This is to certify that the

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Stratigraphic Analysis of the Prairie du Chien Group,
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STRATIGRAPHIC ANALYSIS OF THE PRAIRIE DU CHIEN GROUP
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By

Steven Anthony Rohr

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ABSTRACT

STRATIGRAPHIC ANALYSIS OF THE PRAIRIE DU CHIEN GROUP LOWER PENINSULA, MICHIGAN

By

Steven Anthony Rohr

The Lower Ordovician Prairie du Chien Group of the Michigan Basin has become a realistic target for hydrocarbon exploration since the discovery of natural gas in the sandstones of this Group beneath the Falmouth Field, Missaukee County.

The New Richmond sandstone equivalent of the Prairie du Chien Group is an extensive, thick sheet sand that extends well southward into the Lower Peninsula of Michigan. Several distinct lithofacies are observed in these sandstones including lagoonal, near-shore, offshore, and barrier-bar facies. An offshore barrier-bar facies model is interpreted to best represent the depositional environment for these sands.

Thus far, Prairie du Chien production has been limited to structural traps. However, sandstone porosity does not appear restricted to structure as previously believed. Porosity in the Prairie du Chien sandstones appears to be entirely retained primary depositional porosity that escaped silica cementation. Porosity is not secondary in nature and is not related to the post-Knox erosional episode or to ascending basinal fluids.

DEDICATION

To my parents; their never ending love, encouragement, and unselfish giving and sacrifice made all of this possible.

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INTRODUCTION

Since the discovery of natural gas in late 1980, in the deep Lower Ordovician--Prairie du Chien Group sandstones of the Michigan Basin (Figure 1), exploration for hydrocarbons in this interval has been sporadic at best. The sandstones, and dolomites of the Prairie du Chien Group had previously been considered too tight to produce good petroleum reservoir rocks (Syrjamaki, 1977). Consequently, the Prairie du Chien Group had remained relatively untested for its hydrocarbon potential especially in the northern counties of the Lower Peninsula. However, the discovery of natural gas in Prairie du Chien sands beneath the Falmouth Field of Missaukee County, Michigan has changed the exploration attitude towards the deep strata of the Michigan Basin.

The Dart Oil and Gas/PPG Industries--Edwards 7-36 discovery well (SW, NE, NE, Sec. 36, T22N, R7W, Reeder Township) in Missaukee County was originally intended as a deeper pool test beneath the Falmouth Field (Mississippian and Devonian production). Much to the surprise of the operator, however, dry, sweet natural gas was encountered with an initial production rating of 12.3 Mmcfgd (Bricker, 1982). The Edwards 7-36 produces from the sandstone facies of the Prairie du Chien in an interval ranging in depth from 10,548 to 10,695 feet (Bricker, 1982). Production was confined to the top 150 feet of the Prairie du Chien, directly below the "Lower Glenwood" formation [also known as the

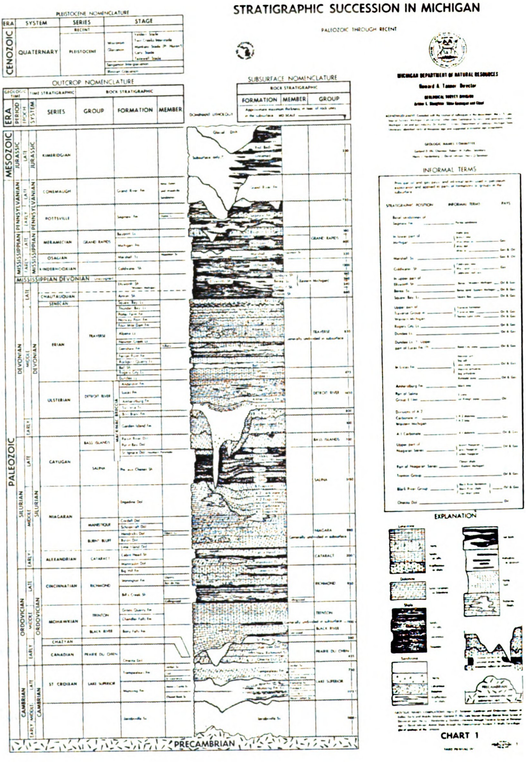


Figure 1. Stratigraphic succession in Michigan.

"Zone of Unconformity" (Bricker et al., 1983)]. Following the discovery at the Edwards 7-36, exploration and testing of the Prairie du Chien increased rapidly because of the initial excitement of other deep play possibilities. However, exploration diminished rather rapidly as follow-up drilling was rather disappointing. Some workers in the Michigan Basin considered that the Edwards 7-36 discovery was a fluke and not representative of the hydrocarbon potential of the deep basin [Montgomery (ed.), 1984].

