuously exposed across the northwest face of the sand pit, but there seems to be little relief on the contact. The interbedded sand and shale are irregularly stratified, and the pinch-and-swell structures in them (PLATE VII, A) appear to have resulted from compaction.

Along the northern part of the southwest face the upper surface of the Shakopee dips steeply southeastward. Between the Shakopee dolomite beds and the typical St. Peter sandstone, the contact zone strata are greatly contorted and drag folded (PLATE VII, B). Shears and minute faults occur in the sandstone layers. These and the drag folds clearly record the relative downward movement of the massive sandstone over the retarding mass of dolomite that crops out below the contact zone. The magnitude of the folds, the character of the indurated sandstone beds in the shaly zone, and the slickolites in the underlying carbonate beds rule out a contemporaneous deformation origin, and nothing present in the exposure, either in the St. Peter or the Shakopee strata, indicates that the deformation resulted from lateral tectonic forces.

The leached character of the Shakopee dolomite strata is notable. Individual beds 15-20 feet laterally from the contact zone are hard gray argillaceous and partly arenaceous crystalline dolomite; but these same beds become progressively less crystalline, softer, more argillaceous, and thinner as the contact zone is approached. Immediately next to that zone the dolomite is leached to a soft putty-like mass, and individual beds can be traced into the contact zone where they are thin wavy shale layers that conform to the contortions of the laminae above and below. All the dolomite beds cannot be so traced, however, for some are broken by the drag of the contact zone beds. Present in these beds is a chert band conformable with the contorted shale bands above and below it. The chert is gray and locally green from included glauconite; it is partly leached to white soft rock. The chert layer is continuous in a limited exposure and is clearly an original bed of primary or replacement silica, not a layer of individual chert fragments as in a basal conglomerate.

The dip of the dolomite beds in the northwest area of the pit ranges from 2° to 3° in the general center of the face to 35° in the southwest side of the face. The origin of the stratification dips, whether mainly primary or mainly secondary, is problematic. Slickolites both on and across stratification planes in the upper beds of dolomite suggest that if the dips are mainly primary, they have been substantially accentuated by solution and compaction.

A second exposure of Shakopee dolomite in the sand pit occurs in the southwest face near the southwest corner of the excavation. Except for the lack of marked shearing and faulting in the base of the superjacent sandstone, the phenomena seen in the northwest face are duplicated here, although generally on a smaller scale. The contact zone is 1.5-4.0 feet thick and its beds are less contorted than in the northwest face. Above the soft decomposed dolomite beds is a continuous medium-green locally arenaceous shale 1.5 feet thick, overlying which is 2.5 feet maximum of intercalated mainly white sandstone, most of which is cemented by a white siliceous clay, and gray well-compacted shales. Drag folding occurs in the intercalated sandstone and shale interval, and the irregular pinch-and-swell character of the beds is identical to that in the northwest face.

The dolomite beds immediately under the contact zone are leached to a soft mass. Slickensides and slickolites in these and lower strata record down-dip movement. These beds dip from 20° to 38° and strike centrifugally from N. 15° W. to east and west in a horizontal distance of about 25 feet.

The entire exposure of St. Peter sandstone, which, as it is interpreted here, excludes the contact zone beds, was closely examined for any evidence that might shed light on the contact problem. Except for the upper 20-30 feet, stratification is obscure or absent, and the sandstone is massive. The basal 5-6 feet of the St. Peter was examined in particular detail, but dolomite, limestone, or chert fragments, derived from the subjacent Shakopee, could not be found in this interval, and samples taken to the laboratory were examined under 10-30 magnification, but no Shakopee-type material could be identified. No glauconite, a common constituent of the Shakopee, was present in the samds examined. The same is true, except for the glauconite, in the contact zone underlying the St. Peter; no rounded or abraded fragments that might compose a basal conglomerate could be found.

The upper surface of the St. Peter sandstone at the contact with the overlying Glenwood shale member of the Platteville formation is essentially horizontal, and no marked relief at this horizon reflects the great irregularity of the basal St. Peter surface.

The evidence in the strata exposed in the sand pit seems to rule out as untenable the erosional hypothesis advanced by Trowbridge (1917b, pp. 178-180) to explain the irregular Shakopee-St. Peter contact visible in that excavation. The absence of a basal conglomerate and of truncated Shakopee beds, notwithstanding the magnitude of the relief on the contact, is incompatible with the erosional concept. On the other hand, the strongly sheared and faulted zone in the basal sandstone, the intense drag folding in the contact zone strata, the slickolites and slickensides, and evidence of extensive leaching in the dolomite strata below the contact, the progressive alteration of dolomite beds into thin shale in the contact zone--all emphasize that the principal geologic process which has operated since deposition is the leaching of the carbonate rocks, the concomitant compaction of the residual material, and the subsidence of the overlying sandstone under gravitational forces. The leached and compacted strata of the contact zone may be transitional from the Shakopee into the St. Peter, but the relatively sharp lithologic break at the base of the pure typical St. Peter quartz sandstone casts some doubt on this possibility.

Because of the limited exposure of Shakopee strata, the question of whether all the relief at the contact is due to localized solution of the Shakopee beds and concomitant subsidence of the St. Peter, or whether the dipping beds represent a primary feature of the upper Shakopee, could not be determined. It is reasoned, however, that a primary irregularity accounts for much of the relief because the marked undulation of the basal St. Peter is not reflected upward to its upper surface. Exactly what kind of structures would appear, however, if a well-rounded, well-sorted, pure friable sandstone like the St. Peter should flow to relieve applied pressure, is an open question. As Dake (1921, p. 24) points out, bedding and other sedimentary features are visible only because of a compositional or textural change in the sediment. Where the sediment is homogeneous both in lithology and texture, internal movements in the sediment, if not well cemented, also would tend to leave no record. Until relatively recent erosion removed a part of it, 320 feet of brittle limestone and dolomite, much of which is thick bedded to massive, has overlain the St. Peter at the sand-pit site. If support were removed locally from under the carbonate beds by subsidence of the St. Peter sandstone into underlying solution cavities, it is possible that the thick carbonate sequence would tend to resist warping to compensate for its unequally supported foundation, and instead would press downward in the manner of a piston, causing the differential pressures to be equilibrized in the much less competent sandstone mainly by individual movement of the rounded sand grains, that is, by flowing. This may have happened in the St. Peter sandstone at the Clayton sand pit. Unquestioned evidence of considerable subsidence is present in the basal St. Peter; its upper contact is horizontal and flat. No other explanation is suggested.

Sand Cave ravine exposures.--Sand Cave is one of the points of interest in Pikes Peak State Park 1.5-2 miles south of McGregor, Iowa (Waukon and Elkader quadrangles). It occurs in the southeast wall of a deeply dissected northward-trending ravine that exposes Decorah, Platteville, St. Peter, Shakopee, and probably Oneota strata. The ravine is the site of "Painted Rocks" mentioned in literature dealing with McGregor, Iowa, and vicinity. McGee's (1891, pp. 330-331) description of the cliffed walls of the ravine and adjacent river bluff areas follows:

> In the "Painted Rocks" near McGregor the cliffs are banded, mottled, and fancifully figured in harlequin coats of gorgeous red, brilliant yellow, dazzling white, deep blue, jet-black, vivid green, rich brown, and an endless variety of mixed tones and shades in an endless variety of patterns. Here the color-loving aborigines gathered, and their tumuli and temples crown the summits and their implements and weapons crowd the talus-flanked bases of the gorgeously painted walls; and here flock the pleasure-seeking whites to marvel at the glory of color, enjoy the grandeur and symmetry of form, and revel in the delicious cool of glens shaded by luxuriant foliage and tempered by refreshing springs.

The area so described, or much of it, is called in this paper Sand Cave ravine. The ravine is well known locally, as it has been readily accessible for years by foot paths leading from the upper bluff area of the park down to the Mississippi River.

Sand Cave occurs in the contact zone of the Shakopee dolomite and the St. Peter sandstone. The cave extends southeastward about 23 feet from the entrance to the back wall and is about 19 feet across its widest part. The greatest distance from the floor to the arched roof is at the entrance where it is no more than 10 feet. The floor of the cave dips about 25° northwestward. The cave's back wall (PLATE VIII, A) consists of irregularly rolling interbedded argillaceous sandstone and shale or clay seams. Pinch-and-swell structures are common, and isolated lenticular blocks of formerly continuous beds occur. In the northeast (left) side of the back wall, the upper face is composed of a white sandstone that is mottled red and brown by ferruginous staining and contains gray clay seams. Below the sand, which shows very indistinct stratification, a pronounced drag fold (PLATE VIII, B) is present in intercalations of argillaceous sandstone and gray and buff clay, the latter having a physical appearance similar to dolomite slightly lower in the Shakopee, but it effervesces only slightly in hot acid. The drag fold has resulted from the subsidence of the sandstone into the underlying dipping dolomite beds. The latter are not well exposed in the cave floor because of a friable sand cover, but outside the cave the irregular sandstone beds overlie punky decomposed dolomite; a similar relationship undoubtedly is present in the cave.

A few inches above the drag fold an isolated lens of brown sandstone has been pulled into the lighter colored clayey sandstone by the movement that caused the drag fold. The lens, which appears in PLATE VIII, A, has been pinched off at both ends and is presumed to be a part of an originally continuous bed. The irregular laminae, the local small-scale brecciation, the squeezing and thinning of the beds, and the general disturbance of the strata are all evident in PLATE VIII, A. The brecciation is surprisingly sparse, considering the amount of evident deformation of the strata.

The cave floor, where not covered by unconsolidated sand and clay, consists mainly of tilted blocks of white partly silica-cemented sandstone that may have spalled from the cave roof. Midway from the entrance to the back wall at the northeast (left) side of the cave the beds, which are a continuation of the crenulated arched beds in the back wall, dip 60°-75° toward the northeast (left). Down-dip movement is evident along the stratification planes that define the beds.

In general the southwest (right) wall is composed of red-brown mottled sandstone, and the contorted beds are not exposed.

In the cave exposure the evidence is clear that the beds have been compacted, stretched and thinned but little brecciated, and that movement under strong gravitational pressures caused the drag folding, the pinching off of beds, and the movement of isolated sandstone lenses.

About 45 feet south of the entrance of Sand Cave and 35-37 feet higher than its entrance floor is an incipient cave that in most particulars is a small replica of the larger cave below. The exposure, under an overhanging ledge (PLATE IX) shows rolling, irregular, contorted thin beds of white and varicolored, iron-stained argillaceous sandstone cemented for the most part by a buff clay that is only slightly calcareous. The similarity between the two exposures of crenulated beds is so marked as to leave little doubt that one is a continuation of the other. Some distance below the overhang, in the path leading past it, westward-dipping Shakopee dolomite beds are exposed at least 25 feet higher than the lowest nearby sandstone of the St. Peter. The thickness of the St. Peter sandstone, by hand-level measurement, from the contact zone at this upper cave to the St. Peter-Platteville contact is about 128 feet.

For several hundred feet downstream from Sand Cave the stream bed is mainly in Prairie du Chien strata, but because of the undulatory contact some sandstone that may be St. Peter occurs in it as isolated patches.

About 55 feet north of Sand Cave in the west ravine wall a small dome of considerably leached Shakopee extends 5-6 feet higher than the lowest St. Peter sandstone, exposed at stream level and above in the opposite ravine wall. Northward (downstream) only a short distance another small dome of leached dolomite extends above stream level a few feet. Beds dip in places more than 25° south and southwest and strike N. 10° W. to N. 80° E.