During the initial stages of exploration for Prairie du Chien gas reservoirs the "highly variable and unpredictable porosity" [Montgomery (ed.), 1984] of the Prairie du Chien sands was considered to be the major cause of the very low wildcat success rate. Sandstone porosities range from essentially zero to approximately 15%, with these extremes being observed in the same well.

Later, during the years 1981-82, following the Edwards 7-36, more than 30 Prairie du Chien test wells were drilled with only three discoveries, one of them significant. Hunt Energy's Winterfield Deep Unit 1-A (NE, SE, NW, Sec. 30, T20N, R6W, Winterfield Township), in Clare County was initially completed at 190 Mcfgd producing from the Prairie du Chien sands. Like the Edwards 7-36 discovery, the Winterfield 1-A test was drilled on a shallow, younger productive structure. This well was later abandoned as dry.

A third discovery was made in 1982 by Wainoco Oil and Gas in Otsego County at the Johannesburg 3-16 (SW, SW, SE, Sec. 16, T30N, R1W, Charlton Township). This well also produced from the sandstone facies of the Prairie du Chien and was initially rated at 625 Mcfgd plus 30 bcpd and 3 bwpd. The Johannesburg 3-16 has also recently been abandoned.

Following these discoveries, Jennings Petroleum made a significant discovery in Newaygo County. The Anderson 1-8A (NE, NE, SE, Sec. 8, T14N, R11W, Goodwell Township) was initially rated at 10 Mmcfgd plus 26 bcpd, also producing from the Prairie du Chien sandstone interval. These latest discoveries confirmed that there is indeed good potential for commercial quantities of hydrocarbons in the Prairie du Chien Group sandstones and that the Edwards 7-36 discovery was not a fluke.

Most recently, Amoco Production Company has made a significant discovery in Gladwin County in the South Buckeye Field (Devonian production) at the Letts Unit 2-36 (SE, SE, SW, Sec. 36, T18N, R1W, Buckeye Township). Again natural gas was encountered in the Prairie du Chien rated at 4.4 Mmcfgd plus 72 barrels of condensate per day (rated at 60 degrees API) from the interval 11,218 to 11,252 feet, making the well Michigan's deepest producing gas well. Again, the Prairie du Chien production is closely related to structure (L. Tolletson and M. Przywara, 1984) and beneath a shallow, productive structure. Surprisingly, however, this well has produced condensate even at the great depth of discovery. This illustrates that condensate may be discovered in the deep basin and is not restricted to shallower Prairie du Chien production like that at the Anderson 1-8A and Johannesburg 3-16.

Even though several significant and encouraging discoveries have been made in the Prairie du Chien Group sandstones of the Michigan Basin (Table 1), the possibilities of hydrocarbons in this and deeper intervals are still poorly understood. Many operators are taking a very tentative approach to the deep Prairie du Chien plays considering that not enough is yet known about the deep basin to justify the cost of exploratory wells on the basis of the low wildcat success rate. Many have taken the approach to let more data become available before an enthusiastic exploration strategy can be developed for the Prairie du Chien reservoirs.

Overall, the variable porosity of the sands is believed to be the main problem with which to be concerned when testing the Prairie du Chien interval. In general, the porosity of the Prairie du Chien sands "appears" to be closely associated with deep structures, with production being confined to the uppermost 100 to 150 feet of the sands.

It is hoped that this study may add to the understanding of the Prairie du Chien interval. However, it is believed that it will be a matter of time before enough data have been accumulated before conclusive information is available concerning the variable porosity of the Prairie du Chien sands and the potential for hydrocarbons in this and other deeper strata of the Michigan Basin.

Table 1. Discovery wells in the Prairie du Chien Group sandstones of the Michigan Basin

Well	Operator	Location	Initial Production
Edwards 7-36 PN 33963	JEM Petroleum Corp.	Missaukee County T22N R7W Sec. 36 SWNENE	12.3 Mmcfgd
Winterfield 1-A PN 33680	Hunt Energy	Clare County T20N R6W Sec. 30 NESENW	190 Mcfgd
Anderson 1-8A PN 36622	Jennings Petroleum	Newaygo County 14N R11W Sec. 8 NENESE	10 Mmcfgd + 26 bcpd
Johannesburg 3-16 PN 35113	West Bay-Wainoco	Otsego County T30N R1W Sec. 16 SWSWSE	625 Mcfgd + 30 bcpd + 3 bwpd
Letts Unit 2-36 PN 37582	Amoco	Gladwin County T18N R1W Sec. 36 SESESW	4.4 Mmcfgd + 72 bcpd
Lease Management et al. 1-12 PN 36666	Hunt Energy	Clare County T20N R6W Sec. 12 SWNWNW	708 Mcfgd + 31 bwpd
Prevost 1-11 PN 37779	Shell	Bay County T14N R4N R4E Sec. 11 SENENE	Rumored gas well; (tight hole)

PURPOSE AND METHODOLOGY OF STUDY

As mentioned previously, the major problem encountered by explorationists searching for Prairie du Chien hydrocarbon reservoirs has been the highly variable and unpredictable porosity of these sands. Many theories have been proposed concerning the development of porosity in these sands (these theories will be discussed later), but to-date a concerted effort has not been made to bring together as much information as possible to test these theories. The purpose of this study, therefore, is to attempt to bring together these data in an effort to draw some conclusions about the origin of porosity in the Prairie du Chien sands of the Michigan Basin. A structural, stratigraphic and petrographic approach is being used in this study to determine if any relation exists between porosity, structure, and stratigraphy.

Several types of data were collected for this study. First, more than 220 electric logs were studied at the Michigan State Geological Survey, Petroleum and Subsurface Division in Lansing, Michigan. From these logs formation tops were picked for the Trenton Group, Black River Group, Glenwood formation, "Lower Glenwood" formation (also known as the "Zone of Unconformity" by Bricker et al., 1983), Prairie du Chien Group and Trempealeau Formation. Typically, the best results were achieved when gamma ray--lithodensity logs were studied together. However, many of the older well logs studied possessed only gamma-ray logs. In these instances drillers logs were also used to determine the best formation top pick. From these data, isopachous and structure contour maps were prepared for each of the above formations. Also, lithofacies distribution of the Prairie du Chien was mapped in an effort to understand the lateral relationships of the Group. Sandstone isopachous and clastic ratio maps were also prepared for this study. Formation top picks are listed in Appendix D of this thesis.

The second form of information gathered for this study was the description of 14 Prairie du Chien cores stored at the Western Michigan University, Department of Geology Core Laboratory. Dr. William Harrison made these cores available for this study along with sample chips from these cores. Descriptions of the cores are also included in Appendix B. Figure 2 illustrates the distribution over the study area of the cores examined for this study. Also, shown is the location of cuttings samples donated by Mr. Stuart Jennings of Jennings Petroleum, Flint, Michigan.

Third, selected samples from the described Prairie du Chien cores were thin sectioned for petrographic study. Over 50 thin sections were prepared and studied for this thesis. These thin sections were point counted (150 counts per slide) to determine the type and percent of framework grains, percent porosity, and percent clay matrix. Also determined were cement types and abundance, grain sizes and shapes, and pore geometry and type (i.e., primary versus secondary porosity). Representative thin section descriptions appear in Appendix C.