About 220 feet downstream from Sand Cave, erosion of the east ravine wall has exposed a sharply depressed bowl-shaped area. The depression, formed by in-dipping beds of Prairie du Chien, probably Shakopee, is filled with quartz sandstone. The sandstone contains irregular clay seams that are warped to conform generally to the bottom and sides of the "bowl". Examined under 30-power magnification with a binocular microscope, a sample of this sandstone taken about 1 foot above its base was observed to be mainly fine, some very fine, and less than 5 percent medium in grain size. Larger grains are frosted and none exhibited crystal overgrowths. The grains are rounded to well rounded and are cemented by a brown siliceous clay and white translucent material thought to be leached silica. The quartz sand and the clay seams contained in it are similar to the contact-zone sand and shale. The sandstone a few feet higher in the depression is somewhat coarser and may be partly St. Peter. Beside and below the depression-filling of sandstone are thoroughly leached dolomite beds containing chert, quartz sand, and clay. The rock has been broken by leaching and differential compaction; the fragmentation, however, does not seem to have resulted from collapse. Bedding continuity, although irregular, is maintained. Much of the chert is leached to a white granular soft rock, but no abrasion-rounding of the generally angular fragments could be detected.

Shearing and (or) bedding-plane slippage occurs in the leached material forming the north wall of the depression. The movement surfaces dip 85° northwest and strike N. 52° E. On the opposite side of the depression, similar surfaces dip 50° northward and strike N. 80° W., and surfaces directly under the depression dip steeply northwestward. Thus, the dips are centripetally directed toward a center lying back in the ravine wall. The steeply dipping shear zones, the leached nature of the underlying dolomitic and siliceous rock, and the warping of the clay seams in the depression-filling of sandstone leave no doubt that the sandstone has subsided under gravity pressures into a subsurface sink that seems to have been produced by pressure solution of the arenaceous, argillaceous cherty upper dolomite beds of the Shakopee formation. The subsurface solution process and product evidenced here is considered pertinent to any conclusions that account for the irregularities at the St. Peter-Shakopee contact. A hint of the magnitude of the sink (its upper part has been removed by recent erosion) is given by the exposure of Shakopee dolomite beds about 25 feet south that are at least 15 feet above the base of the sink, by nearly flat-lying dolomite strata across the ravine more than 20 feet above it, and by dolomite beds due south in the east ravine wall that crop out more than 50 feet above that horizon.

The vertical distance from the basal sandstone in the sink to the highest Shakopee beds at the upper cave in this ravine is more than 70 feet in a horizontal distance of not more than 250 feet, and the maximum thickness of the St. Peter sandstone in the ravine was determined by hand level to be about 198 feet, although Trowbridge (1917b, p. 180) reported 223 feet of St. Peter sandstone in the vicinity.

Any accounting for the highly irregular upper Shakopee surface in this ravine must explain (1) the steeply dipping Shakopee beds, in places centripetally in other places centrifugally directed, (2) the evidence of subsidence in the sandstone, and (3) the undeniable evidence of interstratal solution and compaction of the beds. And those who argue, as Trowbridge does, for the subaerial-erosion origin of the irregularities of the contact surface in this ravine and vicinity, must, in some way, account for the absence of truncated Shakopee beds, for the lack of a basal conglomerate in the basal St. Peter sandstone, and for the conformability of the beds of the two formations at the contact.

Miller ravine exposures.--A natural exposure of domed Shakopee beds occurs on the Carl Miller farm 1 mile south of McGregor, Iowa (SE¼ sec. 27, T. 95 N., R. 1 E., Waukon quadrangle), in a ravine that is about 1 mile northwest of and parallel to the Sand Cave ravine, just described. Dissection in the ravine has exposed the Platteville limestone and the St. Peter sandstone, as well as the Shakopee dolomite.

About 250 feet north of this exposure, downstream in the same ravine, dolomite beds of the Shakopee reappear in the stream bed beyond about 200 feet of almost continuously exposed St. Peter sandstone. An eastward-trending subordinate ravine enters the main one at about the south limit of the Shakopee exposure, and a few feet north from this juncture, a small dome rises 6-7 feet above the stream bed. Stream erosion in the ravine has removed the east dome wall, exposing the north- and south-dipping wall beds. Strata in the north wall dip as much as 26° certrifugally north and northeast. In the south wall the beds dip 17° also centrifugally south-southeast and east-southeast. The strata are not continuous across the summit of the dome but the process that removed them is not determinable from the exposure. The central area of the dome contains abundant white fine- to medium-grained sandstone. The upper 1-2 feet of cremulated strata in the dome walls are iron-stained dolomitic sandstone and punky arenaceous dolomite, underlain by a zone of buff and green arenaceous shale, containing decomposed lenticular dolomite fragments and thin quartz sandstone beds. The shale zone in the north wall of the dome is 4-5 feet thick, but in the south wall the corresponding interval is only about 1 foot thick and the laminae are so drag folded and contorted (PLATE X), the indurated beds so fractured and displaced, that it is impossible to reconstruct accurately the pre-deformation position of the beds.

In the stream bed beside the dome exposure are greatly squeezed and contorted alternate bands of white and gray quartz sandstone, cemented by a translucent white material that seems to be decomposed silica. This sandstone, which is Shakopee for it lies under dolomite beds of that formation, contains decomposed brecciated white oolitic chert. Also the gray bands contain angular fragments of the white sandstone. Small faults in this sandstone have offset the bands about 0.1 foot. The bands have also been stretched, contorted, and irregularly thinned. No preferred direction of yielding is evident in the structures as seen in this essentially horizontal exposure, and the deforming forces seem to have been directed about vertically, either upward or downward, more probably the latter.

In the east ravine wall nearly horizontal decomposed thin dolomite beds crop out under a 2-foot zone of very much decomposed dolomite and shale. The dolomite beds are about 2.8 feet thick, and, about 25 feet north of the dome area, overlie in the stream bed a white quartz sandstone that has the same stratigraphic position as the white sandstone in the central area of the dome. Thus, in 20 feet of horizontal distance, the shale and dolomite zone 4.8 feet thick is thinned to less than 2 feet in the dome beds. Most of the thinning has occurred in the lower 2.4 feet of dolomite, which is represented by 0.5 foot of gray shale in the dome walls. A process of interstratal solution and compaction clearly accounts for much, if not all, of the deformation in the strata.

The vertical distance from the lowest St. Peter sandstone to the highest Shakopee dolomite exposed in this ravine was determined by hand level to be 44-45 feet and the maximum thickness of the St. Peter to be about 100 feet.

Castle Rock exposure.--An outlier of St. Peter sandstone, named Castle Rock, rises about 250 feet above the flood plain of Fennimore Fork of Blue River half a mile east of the small village of Castle Rock, Wisconsin (NE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 32, T. 7 N., R. 1 W., Boscobel quadrangle). Extending northwestward from the sandstone outlier is a low spur that has been truncated by an excavation for road material; the exposure is 60-90 feet southeast of Grant County Highway Q (Fig. 7).

The excavation is important in this discussion because in it a buff quartz sandstone that may be St. Peter crops out. The vertical distance from the base of this buff sandstone to the top of Castle Rock is about 224 feet, which, assuming no structure in the 700-800 feet horizontal distance between the two places, discloses a minimum thickness of St. Peter much greater than was observed elsewhere in this study, although such thicknesses are known from subsurface studies. Whether or not the sandstone is St. Peter is problematic. A sample, studied under the binocular microscope at 20-power magnification, is generally finer than the average St. Peter sand. No more than 15 percent of the grains in the sample were of medium size, none were larger, whereas 55-65 percent of the St. Peter sand commonly is in the medium-size range. Larger grains of the problematic sand are well-rounded and frosted. This sandstone contains an estimated 4-5 percent of clay-size material and also abundant very fine sand, whereas the St. Peter sandstone commonly has very little very fine sand and clay-size material in it. The sandstone at Castle Rock is at least 30 feet thick in the exposure and, similar to the St. Peter elsewhere, contains no shale beds of any consequence. The evidence is inconclusive.

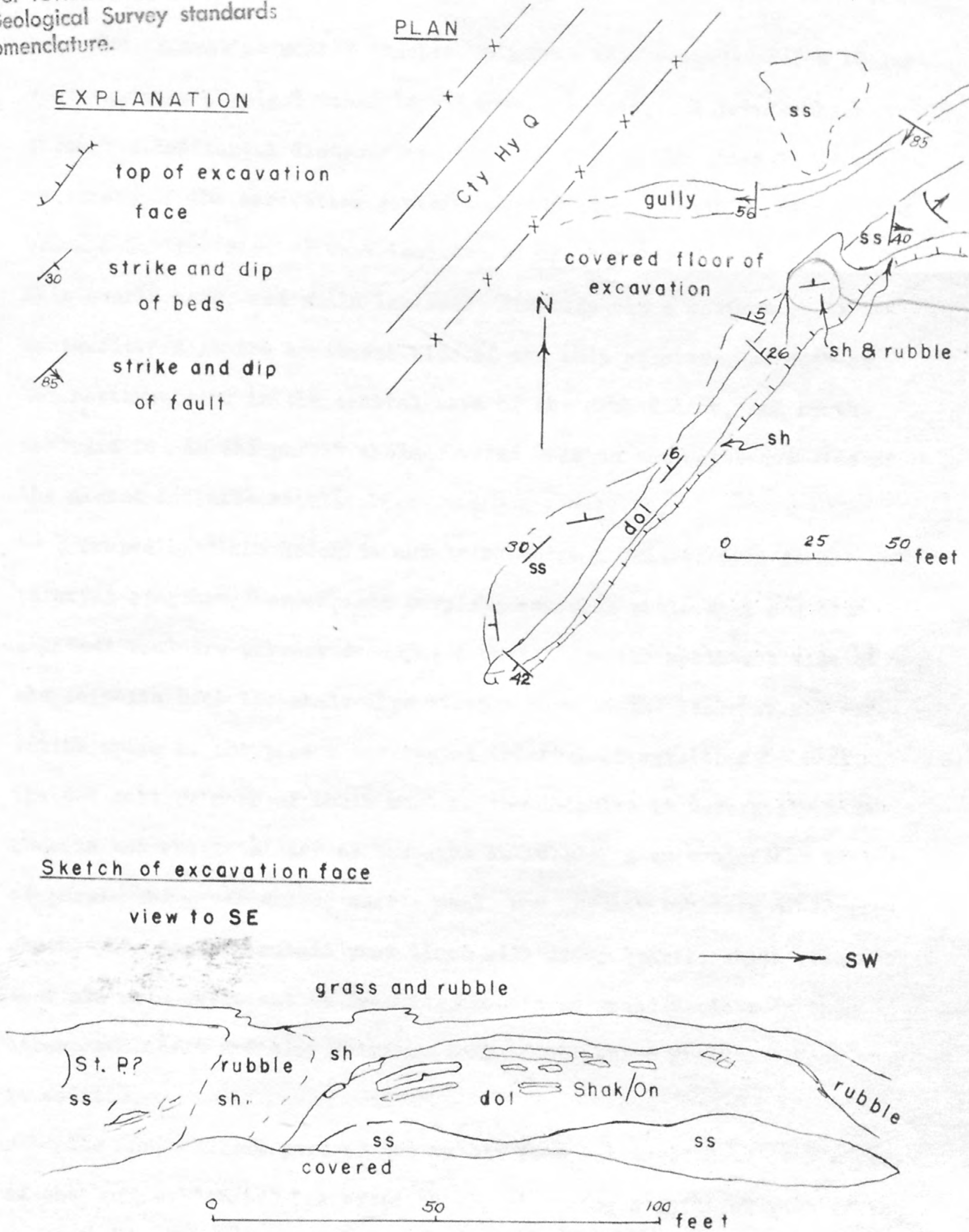


Figure 7: Map and related sketch of an excavation 0.5 miles east of Castle Rock, Wisconsin. Shak = Shakopee; St P = St. Peter; On = Oneota

The excavation poorly exposes, adjacent to the sandstone, a 10-foot vertical zone of algal dolomite and green, maroon, and purple shale through a horizontal distance of about 200 feet. The central and southwest face of the excavation contains gently arched, mainly thick-bedded brown dolomite (Fig. 7) that includes algal structures and local chert, thin quartz sand, and shale laminae. The beds dip a maximum of 42° southwestward at the southwest side of the main exposure, as much as 16° northwestward in the central area of the arched dome, and northeastward 26° in the partly shale-covered beds on the northeast side of the arched dolomite strata.