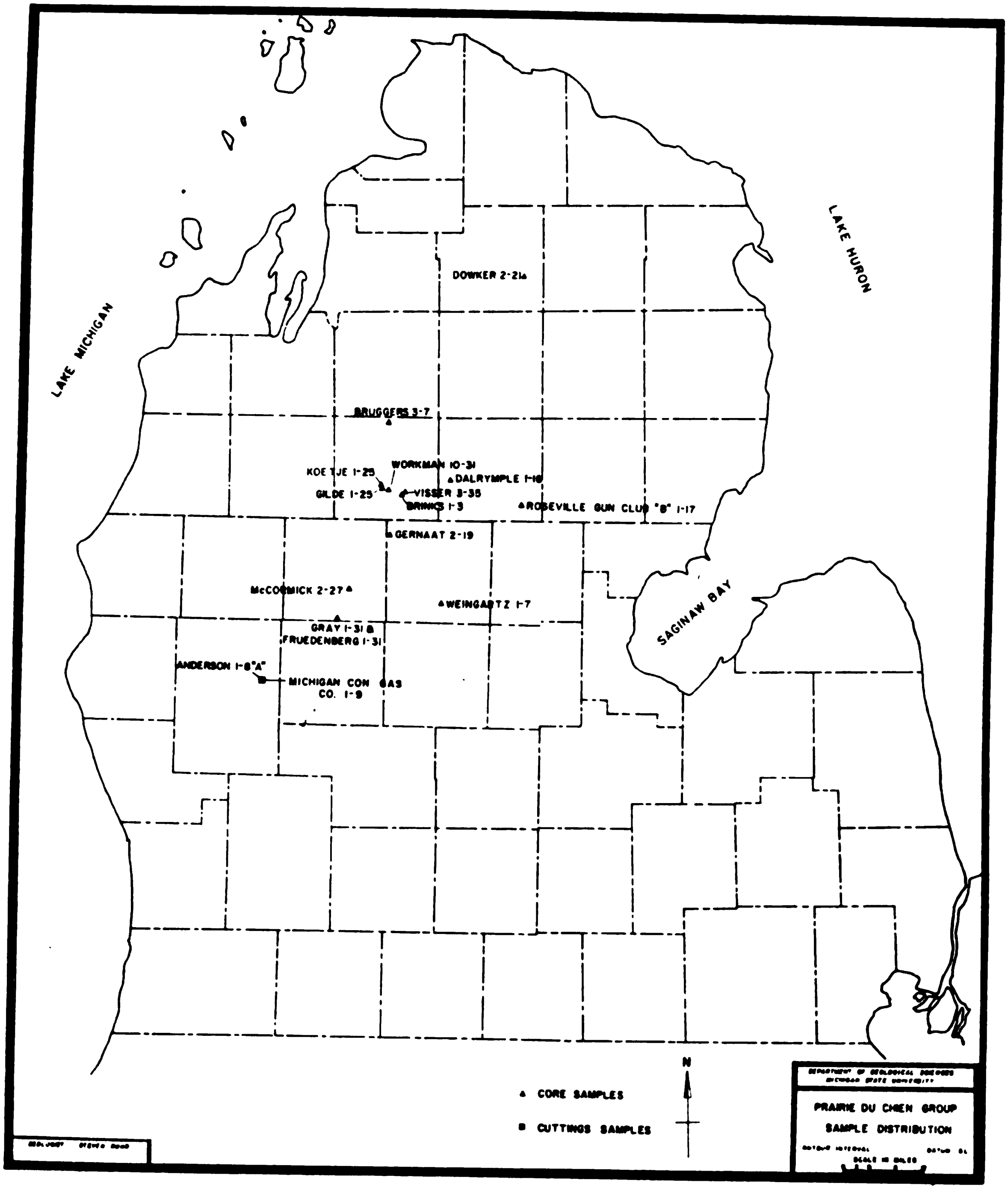


Figure 2. Sample distribution of Prairie du Chien Group.

In an effort to better determine clay mineral types present in the sands, clay was separated from the matrix of several porous and friable sand samples and studied by the x-ray diffraction technique.

AREA OF STUDY

The northern two-thirds of the Lower Peninsula was delimited as the area of study for this thesis. An arbitrary southern limit for the study area was chosen along the Township and Range system base-line for Michigan. This base-line trends east-west from Lake St. Clair to the shore of Lake Michigan and forms the southern boundary for Allegan, Barry, Eaton, Ingham, Livingston, Macomb, and Oakland Counties. The study area is shown in Figure 3.

There are several reasons for choosing this study area. As the sandstone facies of the Prairie du Chien Group is best developed in this area and some impressive production from a few wells would likely lead to further testing of the deeper section, this appeared the ideal part of Michigan to focus this study.

Preliminary investigation indicated that the sands of the Prairie du Chien pinch out north of the base-line defined above. Well distribution in the study area was sufficient to enable the mapping of the distribution of the sandstone and omitting the area of distribution of the carbonate facies as much as possible. The study area also was designed to include the known Prairie du Chien sandstone productions up to the time of this study.

The most concentrated well distribution in the study area is along the southern and southeastern edge (Figure 3) where the Prairie du Chien