Draped over the dolomite and lying below a grassed area is an interval of green, maroon, and purple arenaceous shale that contains abundant boulders of very decomposed chert. On the northeast side of the dolomite beds the shale dips steeply down to the floor of the excavation where it occupies a horizontal interval of more than 20 feet. The 4-5 feet or more of shale next to the dolomite is moderately homogeneous but the remainder of the zone is rubbly, a heterogeneous mixture of purple and green shale, quartz sand, and angular boulders of leached chert. The latter contain vugs lined with drusy quartz, which, because they are more resistant to leaching, remain as rounded clots in the decomposed chert and clay matrix. Some of the white granular chert is oolitic.

The northeastern part of the rubble zone has moved down over a part of the buff sandstone, described above, obscuring a critical part of the interval between the dolomite and the sandstone. A part of this rubble veneer was cleared away disclosing vertical to steeply inclined smoothed surfaces caused by differential movement down dip to the northeast.

Northeast of the rubble zone the buff sandstone is cleanly exposed. Northwestward dips on faintly visible stratification in it about conform to the adjacent dipping shale. The sandstone contains shear fractures dipping gently to steeply north and northeast. Much of the down-dip movement has been absorbed in incompetent sand layers between beds and large lenticular boulders of indurated sandstone. One well-defined fracture along which movement is indicated is regularly curved, viewed either in vertical or horizontal section, and seems to record differential subsidence of the sandstone.

Exposed in front of and underlying the dolomite in the central face is a platy light-gray, silica-cemented sandstone that ranges from fine to coarse; grains are rounded, and larger ones are frosted; abundant white siliceous oolites are strewn over the sandstone surface.

A small wet-weather stream that flows in the ravine northeast of the exposure is discharged across the sloping excavation floor 10-20 feet in front of the face and has eroded a narrow, shallow southwestward-trending channel, or gully. Loose debris has been removed along this channel, and bedrock is exposed for most of its course. A small fault occurs in it about 30 feet north of the northeast end of the exposure face (Fig. 7), and about 45 feet southwest another fault is present in the channel. The bedding offset in this second fault is 0.5-0.6 foot. In these faults, the dip of the slickened surfaces are in a direction opposite to the direction of movement indicated by the shears and tension fractures in the buff sandstone. Neither fault appears to have resulted from a sudden rupture of the rock. The stretched and thinned beds, and slickolites associated with the slickensides on the fault surfaces suggest a slow displacement by a movement that continued for a moderately long period of time.

The highly variable bedrock along the walls and floor of the small gully is composed of thin platy irregular ferruginous sandstone and shale laminae and fragments of brecciated gray oolitic chert. On many of the exposed surfaces is a white clay that also appears on the fault surfaces. All the structures visible in this channel indicate the rock has been greatly deformed and contorted, mainly without fracturing, for only at the faults are the strata distinctly broken.

The evident amount of undoubted leaching activity here is much greater than that observed in any other exposure in the area of study. How much carbonate was removed from the bedrock to accumulate the vast amount of clay and decomposed chert residuum is difficult to guess, but necessarily it was very considerable.

A genetic relationship between the thick shale, the abundance of decomposed chert, the subsidence of the buff sandstone and the small faults and deformed strata of the channel exposure, must surely exist. How much of the total thickness of the buff sandstone here is due to subsidence after deposition and how much is due to primary deposition into an interdome area on the Shakopee surface is not determinable. The extensive rubble zone, however, suggests the subsidence of the sandstone may have been considerable.

To argue here for a St. Peter sandstone (if it is) and residual Shakopee filling in a channel eroded subaerially in the upper Shakopee upper surface is difficult. The apparent conformability of the dolomite, shale, and buff sandstone strata, and the concentration of the shale and rubble between the sandstone and the dolomite in a steeply dipping zone seem to require a different origin. The abundant leached chert randomly disposed through the shale, neither concentrated in more-or-less horizontal imbricated accumulations nor showing effects of abrasion, tends to deny either stream or submarine deposition of these sediments in about their present position. The leaching, which, because of evident sandstone subsidence, is clearly post-sandstone deposition, is not readily explained by the subaerial erosion concept. For these reasons the interpretation is considered unacceptable.

Emphasized at this exposure is the problem of differentiating the St. Peter sandstone, where stratigraphic position is in doubt, from the quartz sandstone that occurs through formations of the Prairie du Chien group. The buff sandstone designated possible St. Peter may be a moderately thick sandstone lens in one of the Prairie du Chien formations. Where sand grains do not exhibit crystal overgrowths, a feature common in the sand of the Prairie du Chien formations, the quartz sands of the St. Peter, of the Prairie du Chien group, and of the Cambrian sandstone strata underlying the Oneota formation, defy megascopic distinction. Dake (1921, p. 172) and Lamar (1928, p. 28) seem to be in general agreement with this conclusion.

Patch Grove exposure.--Dipping beds of three closely spaced Shakopee domes are exposed in road cuts on the east side of U. S. Highway 18 where it follows down a long north-facing slope about 2.5 miles north-northwest of Patch Grove, Wisconsin (NW$\frac{1}{4}$ sec. 29, T. 6 N., R. 5 W., Lancaster quadrangle). Above the Shakopee outcrops, which are near the bottom of the slope, St. Peter, Platteville, Decorah, and Galena beds are consecutively exposed along the highway.

The uppermost of the three domes occurs about four-fifths of the distance down the hill. At the center of this outcrop, about 16 feet of dolomite is exposed. The lower 8 feet bears faint algal markings and has been partly brecciated and rehealed; the upper 8 feet comprises regularly stratified, arched beds that have gentle dips directed away from a central structural high. The dips steepen toward the covered intervals that separate the Shakopee strata from those of the St. Peter on both flanks. Near the south side of the exposure the dolomite beds dip 14° northwest, strike N. 13° E.; near the north side they dip 13° northeast and strike N. 55° W. Removal of the surficial material that covers the contact zone on the north side of the outcrop made it possible to trace a single dolomite bed from a hard crystalline rock near the center of the exposure to an unindurated dipping layer of red-brown dolomite sand and silt- and clay-size material in the contact zone. Clearly, the decomposition of the crystalline dolomite, as well as the marked increase of the stratification dip, is due to solution action and compaction-thinning. All of the bedding dip across the exposure does not appear, however, to have resulted from this process alone.

A section measured normal to stratification in and above the uncovered contact zone on the north side of the outcrop is described below:

	Thickness (feet)
Sandstone, quartz, brown, fine- to medium-grained, moderately sorted.	20+
Sandstone, quartz, light-brown, mainly fine-grained, poorly sorted, contains much silt- and clay-size material.	1.5
Shale, green, containing small white quartz sand lenses and stringers.	3.0+
Sandstone, white, containing a 0.1-foot, partly decomposed green and white arenaceous chert bed.	0.3
Shale, light-green, poorly consolidated.	0.2
Dolomite sand, red-brown; silty and clayey material included; soft.	0.2

The uppermost unit is distinctly St. Peter sandstone. The remainder of the units, based on lithologic sililarities, either are Shakopee beds or are transitional from that formation into the superjacent St. Peter.

There can be no doubt that in this outcrop the Shakopee beds dip under the St. Peter sandstone at a conformable contact and bear no evidence of pre-St. Peter erosional truncation. Likewise, no basal conglomerate is evident in the road cut.

Another small Shakopee dome crops out about 0.1 mile farther north along Highway 18 at the lower altitude and rises above road level a maximum of 7 feet. Beds on the south side of this outcrop dip a maximum of 31° south-southwest, strike N. 65° W. Upper dolomite beds exposed in the north side dip 17° north-northeast and strike N. 76° W. The lowest dolomite in this road cut is a mass of rehealed breccia fragments, all of which are decidedly angular and appear not to have been abraded. No stratification is evident in this mass, but in the overlying beds stratification is well defined. In the south limb, particularly, abundant flutings and slickolites are present on fracture surfaces, and a small sharp drag fold is present at about the midpoint of the exposed north dome wall. It occurs through only a few thin beds and is due to differential down-dip movement of overlying strata.

North from this dome the south side of a larger dome crops out beyond a sag in the beds. The highest bedrock exposed is Shakopee. A maximum of 16 feet of moderately thick-bedded, sparsely cherty dolomite that contains white sandstone lenses is exposed. Both the dolomite and chert have been partly brecciated. Toward the sag (south) side of the exposure beds dip as much as 29° southwest, but beds on the north side of the exposure, which rise northward until truncated by recent erosion, dip only 12° south. In general, strikes are variable.

In the sag between the two domes are several large blocks of sandstone, not far out of position, that may be St. Peter. If they are not St. Peter, then only the upper (south) dome of the three exposed is distinctly in contact with the St. Peter sandstone. The upper beds of the other two probably are no more than 10-15 feet below the St. Peter, and undoubtedly the domed strata, if reconstructed, would reflect in equal or greater relief into the contact zone.

No evidence of pre-St. Peter truncated Shakopee beds or of a basal conglomerate in the St. Peter sandstone was observed in these exposures.

<u>Other exposures</u>.--Many good exposures examined during the course of this study contained essentially the same features as the road cuts and quarries that thus far have been described in detail. Locations of these are given below, but to avoid descriptive repetition only a brief identifying statement as to type of exposure and significant features in it is included for each.

Ellenboro road cut: A good but ephemeral exposure of the contact zone, similar to the Beetown road cut, occurs on the east side of Wisconsin Highway 81 in a road cut half a mile southeast of Ellenboro, Wisconsin (NE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 33, T. 4 N., R. 2 W.).

U. S. Highway 61 road cut: An exposure of St. Peter sandstone lying against Shakopee dolomite beds on the east side of U. S. Highway 61 about 6.2 miles northeast of Lancaster, Wisconsin (NE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 13, T. 5 N., R. 3 W.), at the base of a long north-facing slope. The Shakopee beds dip steeply under St. Peter sandstone, as they do in the Anaton road cut.

Blue River road cut: This Shakopee exposure, on the east side of Wisconsin Highway 81, 300-500 feet south of the bridge spanning Blue River (NW¼NW¼ sec. 18, T. 6 N., R. 1 E.), exhibits substantial inter-stratal solution and concomitant concentration of green shale in upper Shakopee formation. Individual crystalline dolomite beds can be traced into dolomitic shale layers in the solution zone.

Platte River outcrop: The summit of a Shakopee dome, the contact zone, and the St. Peter sandstone have been exposed by lateral stream cutting in the southeast stream bank of the Platte River about 7 miles west of Platteville, Wisconsin (near the center, W½NW¼ sec. 9, T. 3 N., R. 2 W.). The dome rises above stream level about 60 feet north of a township road concrete bridge.

Grant County Highway K road cuts: The contact zone is repeatedly exposed in road cuts along this highway 2.7 to 6.2 miles northwest from the Lancaster, Wisconsin, city limits. The green contact zone shales, commonly deformed and contorted, are well exposed. A particularly good display of cryptozoan structures (PLATE XI) occurs in a road cut 3.2-3.3 miles from Lancaster, and several large free blocks of these structures have been dumped in the ravine west of the highway at this place.

Iowa County Highway K road cuts: About 1.7 miles north of Hollandale, Wisconsin, and about 1.0 miles north of the junction of Highway K and Wisconsin Highway 191 (near center, W½W½ sec. 20, T. 5 N., R. 5 E.), two exposures of small algal domes and very contorted contact-zone shales crop out in road cuts on the west side of the highway.

Wisconsin Highway 35 road cut and borrow pit: A flat-lying contact zone is well exposed in a road cut on the north side of Wisconsin Highway 35 about 6.8 miles west of the city limits of Lancaster, Wisconsin (NE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 22, T. 4 N., R. 4 W.), and 0.4 mile farther west (700 feet west of junction of Highways 35 and 81) it is again exposed in a St.Peter sandstone borrow pit. In both places upper dolomite beds of the Shakopee and relatively thin, complete St. Peter sandstone intervals also are exposed.

Bloomington sand pit: About 2 miles east of Bloomington, Wisconsin (SW$\frac{1}{4}$SE$\frac{1}{4}$ sec. 19, T. 5 N., R. 4 W.), on the north side of Grant County Highway A, nearly flat-lying upper Shakopee dolomite beds are exposed in a road cut, above and behind which is a sand pit that exposes the full thickness of the St. Peter sandstone. The sandstone, less than 28 feet thick, is the thinnest complete section of that formation seen in outcrop in the studied area. Of particular interest here is the very thin contact zone, no more than 1 foot thick, and an oolitic chert band that in size, appearance, and continuity is identital to the oolitic chert band observed, for example, in the contact zone at the Beetown road cut. The chert in the Bloomington road cut, however, is nearly 9 feet below the top of bedded impure, fine-grained dolomite and dolomitic limestone, and siltstone. If the carbonate were to be leached from this 9-foot zone it is not difficult to imagine that the residues would compose an interval very similar to areanacous shale of the contact zone seen in other exposures.

Olson quarry: About 23 feet of Shakopee dolomite is exposed in this quarry on the south side of Wisconsin Highway 30 about 300 feet west of Blue Mounds Branch (SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 35, T. 5 N., R. 5 E.). Upper exposed beds of arenaceous dolomite and shale dip as much as 21° radially through a horizontal arc of 85°. Lower beds are hard brecciated and rehealed gray dolomite, and algal structures are common in the quarry beds.

SUBSURFACE DATA

The inclusion in this paper of a subsurface section is intended to serve a twofold purpose. First, deep wells that have been drilled throughout the area of study have provided data showing the great variance in thickness of the St. Peter sandstone. This variance is reflected entirely in the lower boundary of that formation, its upper surface being flat or only gently warped by regional tectonism. Secondly, the information from drilling samples and, particularly, from drill core, supplies a better picture of the lithology and structures in the contact zone strata, and a more accurate thickness measurement, than can be observed in outcrops.

Thicknesses of the St. Peter sandstone, as determined by well and prospect drilling in the area of this study are given, and the approximate location of drill holes are shown, in Figure 8. Uncommon thicknesses of contact-zone shale and sandstone are also indicated in Figure 8. The data from many of these wells, the logs of which are on file in the Wisconsin State Geologist's office in Madison, Wisconsin, come from unpublished descriptions of the samples by F. T. Thwaites. It is desirable to emphasize here that the thicknesses shown in Figure 8 are based on the interpretation that the contact zone of interbedded shale, fine sandstone, chert and dolomitic limestone (or dolomite) is correctly assigned to the Shakopee formation, a conclusion that results from this study. In some places this reinterpretation has reduced substantially the previously interpreted thickness (by Thwaites, by U. S. Geological Survey personnel, and by others) of the St. Peter sandstone. For example, Thwaites (1927, p. 19) gives a partial log of the city well of Galena, Illinois. The descriptive log records 130 feet of medium- and fine-grained gray, pink, yellow, and white sandstone, below which are successively 30 feet of pink sandstone and red shale, 20 feet of brownish-red sandstone, green and purple shale, chert, and some dolomite, and 10 feet of purple and green hard micaceous shale with some sand. Thwaites includes the entire 190 feet of sandstone and shale in the St. Peter. The interpretation preferred here places the lower 60 feet of shale and sandstone in the undifferentiated Shakopee and Oneota formations, leaving a thickness of only 130 feet for the St. Peter sandstone. (The basis for the preferred interpretation becomes clear in the description of the James Mine diamond drill core discussed below).

Data from the wells at Dodgeville, Mount Horeb, and Cuba City, Wisconsin, show the local variation of the sandstond thickness. The two city wells at Mount Horeb are only 1700 feet apart but in that distance the St. Peter thickness ranges from 14 feet to 115 feet. At Dodgeville the Iowa County Cooperative Dairy well penetrated 20 feet of St. Peter, and the Dodgeville Creamery Company well 145 feet of St. Peter. These wells are less than a mile apart. The Cuba City well penetrated 30 feet of sandstone, but about 4200 feet east the Cambria Canning Company well penetrated 210 feet of St. Peter.

The sharpness of the relief on the St. Peter-Shakopee contact surface, which is the amount of variation of the sandstone thickness, also is well illustrated by data from U. S. Geological Survey drilling (Agnew, Flint, Allingham, 1953) in the vicinity of Highland, Wisconsin. Using a solid bit churn drill, three holes alined nearly east and west on the Steil property (N$\frac{1}{2}$ sec. 6, T. 6 N., R. 1 E.) penetrated successively 87 feet, 215 feet, and 52 feet of St. Peter sandstone. From the first to the second hole is 235 feet horizontally, and the minimum relief on the contact indicated in that distance is 128 feet; from the second to the third hole is 450 feet horizontally, and the minimum relief indicated is 165 feet. Only a thin shaly contact zone of no more than 4 feet was found in any of these three holes.

A detailed knowledge of the arenaceous cherty dolomitic shaly zone that, in many places, lies below the typical St. Peter sandstone but commonly is very poorly exposed in outcrop because of its rock character, is critical in this study. However, the nature of the constituent sediments, and of the structures in them, to a great extent is lost or obscured in fragmented solid bit drill samples, and it is believed that much of the misinterpretation of the St. Peter-Shakopee contact relations, and of these thick shaly zones, has arisen because of the understandably inaccurate picture constructed almost wholly from subsurface studies of churn drill cutting samples. For that reason, the availability for study of rock core recovered from a diamond drill hole that penetrated a thick zone of shale, sandstone, dolomite, and decomposed chert between the St. Peter sandstone and the Shakopee (or Oneota) dolomite is of inestimable value in providing structural and lithologic data through this problematic zone. Cores from two diamond drill holes, one of which contains an uncommonly thick shale and sandstone interval, are described in the discussion that follows.

James mine diamond drill core.—The U. S. Geological Survey, in 1949, explored by drilling the formations of the Prairie du Chien group for evidences of zinc and lead mineralization (Heyl, Lyons, and Agnew, 1951). In this exploratory program a diamond drill penetrated 110 feet of shale, sandstone, and dolomite in the zone, or a part of it, that has been referred to throughout this paper as the contact zone. For consistency, the designation is here retained for the full interval. The rock core recovered from the diamond drilling provides data that help immeasurably to correctly interpret the origin of this zone and its relation to the irregular St. Peter-Shakopee contact. The drill hole from which the core was taken is on the Thomas Doyle property in the James mine area about 2 miles west of Shullsburg, Wisconsin (SE¼NW¼SW¼ sec. 9, T. 1 N., R. 2 E., Mineral Point quadrangle). A skeletonized log of the St. Peter-Prairie du Chien interval represented in the core is given below (see Log 1 for detailed description):

	Thickness (feet)
St. Peter sandstone:	
Sandstone, quartz, white and light-buff upper 69 feet, faintly banded maroon, pink, and purple lower 93 feet. Small sealed faults in lower half of unit.	166
No recovery.	3
Shakopee formation:	
Shale, maroon and green, arenaceous; hard slickened surfaces.	2
Limestone, dolomitic, and dolomite, thin beds broken and offset.	13
Dolomite, vuggy; contorted shale laminae and slickened shale surfaces dipping as much as 27^o.	11
Shale, maroon; interbedded gray sandstone; hard slickened shale surfaces dipping as much as 28^o; greatly contorted shale laminae.	13
Dolomite and dolomitic limestone, brecciated in part; white leached chert.	6
Shale, maroon, interbedded with white sandstone; hard slickened shale surfaces dipping 12^o-28^o; greatly contorted shale laminae.	34
Oneota (?) formation:	
Chert, white, leached, and shale (poor recovery).	28
Shale, green and brown; white leached chert.	7
Dolomite, gray, vuggy, and white leached chert.	19
No recovery.	4
Sandstone, gray; green shale, white leached chert.	2

The remainder of the core below this sandstone unit is about normal Oneota dolomite.

The maroon and green shale, considering its location in normally flat-lying craton sediments, is unbelievably contorted and faulted. An attempt has been made to show (PLATES XII-XV) both the slickened faulted surfaces and the contorted shale laminae in the rock core. The shale in this interval is mainly homogeneous but locally is very arenaceous. Hard shiny, slickened shale surfaces, including those in the thin shale partings in the dolomite, are abundant throughout the shale areas of the core. Some faulted surfaces are oriented about normal to the axis of the core, others cut it at steep angles. Assuming that the hole from which the core was taken is vertical, dips of faulted surfaces were measured from 1° or 2° to 53°, many ranging from 20° to 30°. Some surfaces differ substantially in angle of dip from similar surfaces above and below. The shale laminae dip at all angles (PLATE XIII, A and B) and in places are overturned. In the deformation, elongate twisted fragments of sandstone were pulled from the parent beds and enclosed in the shale (PLATE XIII, A).

The white sandstone, in beds generally from 0.3 to 0.6 foot thick, contrasts colorfully with the interbeds of dark maroon and green shale. Except where it has been separated by drag of the shale, the sandstone shows relatively little effect of the deformation; only in a few places is it obviously brecciated or faulted.

Of particular interest in the contact zone is the presence of moderately thick dolomitic limestone and dolomite zones. Although the dolomitic limestone appears to contain more argillaceous material and is slightly darker than similar Shakopee dolomitic limestone observed elsewhere, the dolomite (PLATE XIV, B) is identical to Shakopee dolomite observed both in outcrop and in other diamond drill cores. The former is hard, finely crystalline and contains green or maroon shale partings; the latter is gray, more coarsely crystalline and characterized by many small vugs. The dolomite is fractured and locally brecciated, but the fragments appear not to have been rotated out of position. Stratification in this carbonate rock interval is nearly normal in some places to the axis of the core but dips as much as 10°-12° in other places.

The chert, except for that in the heavy cherty zones in the lower 34 feet of the contact zone, occurs in the core mainly as small displaced fragments in the shale, although a minor amount also is present in the dolomite. It is considerably leached, almost to the "cotton rock" stage. The core recovered in the lower 34 feet of the contact zone contains a higher chert concentration, owing partly to poor recovery, than has been observed anywhere in outcrops of Shakopee or Oneota dolomite. The chert in the concentrated zones, like that higher in the contact zone, is considerably leached, but in places the original porcellaneous and (or) opaline character is preserved. Much of the chert is oölitic. Similar chert zones penetrated in well drilling have been considered basal conglomerates of the St. Peter; the zones here distinctly are not.

Shaly, arenaceous, cherty zones, very similar in lithology and thickness to the interval described above, have been penetrated by solid bit churn drilling in widely separated areas in southern Wisconsin, northern Illinois, and eastern Iowa. Some of these deposits have been described by Thwaites (1927, pp. 19-21) who considers them to be basal St. Peter. Norton (1912, p. 79) conjectured that similar maroon shale in Iowa might comprise continental sediments deposited in a small trough or basin, but Anderson (1919, p. 109) described a thick shaly interval, which contained more dolomite, as mainly Prairie du Chien strata, placing only the upper 30 feet of that interval in the basal St. Peter. Lamar (1928, p. 20) noted that several deep wells in Illinois had penetrated thick zones of "red shaly marl, or red marl shale, or green, blue, or gray shale" below sandstone of the St. Peter. He concluded that the shale is a clay residuum from solution of the Shakopee dolomite, presumably during emergence of that formation, for he speaks later of the encroaching St. Peter sea. Dake (1921, p. 112) cites the presence of this shaly interval as evidence to support the hypothesis of erosional unconformity of the upper surface of the Shakopee, considering it and the chert it contains as a basal phase of the St. Peter.

The lithologic relationships, the structures, and the alteration features in the diamond drill core establish beyond any reasonable doubt the following:

1. The lithologic character of the zone of typical Shakopee dolomite and dolomitic limestone, 24 feet thick, that occupies the interval starting only 2 feet from the upper limit of the 110-foot shale and sandstone interval, requires that the entire interval, excepting possibly the uppermost 2 feet, be Prairie du Chien strata. The primary sediments, before alteration by subsurface leaching, were deposited during Prairie du Chien time.

2. No reasonable interpretation can fit the lithologies and structures of this rock core into a postulated origin related to subaerial erosion. Aside from the presence of Shakopee dolomite in the upper part of the contact zone, the slickened shale surfaces, the contorted shale laminae, and the brecciated dolomite are evidence opposing a channel-fill origin for these sediments. The faulted and contorted laminae required the application of forces much greater than could derive solely from gravitational pressures applied during deposition. Moreover, the carbonate rocks are fractures, a post-lithification, hence a post-depositional, feature.

3. The main process altering the rock constituents was interstratal solution, as evidenced by the advanced stage of the chert leaching, and inferred from the contorted shale laminae.

Only two possible explanations are reasonably suggested to account for the phenomena observed in the drill core. First, there is the possibility that the drill penetrated a fault zone. This proposal gains support from the great number of very hard slickened surfaces in the shale. Fault zones, likewise, may provide channels for circulation of subsurface waters, consequently the solution activity so evident in the core is not incompatible with the fault-zone explanation. But faulting, in the magnitude required to explain the 110-foot interval of leached and deformed rock, is unknown in the general area of this drill hole. Some indication, more than the small 0.1-foot offsets along minor adjustment faults, should probably be present in the interval of the core occupied by the St. Peter sandstone, if faulting on a large scale has occurred. None, however, is present. Nor does the concentrated prospect drilling in the James mine vicinity disclose a major fault in the Platteville, Decorah, or Galena strata above the St. Peter. Moreover, the occurrence of similar thicknesses of similar rocks in the same stratigraphic position at random places throughout the area of study, and beyond, requires a considerable amount of faulting at diverse places in the Prairie du Chien group; yet nowhere in the excellent exposures of the Oneota dolomite in southwestern Wisconsin has a single fault been observed.

The second possible explanation, and the one that is preferred, involves areally restricted, interstratal solution and removal of carbonate rock and concomitant compaction of residual clay, silt, and sand under strong gravitational pressures. The contorted and slickened shale, the leached chert, the varying inclination of stratification, of contorted shale laminae, and of the shale slickensides--all these evidences of solution and internal deformation should be expected where the processes as visualized have occurred. By this explanation other randomly located areas of similar lithology are more easily explained.

There can be no question that the 110-foot shale interval in the James mine core is the same type of phenomenon, originating from the same causes, as the many other zones penetrated at the same stratigraphic position. The exposed maroon shale in the Saw Mill Creek road cut, the shale intervals represented in the diamond drill core from Crow Branch hole 5 and in the samples from Kennedy mine hole 4 (both described below), all show nearly identical characteristics, and to argue that the deposits have different origins seems unreasonable.

It is believed that an interpretation, which requires these maroon shale, sandstone, and chert zones to be either the basal phase of the St. Peter or a leached residual accumulation on an emerged surface arises understandably from the nature of the fragmented incomplete drill samples that supplied the data on which the interpretations are based.

Crow Branch diamond drill core, hole 5.—Crow Branch hole 5, fro the same U. S. Geological Survey drilling program (Heyl, Lyons, Agnew 1951) as the James mine drilling, is one of four put down in the Crow Branch area (SW$\frac{1}{4}$ sec. 22, T. 5 N., R. 1 W.)(fig. 1), but the only one that recovered core from the contact zone.

A skeletonized log of the drill core recovered from diamond dril hole 5 follows:

	from	to	Thickness (feet)
Surficial and residuum.	0	12.4	12.4
St. Peter sandstone:			
Sandstone, quartz, much silica cement and common quartz druses in vuggy basal 1 foot.	12.4	63.7	51.3
Shakopee formation:			
Shale, green; hard slickened shale surfaces, contorted shale laminae, dipping stratification.	63.7	65.7	2.0
Shale, green, glauconitic, silty; pronounced slickened shale surfaces and contorted laminae.	65.7	69.8	4.1
Shale as above, but soft, arenaceous. . . .	69.8	72.9	3.1
Sandstone, quartz, white, local glauconite; silica cement and quartz crystal overgrowths on grains.	72.9	74.4	1.5
Dolomite, gray, vuggy, cherty; stratification dips as much as 14°; green shale as thin laminae, slickened and hard; shale identical to that above.	74.4	76.4	2.0

The shaly contact zone here differs from the corresponding stratigraphic zone in the James mine drill core in thickness and in the absence of maroon coloration. The green shale, hard slickened surfaces, contorted laminae, and the dipping stratification are very similar, and the dolomite is identical in rock cores from both holes. The core from the Crow Branch drilling is described because it shows an intermediate stage between the very thick multicolored shale and the 2-4 feet of arenaceous shale or argillaceous sandstone in outcrops of the contact zone. The fact that the shale, except for color, and the white leached chert in the 110-foot shale interval in the James mine diamond drill core are identical to the 14-foot shale interval in the Crow Branch diamond drill core, that the hard shiny slickensides, the deformed shale laminae, and the variously dipping stratification are likewise similar, and that both zones occur at the same stratigraphic position seems to permit only the conclusion that the sediments in this zone of these two holes have a common origin and a common history.

Kennedy mine churn drill hole 4.--Included in the U. S. Geological Survey exploratory program, mentioned in connection with the two diamond drill cores described previously (Heyl, Lyons, Agnew, 1951), was one diamond-drill hole and four churn-drill holes that penetrated the St. Peter and Shakopee formations in the Kennedy mine area, 1.5-2 miles east of Hazel Green, Wisconsin ($SW\frac{1}{4}SW\frac{1}{4}$ sec. 29, T. 1 N., R. 1 E.)(Fig. 1). Of the four holes, three are through nearly normal St. Peter and Shakopee lithology, but hole 4 is extraordinary in several respects and deserves a brief description in this paper. A summary of the rock penetrated from the top of the St. Peter to the bottom of the hole is given below (see Log 2 for detail):

	Thickness (feet)
St. Peter sandstone:	
Quartz sandstone, rounded, well sorted.	74
Shakopee formation:	
Mainly green shale.	4
Mainly dolomite.	10
Mainly shale.	25
Dolomite and shale.	20
Mainly shale.	15
Mainly dolomite.	5
Dolomite, chert, and sandstone.	5
Dolomite, maroon and green shale.	60
Mainly green, maroon, and purple shale.	20
Mainly chert.	50
Chert, dolomite and shale.	5
Chert and sandstone.	5
Dolomite and sandstone.	5
Mainly shale.	5
Red and green shale.	5

The sample interval for this hole was 5 feet. It will be noted that the above summary, as well as the detail in Log 2, differs, in some respects, from the published skeletonized log (Heyl, Lyons, Agnew, 1951, p. 31) of Kennedy mine hole 4. The discrepancies arise from the fact that the published description was prepared from a study of washed samples, whereas the above description results from study of unwashed samples that included the clay-size material, which commonly is lost in sample washing.

The strata, as indicated by the samples, penetrated in this drilling are similar in several respects to those in the James mine drill core. Typical Shakopee dolomite and dolomitic limestone were penetrated very near the upper limit of the shaly interval, and, therefore, the entire shaly zone is assigned to the undifferentiated Shakopee and Oneota formations. The interval, however, has more interbedded dolomite than occurs in the James mine core, and more of the shale in the samples from this hole is green and purple, less is maroon. Noteworthy is the fact that the shale recurs at various horizons through the entire Shakopee and Oneota formations and perhaps into Upper Cambrian strata, for data from adjacent drill holes indicate that the base of the Oneota, assuming no thinning, should occur at a depth of about 525 feet. The probability is strong, however, that thinning has occurred, hence the deepest rock penetrated may be Cambrian.

Another similarity to the James core is the zone of extremely heavy chert. Interestingly, other drill holes 300-900 feet away did not penetrate such chert concentrations. Although the phenomenon is not clearly understood, it is suspected that the chert represents areas of former dolomite replaced by silica from the solutions that dissolved out much of the carbonate in the interval.

The samples recovered from this drill hole and the core taken from the James mine drill hole are so alike in all important aspects and dissimilar in none, that there can be little doubt that the origin and geologic history of the Prairie du Chien shale strata penetrated in the Kennedy mine drill hole 4, like that penetrated in Crow Branch drill hole 5, is identical to Shakopee and Oneota shale zones represented in the James mine diamond drill core.

One incidental problem arises in connection with the Kennedy drill hole. Some of the dolomite above the maroon shale is pyrite-bearing. Why the sulfide form remains where below it presumably oxidized iron has colored the shale a deep maroon is not clearly understood.

REVIEW OF PERTINENT EVIDENCE

A review of outcrop and subsurface evidence, described in the appropriate sections of this paper, discloses a recurrence of certain phenomena pertinent to the contact problem. These are summarized below.

Contact irregularity.--The contact of the Shakopee dolomite with the overlying St. Peter sandstone is almost continuously irregular, and local relief on it in places may exceed 165 feet. Evidence of this irregularity was observed in most outcrops, in subsurface studies of samples from U. S. Geological Survey drilling, and in descriptions of samples from wells. The magnitude of irregularity observed in this investigation agrees with that found by Chamberlin (1877, p. 271; 1883, p. 138), but the maximum relief is less than that reported in some places by Thwaites (1927, p. 19).

Shakopee domes.--The relief on the contact is due mainly to irregular dome-shaped features of Shakopee dolomite that lie below the St. Peter sandstone. None of the larger domes is entirely exposed in the area of this study, but if the evidence in the many that are partly exposed is pieced together the domal nature of these features seems clearly established. Where observed, the summit areas of the domes are composed of gently arched beds that break into steep dips on the flanks of the domes. The maximum dip measured in the dome strata was 54°, but more commonly the bedding dips range from 20° to 40°. Dip directions in a given dome area are irregularly centrifugal. Sardeson (1916, p. 5) noted the domal nature of the upper Shakopee beds, as did Chamberlin (1877, pp. 265-290; 1883, pp. 138-140), who found a vertical distance of more than 100 feet from the base of the summit of these features. In southwestern Wisconsin no single outcrop exposes both the summit and the base of any of the large domes. Consequently, total relief on a single dome has not been determined. However, if the Steil property drilling (U. S. Geological Survey) penetrated in successive bore holes a dome and interdome area, a minimum relief for that structure of 164 feet is indicated.

The interiors of the domes, where observed in a few exposures, display some of the characteristics of organic reefs, including algal structures, solution vugs, rehealed breccia, reef conglomerates, and quartz sand as a plaster in and around oblate cryptozoan masses.

At no place in the more than a hundred outcrops studied during this investigation do the dolomite beds immediately below the contact zone, whether dipping steeply on the sides of the domes, gently arched over their summits, or lying in interdome areas, exhibit truncation by erosion or by any other process except faulting or drag-folding. Everywhere observed, the upper Shakopee beds are conformable with the contact zone strata and with stratification, where visible, in the overlying St. Peter sandstone. Although the lower St. Peter beds conform to the irregular contact, they reflect the basal irregularity progressively less upward through the sandstone interval until the beds in the upper part of the formation are flat-lying, which seems to require much of the compaction in the Shakopee strata to have occurred during early and middle St. Peter time.

The contact zone.--Between the uppermost dolomite beds of the Shakopee and the basal typical St. Peter sandstone is a zone as much as 110 feet thick of contorted beds of soft arenaceous shales and argillaceous, mainly fine-grained, white sandstone, both of which are locally dolomitic. Dolomite, dolomitic limestone, and white leached, commonly oolitic, chert may occur in this zone, and in places these are common. The zone grades downward through soft, punky, leached impure dolomite beds into normal hard dolomite or dolomitic limestone. The oolitic chert, similar to the oolitic chert in the Shakopee dolomite beds is, in most places, a distinctly bedded primary or replacement feature, not a stratified deposit of chert fragments. The sandstone and shale of the contact zone grade upward into the St. Peter sandstone, but, at most places, a moderately abrupt transition from the impure mainly fine-grained sandstone, interbedded with shale, to the relatively pure fine- to medium-grained sandstone of the St. Peter occurs.

The soft shale in this zone, commonly green, may be maroon, purple, or buff. In several exposures these varicolored shales are intercalated. Locally the shale may be a homogeneous, unstratified mass of unconsolidated green clay. The presence of typical Shakopee dolomite and dolomitic limestone only a few feet below the base of the typical St. Peter sandstone requires that all but possibly the upper 2-3 feet of the entire shaly zone, regardless of thickness, be assigned to the Shakopee formation.

The sandstone in the contact zone is finer than that in the St. Peter or that lower in the Shakopee, and, as a rule, it is less iron-stained than the St. Peter sandstone. It differs from that sandstone also in that successive thin beds contain notable grain-size differences. It is megascopically similar to the typical sandstone of the St. Peter in the other textural features of rounding, and frosting of larger grains.

Interstratal solution and compaction.--Structures and rock characters in the contact zone and lower beds indicate that interstratal solution and compaction have been important processes in altering the rocks to their present state. Pinching-and-swelling of the shale and the sandstone beds is common. In places beds have been pinched off by compaction, segregating portions of the beds as isolated lenses. The advanced stage of leaching of the chert indicates a long duration for the solution process and suggests that most of the carbonate which originally may have been in the contact-zone sediments, in all liklihood, has been solutionally removed. Because the zone grades downward into carbonate rock through beds of partly leached dolomite, the inference is not unreasonable that dolomite was present in the leached zone above. This supposition gains support from the fact that individual dolomite beds can be traced, at steeply dipping contacts, from a hard crystalline carbonate rock laterally and down dip into a much thinner, more steeply dipping shale bed in the contact zone. Local extensive rubble zones of partly dissolved chert in the contact zone shale bear further evidence of the nature and amount of interstratal solution that has occurred in these beds.

The contact zone of shale, sandstone, and chert tends to be thickest underlying the thickest St. Peter sandstone and thinnest where the overlying sandstone is thinnest. Where abundant maroon shale occurs in the contact zone it is overlain in places by maroon, ferruginous St. Peter sandstone. Maroon and purple shale, similar to that in the contact zone, also occurs in the Shakopee bedded dolomite well below that zone, and the green shale of that zone is exactly like the green shale partings that occur throughout the Shakopee. Consequently, the color of the rock strata in the contact zone is not unique to that zone and appears to offer little evidence that bears on the origin of the clastics that compose the sediments.

Down-dip movement of higher over lower strata is indicated in all the exposures of a dipping contact zone. The curved, fluted, and slickened irregular surfaces in the basal St. Peter sandstone, and the less-notable shearing in that sandstone emphasizes the fact that the overburden on the subsided sandstone necessarily was thick. Similarly, the drag folding in the beds of the contact zone and the smoothed hard inclined slickened surfaces extending obliquely across the rock core of the James mine drill hole indicate subsidence and compaction under a heavy superjacent load. Local areas of greatly squeezed and contorted beds occur where the strata are more nearly horizontal; these are due to intensive solution and compaction, where yielding to gravity pressure has taken place in several directions. The squeezed, contorted, beds at these places seem to require the pressure to have been both severe and directed essentially downward. The James mine diamond drill core, taken from a 110-foot zone of shale, sandstone, and dolomite below typical St. Peter sandstone, shows the shale to be greatly contorted and faulted, the dolomite brecciated, and the chert substantially leached. Slickensided surfaces are very hard, smooth, and shiny, and these cut across the core at dissimilar angles ranging from 2^{o} to 53^{o}. The core presents a general picture of substantially leached and greatly deformed strata.

Absence of a basal conglomerate in the St. Peter.--Neither in the St. Peter sandstone nor in the contact zone, which is considered by some to be basal St. Peter, is there any evidence of a conglomerate. The basal St. Peter sandstone is even-grained quartz sand and virtually nothing else. The angular fragments in the contact zone are distinctly non-abraded and result from compaction fracturing.

REVIEW AND TESTING OF HYPOTHESES

Of the several explanations that have been advanced to account for the St. Peter-Shakopee contact irregularities, the one that is currently accepted requires extensive pre-St. Peter subaerial erosion of Prairie du Chien formations. Trowbridge and Atwater (1934, p. 77) probably expressed a concensus when they said of the St. Peter-Shakopee relations in the upper Mississippi valley:

> It has long been known that there is an important unconformity at the base of the St. Peter sandstone. So much has been written about it and so conclusive is the evidence that it can be stated confidently that this break exists and that it is an important one. The magnitude and the wide distribution of this break makes it exceptionally important as a basis of classification.

The subaerial erosion hypothesis is the first of several to be tested in the discussion that follows:

Subaerial erosion of upper Shakopee surface.--If the Prairie du Chien group, or a part of it, were elevated above sea level in pre-St. Peter time and subjected to subaerial destructive processes, a very youthful topography of steep-walled valleys and, in places narrow divides, was present on that surface at the inception of St. Peter sandstone deposition. Reasonably, a record of this subaerially eroded surface should be preserved in Shakopee and basal St. Peter strata. No record of such a period in geologic history was observed in this study, and those who would postulate it must account for the following:

1. The complete absence of erosionally truncated Shakopee, or lower, strata, notwithstanding the sharpness of the relief at the contact.

2. Shakopee beds with steep dips that account for all the relief visible in the contact exposures.

3. The absence of a basal conglomerate in the St. Peter sandstone.

4. The absence of large slump boulders of Shakopee and (or) Oneota dolomite in the sandstone adjacent to the steep, supposedly eroded, valley walls, and the lack of talus accumulations at the base of these steep slopes.

5. The presence of an essentially unconsolidated shale and sandstone zone on divides, on valley walls, and on valley floors--everywhere at the contact.

6. The presence in places of a zone as much as 110 feet thick, of mainly maroon and green shale and white sandstone, but including also dolomite and leached chert, that beyond a doubt represents sediments deposited during Shakopee and Oneota time.

Results of this study indicate that, in the area of investigation, any subaerial erosion on the upper Shakopee surface was so insignificant as to leave no record in the rock strata, and it is strongly doubted that that surface ever emerged more than fleetingly, if at all. Hence, it is concluded that the subaerial erosion hypothesis is deficient in all respects to explain existing Shakopee-St. Peter relations.

Karst topography.--Some of the evidence suggests that possibly a karst topography developed on the exposed Shakopee surface, and Lamar (1928, p. 29) may have had something of this nature in mind when he noted that considerable thicknesses of residual clay accumulated on comparatively narrow divides of Shakopee strata, and concluded, "It seems likely, therefore, that solution played a very important part in shaping the pre-St. Peter land mass." The subaerial-solution surface concept, however, is faced with the same problems as the subaerial erosion explanation, namely, that evidence indicating that the upper Shakopee surface was subaerially exposed is entirely lacking, and the residual material at and below the contact accrued as a residuum not before, but after at least a part of the St. Peter sandstone was deposited. For these reasons the explanation of karst topography seems untenable.

Pre-St. Peter deformation.--Some investigators have proposed that pre-St. Peter tectonism warped the Shakopee strata causing the steeply dipping beds observed in most outcrops of the contact zone. In the light of substantial evidence that at least most of these structures are roughly dome shaped, they cannot be explained, in any simple way, by the application of lateral compressive forces. Moreover, the interiors of some of the upswelled areas are exposed, and these indicate clearly that the tilted beds are a compaction, not textonic, phenomenon.

Solution-compaction.--As an alternative to the unacceptable interpretations just discussed, an hypothesis that embodies elements of primary compaction of sediments over relatively incompressible rock masses, and subsequent interstratal solution and concomitant subsidence, is proposed to explain the irregularities of the Shakopee-St. Peter contact. The possible variations that are discussed under this general hypothesis are: a--differential solution and compaction of the Shakopee carbonate sediments; b--compaction of Shakopee lime muds over erosional irregularities at an unconformity in the Prairie du Chien group; c--compaction of Shakopee lime muds over organic reefs and subsequent accentuation of this initial irregularity of subsidence simultaneous with interstratal solution.

Variation a of the general solution-compaction hypothesis requires the total relief on the upper Shakopee contact to result solely from differential solution and compaction of Shakopee and Oneota beds. Aside from the clear-cut evidence of a primary relief on that surface, notably at the Dill railroad cut, it seems unreasonable to suppose that a thickening of the St. Peter sandstone, for example, from 52 feet to 215 feet in a horizontal distance of about 450 feet, as recorded in the Steil property could be due entirely to localized solution in the Shakopee dolomite and subsidence of the sandstone into these solution areas without some reflection of the subsiding basal sandstone strata in the upper beds of the St. Peter and in the beds of the overlying formation. Because of this objection variation a is least preferred to the three outlined here.

Variation _b_ of this general hypothesis requires compaction of Shakopee lime muds over irregularities on the sea floor that originated from pre-Shakopee subaerial erosion of Oneota sediments. The evidence supporting the post-Oneota erosion is twofold. Ulrich (1924, p. 102) believed that he found an important faunal break at the top of the Oneota formation in central Wisconsin, and for this reason he placed the systemic break between his Canadian and Ozarkian systems at that horizon. In addition to this paleontologic evidence, conglomerates that might be considered to mark an erosional unconformity are present in many exposures of Prairie du Chien strata. Sardeson (1916, p. 5) believed that the Oneota surface emerged and was eroded before the deposition of Shakopee sediments, and Chamberlin (1883, p. 139) interpreted the Shakopee domes as reflecting erosional irregularities at an unspecified horizon in or below the Shakopee formation. He visualized the upper bedded dolomite of the Shakopee to be draped over these erosional irregularities like "an undulatory blanket." The conglomerates observed in this study, however, are local, discontinuous, and appear commonly to be associated with algal masses and not with an underlying irregular eroded surface. It is believed, therefore, that the conglomerate is a reef-type accumulation resulting from wave abrasion acting on organic reef projections above the sea floor in a shallow sea. Variation _b_ meets many of the requirements of the field evidence, but because the central masses of the domes, where observed, were not erosional remnants the hypothesis is less preferred than the one next discussed.

Variation _c_ of the general solution-compaction hypothesis requires the total relief on the upper Shakopee surface to represent the sum of two processes, diagenetic compaction of lime muds over relatively incompressible rock masses, probably organic reefs, and epigenetic intensive interstratal solution and concomitant compaction under gravity pressures. In connection with the first episode, Terzaghi (1930, pp. 78-79) found, in controlled laboratory experiments, that some lime muds may acquire dips of as much as 60° if deposited over steep-sided relatively incompressible reef cores. None of the dipping Shakopee strata measured during this study was inclined that steeply, and beyond a doubt primary compaction of sediments over relatively incompressible rock masses, which appear to be bioherms, has caused much of the irregularity of stratification within and at the upper boundary of the Shakopee. Exposures are not of the magnitude to show more than a part of these irregularly mounded features and their interiors, but the abundance of algal structures in both the Shakopee and Oneota formations is strongly suggestive that the domes have an algal reef origin. Whether the cores of the large domes are composed of one continuous mass of algal and allied material, or whether the upswelled areas are caused purely by a greater abundance of algal growth in a more-or-less vertical zone under the domes while the surrounding clastic sediments accumulated, is not clear. The appearance of most of the exposures suggests that, of the two, the second possibility is more probably correct. The evidence in no one outcrop entirely substantiates this proposal, but the criteria in several, if pieced together, strongly support it. A detailed study of the biohermal aspects of the Shakopee domes is, in itself, a problem that is beyond the scope of this paper. Compaction over cores of essentially algal material is believed to account for as much as 100 feet, perhaps more, of local relief on the upper Shakopee surface.

The second episode in geologic history that influenced the shape of the contact surface was one of intensive interstratal solution, restricted mainly to the interdome areas. Such solution zones are characterized by abundant maroon and green shale, concentrations of leached chert, by sandstone and dolomite, in which marked internal deformation has occurred. Shale laminae are greatly contorted and faulted, and the dolomite and sandstone are brecciated and disturbed. As noted earlier, these intervals, which may be more than 110 feet thick, are sediments, subsequently altered, that were deposited beyond any doubt in Shakopee time, although from subsurface studies they long have been considered either the basal phase of the St. Peter or stream deposits accrued during a supposed period of Shakopee emergence and erosion. Clear-cut evidence that this interpretation is erroneous is found in diamond drill cores recovered from the problematic zone.

Concomitant with the interstratal solution, compaction of the residues under strong gravity pressures occurred, and the compaction further depressed the upper Shakopee surface and accentuated the total relief on it.

Exactly why the solution activity has been localized mainly in the interdome areas is not entirely clear, but probably it is related to the continuity and density of fractures that functioned as conduits for phreatic water circulation. Evidence from wells in the formations of the Prairie du Chien and from the abundant strong-flowing springs that characterize these formations in the area of this study indicates that the necessary difference in hydrostatic pressure is present to cause the underground water to circulate laterally or vertically through the natural conduits. In most places where observed the arenaceous, shaly contact zone in itself does not appear to be sufficiently impermeable to establish a marked difference in hydrostatic pressure across the St. Peter-Shakopee contact zone.

Undoubted evidence of marked subsidence in the St. Peter sandstone above these solution zones is present and has been described in connection with some of the surface exposures discussed in this paper. It was not observed, however, that the subsidence was reflected upward to the upper strata of that formation. A proposed explanation for this seemingly anomalous situation was offered in the discussion of the Clayton sand pit (p. 41-48), and is briefly reviewed here. If, in a limited area, support were removed from below an incoherent sandstone, like much of the St. Peter, and that sandstone underlay a thick sequence of hard, unyielding limestone or dolomite bearing evenly on the sandstone, the differential pressures set up by the subsidence in the basal sandstone might be equalized by sand flow, not by downwarping of the carbonate beds.

Moreover, if the sand were homogeneous in texture and composition, structures to record this flowing of the sand might not be preserved, except near retarding masses that might restrict the free flow of the sand. Some evidence that this process may have occurred is described in the Clayton sand pit discussion.

In the light of present evidence, variation c of the general solution-compaction hypothesis, outlined above, is the explanation preferred to account for the highly irregular boundary separating the Shakopee dolomite from the superjacent St. Peter sandstone, for other phenomena observed in the contact zone, and for features in the dolomite beds of the Shakopee and in the sandstone strata of the St. Peter.

CONCLUSIONS

The significant conclusions drawn from this study, and directly applicable of course only to the area in which it was made, regarding the St. Peter sandstone-Shakopee dolomite contact relations are:

1. The undulating upper Shakopee dolomite surface, bearing a relief of as much as 160 feet, perhaps more, is due to the combined effect of two processes; diagenetic compaction of lime muds over relatively incompressible rock masses, probably organic reefs, and epigenetic local intensive subsurface interstratal solution and concomitant compaction.

2. The Shakopee formation was not emergent and significantly subaerially eroded before St. Peter sandstone deposition.

3. The interbedded shale, sandstone, dolomite, and chert that compose the stratigraphic interval, of greatly varying thickness, below the continuous relatively pure, well-sorted and well-rounded sandstone of the St. Peter and above the essentially continuous typical dolomite and dolomitic limestone of the formations in the Prairie du Chien group, were deposited in Prairie du Chien seas, and are properly assigned to the formations of the Prairie du Chien group.

4. Upper strata of the Shakopee formation are nowhere absent in the area of this study except where they have been removed by the present episode of erosion.

5. The break in sedimentation, if any, between the Shakopee and the St. Peter formations was insignificant.

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OUTCROP STRATIGRAPHIC SECTIONS

SECTION 1

Ryan quarry, 1.7 miles northwest of Hollandale, Wisconsin, near the center, $NE\frac{1}{4}$ sec. 24, T. 5 N., R. 4 E.

	Thickness (feet)
St. Peter sandstone:	
Sandstone, brown, rounded and frosted, fine- to medium-grained, ferruginous stained and, locally, cemented.	2+
Shakopee dolomite:	
Clay, green and purple, interbedded with buff and white sandstone; near middle of unit is 0.1-foot bed of white leached chert, bedded as primary or replacement deposit; recent slumping obscures true unit thickness.	3-4
Dolomite, yellow-buff, gray; bedded irregular 0.05-0.4 feet, soft, punky; green shale partings.	2.5
Dolomite, yellow-buff, mottled, bedded 0.6-1.0 feet, upper 0.8 foot brecciated.	3.1
Dolomite, yellow-grown, argillaceous, irregularly bedded 0.1-0.2 foot.	1.2
Sandstone, dolomitic, yellow-buff; massive; 0.1 foot of green shale at top.	3.0
Shale, green and purple, interbedded with 0.5-foot beds of buff dolomite; local quartz sand lenses; leached, punky white chert at top of unit.	4.8

SECTION 1, continued

	Thickness (feet)
Shakopee dolomite, continued:	
Dolomite, brown-gray to yellow-buff, very hard; chert in lower 1.0 foot and in upper 0.2 foot	4.4
Shale, green.	0.2
Dolomite, gray, buff mottled, fine to medium, crystalline, stands as one bed; crenulated laminated structures; thin green shale partings in upper part of unit.	3.0
Dolomite, buff-gray, bedded 0.1 foot; thin green shale partings.	2.0
Dolomite, gray, hard, massive, knobby; contains nodular chert.	1.0
Shale, yellow-green, except purple in middle 0.4 foot.	1.0
Dolomite, yellow-buff, medium- to thin-bedded; green shale partings; manganese dendrites.	2.0
Shale, purple.	0.2
Dolomite, buff-gray; medium-grained, crystalline; manganese dendrites.	0.3

SECTION 2

Saw Mill Creek quarry, 4.5 miles north of Argyle, Wisconsin, NE$\frac{1}{4}$NE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 2, T. 3 N., R. 5 E., east of Wisconsin State Highway 71.

	Thickness (feet)
Shakopee dolomite:	
Dolomite, brown-buff, bedded 0.2-0.6 foot; minor amounts of shale and siltstone; entirely in weathered zone.	6.0
Chert, white, leached.	0.1-0.2
Shale, green, purple, and tan.	2.2-3.1
Dolomite, buff-gray, fine to medium, crystalline, hard, brecciated and rehealed, algal in part; contains a few chert stringers.	3.6-4.0
Chert, white, very decomposed.	0.1
Shale, gray-green.	0.8
Chert, brown and white, partly leached, vesicular locally.	0.1-0.3
Sandstone, white and brown, mainly fine, marked crystal overgrowths; green shale partings; conglomeratic in part with sandstone pebbles; green shale 0.3 foot thick in middle of unit.	1.4-1.7
Shale, gray-green.	0.1-0.2

	Thickness (feet)
Shakopee dolomite, continued:	
Dolomite, gray, fine- to medium-grained, crystalline, hard, contains local tan dense dolomitic limestone areas; bedded irregularly 0.3-0.5 foot; local glauconite on stratification planes; green shale partings at top and at about each 1.0 foot through the unit.	4.5-5.5
Dolomite as above, but much is covered and poorly exposed down to main floor of quarry	10.0
Dolomite, gray, weathers buff, hard irregularly bedded about 1.5 feet; chert stringers in upper part of unit.	3.8
Dolomite, pink-gray, hard; 0.2-foot layer of yellow-buff, fine-grained dolomite in middle of unit; local green shale.	0.8-1.0
Chert, white, glauconitic at top, leached in part; algal structures preserved in the chert.	0.8-1.5

LOGS OF DRILL HOLES

LOG 1

U. S. Geological Survey James mine diamond drill prospect hole 1, 2 miles west of Shullsburg, Wisconsin, SE¼NW¼SW¼ sec. 9, T. 1 N., R. 2 E.

	Depth From	Depth to	Thickness (feet)
St. Peter sandstone:			
Sandstone, white to gray, fine- to coarse-grained upper 10-12 feet, remainder mainly fine- to medium-grained, partly crossbedded	194	263	69
Sandstone, fine- to medium-grained, light-tan, yellow and red clots and bands, local small faults sealed with white siliceous material	263	358.6	93.8
No recovery	356.8	359.7	2.9
Shakopee dolomite:			
Shale, maroon and green, arenaceous; slickened shale surfaces	359.7	362.0	12.3
Limestone, dolomitic and dolomite, finely crystalline, buff to light-purple, argillaceous; abundant maroon and green shale partings, all slickened; local brecciation in limestone and dolomite; sparse leached chert nodules	362.0	375.0	13.0

	Depth From	To	Thickness (Feet)
Shakopee dolomite:			
Dolomite, light-gray, finely crystalline, vuggy; thin purple shale laminae; dolomite brecciated; slickensides on shale dip 27°; shale laminae much contorted; sparse white leached chert clots.	375.0	386.0	11.0
Shale, dark-maroon interbedded with white sandstone; shale surfaces slickened and sandstone fragments pulled or squeezed into shale; fault surfaces dip as much as 28°.	386.0	393.7	7.7
As above except green shale common in lower 1.0 feet.	393.7	399.0	5.3
Limestone, dolomitic, finely crystalline, upper 1 foot; dolomite, gray, finely crystalline, vuggy, brecciated (like dolomite 375-386); local white "cottonrock" chert.	399.0	405.0	6.0
Shale, maroon, interbedded with white sandstone; many hard slickened surfaces that dip 12°-28°; shale laminae much contorted; sandstone cemented by white leached silica.	405	413.5	8.5

	Depth From	To	Thickness (feet)
Shakopee dolomite, continued			
As above but more maroon shale; very hard slickened surfaces; much contortion of laminae, some of which are vertical in core.	413.5	439	25.5
Chert, white, mainly leached to granular rock but some unleached is white-gray, opaline, may be partly oolitic; common purple and green shale (recovery 6-7 percent).	439	456.8	17.8
No recovery.	456.8	457.6	0.8
Chert, white, much leached; finely crystalline quartz along thin irregular fractures; poor recovery.	457.6	463.5	5.9
Shale, green and brown, slickened; sparse leached chert; fine sandstone in lower 2 feet.	463.5	470.0	6.5
Dolomite, pink-gray, finely crystalline, brecciated, partly vuggy; sparse white leached oolitic chert.	470.0	484.0	14.0
Dolomite, gray, finely crystalline, interbedded with abundant white decomposed oolitic chert; poor recovery.	484.0	489.2	5.2

LOG 1, continued

	Depth From	Depth To	Thickness (feet)
Shakopee dolomite, continued:			
No recovery	489.2	493.0	3.8
Sandstone, gray, and green arenaceous shale; white decomposed oolitic chert at base.	493.0	494.9	1.9
T. D.			494.9

LOG 2

U. S. Geological Survey Kennedy mine prospect hole 4, about 2.0 miles east of Hazel Green, Wisconsin, SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 29, T. 1 N., R. 1 E.

	Depth From	Depth To	Thickness (feet)
St. Peter sandstone:			
Sandstone, quartz, white and buff, mainly medium-grained, rounded, larger grains are frosted.	251	326	75
Shakopee dolomite:			
Shale, green, arenaceous; sparse light-brown dolomitic limestone; sparsely cherty and pyritiferous.	326	330	4
Dolomite, gray and brown, fine- to medium-grained; common gray-green shale; sparse oolitic chert; pyritiferous.	330	340	10
Shale, green; gray and brown dolomite; sparse white silty shale and chert; common quartz sand.	340	347.5	7.5
Shale as above; sparse dolomite, quartz sand and glauconite.	347.5	355	7.5
Shale, mainly buff but some red; sparse quartz sand.	355	360	5
Shale, green; sparse white leached chert; and quartz sand.	360	365	5
Dolomite, gray and light-gray, and green shale in about equal amounts; sparse chert.	365	370	5

	Depth From	Depth To	Thickness (feet)
Shakopee dolomite, continued:			
Shale, green and brown, micaceous; brown dolomite.	370	375	5
Dolomite, brown, and green-gray shale in about equal amounts; sparse to common leached chert.	375	385	10
Shale, green and maroon; quartz sand common; sparse gray dolomite.	385	400	15
Dolomite, buff, arenaceous; quartz sand and green shale sparse to common.	400	405	5
Oneota (?) dolomite:			
Chert, light-brown to white, leached, partly oolitic; buff dolomite and white quartz sandstone together make up about one-half of sample; maroon and green shale.	405	410	5
Dolomite, gray-brown; common white oolitic chert; sparse to common maroon and green shale.	410	415	5
Dolomite, gray and brown, in part arenaceous, composes about one-half to four-fifths of samples, present in all of them; green and maroon shale and gray siltstone common to abundant in all samples.	415	465	50

	Depth From	Depth To	Thickness (feet)
Oneota (?) dolomite, continued:			
Shale, maroon, purple, and green; common oolitic chert; sparse dolomite and quartz sand.	465	470	5
Dolomite, brown and gray, arenaceous; green and maroon shale composes about one-fourth of sample.	470	475	5
Shale, green and purple; abundant oolitic chert.	475	485	10
Shale, green and red-brown; sparse chert and quartz sand.	485	495	10
Chert, light-brown to white, partly leached and oolitic 50 to 90 percent of each of the samples; remainder is green, maroon, brown shale; very sparse siliceous dolomite in a few samples.	495	545	50
Chert, white, oolitic, one-third; one-third is arenaceous dolomite, and one-third is green and maroon shale.	545	550	5
Chert, white and buff, and quartz sand in equal amounts; sparse shale.	550	555	5
Dolomite, shale and quartz sandstone in about equal amounts.	555	560	5

LOG 2, continued

	Depth From	Depth To	Thickness (feet)
Oneota dolomite, continued:			
Shale, red-brown and green, and quartz sandstone; common white chert and sparse dolomite.	560	565	5
Shale, red and green; cream to white chert, and quartz sandstone in about equal amounts.	565	570	5

T. D. 570 feet.

PLATE I

Contact of typical St. Peter sandstone and subjacent white argillaceous sandstone and shale of the contact zone; east side of Grant County Highway U, 1.4 miles southeast of Beetown, Wisconsin

PLATE II

A. Fault in Shakopee strata, southeast face of Ryan quarry about 1.6 miles northwest of Hollandale, Wisconsin.

B. Dipping dome-wall strata in the upper Shakopee formation, Ryan quarry.

PLATE III

A. Tilted Shakopee beds in the south face of Saw Mill Creek quarry about 4.5 miles north of Argyle, Wisconsin.

B. Slickolites on dolomite surface in Saw Mill Creek quarry

PLATE IV

A. Brecciated unstratified dolomite core, interpreted as a reef, in northeast wall of Cleary quarry 4.0 miles northwest of Hollandale, Wisconsin. Quarry is in Shakopee and (or) Oneota strata. Survey rod in right center is 6 feet high.

B. Similar reef core in southeast face of Cleary quarry.

PLATE V

Curved fault surface between dipping Shakopee beds (below and left) and St. Peter sandstone; northeast side of northwest face, Clayton sand pit, 1.5 miles south of Clayton, Iowa.

PLATE VI

Curved shear zone in St. Peter sandstone caused by subsidence under heavy superjacent load, northeast corner of Clayton sand pit at entrance to excavation.

PLATE VII

A. Contorted shale and sandstone beds in the contact zone, northwest face of Clayton sand pit.

B. Drag fold of contact-zone shale and sandstone between dipping Shakopee strata and St. Peter sandstone, northwest side of southwest pit wall in the Clayton sand pit.

PLATE VIII

A. Crenulated beds of the contact zone in the back wall of Sand Cave, Pikes Peak State Park, Iowa.

B. Drag fold in contact-zone beds north side (left) of back wall of sand cave. (feature shows also in the left side of A). Note brown sandstone lens pulled into the lighter matrix.

PLATE IX

Detail of back wall of incipient cave about 45 feet south and 28 feet above the same stratigraphic zone in Sand Cave (Plate VIII, A and B). Lenticular fragment in the center has been isolated by compaction. Crenulated beds are about 1.4 feet thick.

PLATE X

Deformed contact zone strata in Miller Ravine about 1 mile south of McGregor, Iowa

PLATE XI

Concentrically laminated algal structure on the east side of Grant County Highway K about 3.2 miles northwest of Lancaster, Wisconsin.

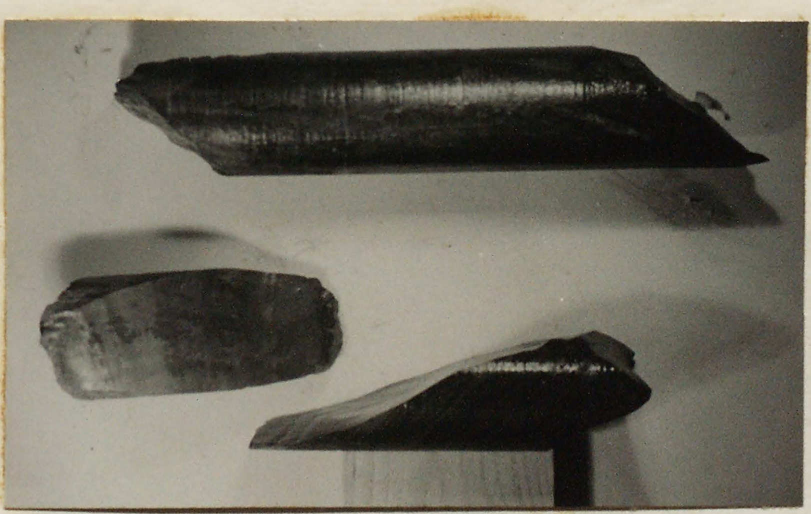
PLATE XII

A. A part of the core recovered from the James Mine diamond drill hole about 2 miles west of Shullsburg, Wisconsin. Interval represented in the photograph is from 66 to 76 feet below the base of the St. Peter sandstone in a 110-foot zone of maroon shale, sandstone, dolomite, and chert. The core is broken at faulted surfaces; note the varying angle the core is intersected by the fault surfaces (NX core; diameter is $2\frac{1}{4}$ inches).

B. Detail of James Mine core showing contortion of shale laminae and isolation of shale fragments by deformation.

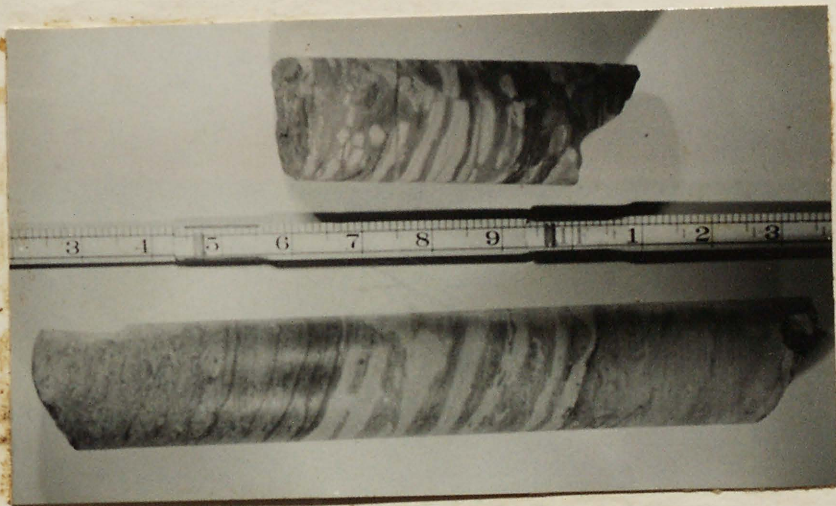
PLATE XIII

A. Detail of James Mine drill core showing extreme contortion of maroon shale (dark) and white sandstone due to internal deformation.



B. Detail of James Mine drill core showing faint steeply dipping to vertical shale laminae truncated by hard slickened fault surfaces; material is maroon shale.

PLATE XIV



A. Detail of James Mine drill core showing light thin dolomitic limestone layers in darker dolomite matrix. Thin dark laminae are maroon shale. Fracture and offset of light layers are due to interstratal solution and compaction. Pieces of core are from a zone about 15 feet below the St. Peter sandstone.

B. Vuggy, brecciated and rehealed, partly stylolitic dolomite from the James Mine core about 20 feet below the base of the St. Peter sandstone.

Pocket contains 1 piece

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