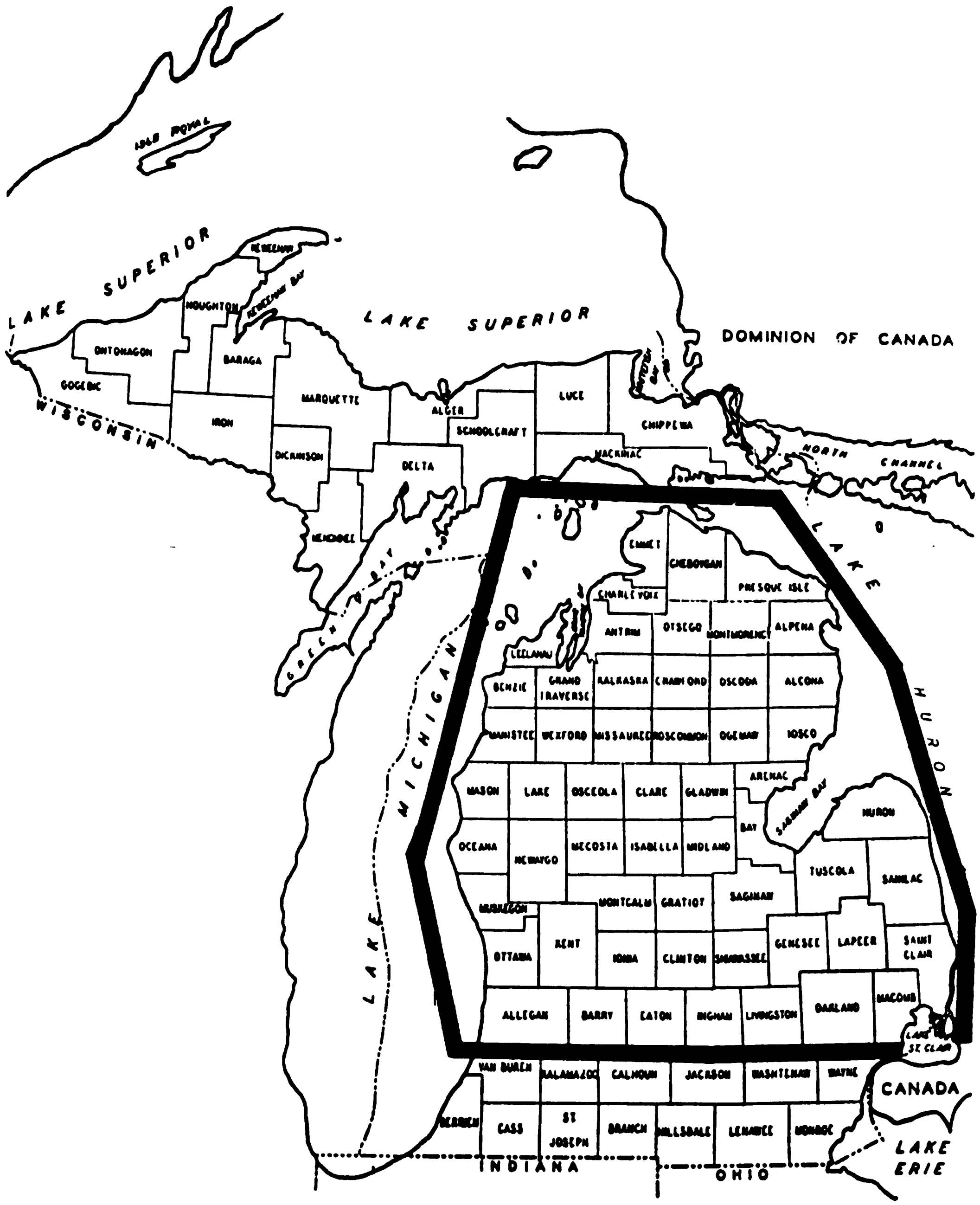


Figure 3. Area of study.

is found at fairly shallow depths. Along the south and southeast areas of the study location the Prairie du Chien is dominated by carbonate/ shale lithologies. Therefore, it was concluded that extending the area any farther south into the region of carbonate facies would be beyond the immediate scope of this study. However, work in progress by Nelson (1985) is being directed toward a detailed study of the Prairie du Chien carbonates of the southern shelf area in an effort to determine the hydrocarbon potential of the Group in this portion of the Michigan Basin. Excluding the shelf area, the concentration of wells in the central and northern portions of the Basin is scattered and generally sparse. The enormous cost of the deep test wells precludes the drilling of a large number of exploratory wells in the deeper basin. Furthermore, the deep Michigan Basin had not been considered worth testing for its hydrocarbon potential, until recently. But with the Devonian strata of Michigan well within the "stripper" stage of production and the northern Silurian Reef trends production leveling out, explorationists are beginning to look toward and test the deeper strata of the basin like the Ordovician Trenton, Black River and Prairie du Chien Groups. The near future should see numerous wells being drilled to these strata, and possibly to the basement, adding to our knowledge of the hydrocarbon potential and structure of the deep Michigan Basin.

PREVIOUS WORK

Owing to the lack of deep-well control in the Lower Peninsula of Michigan, the work dealing with Ordovician stratigraphy has been sparse in previous years.

Cohee (1945, 1946, and 1948) was one of the earliest workers to study the Ordovician system in the Michigan Basin. He was the first to recognize and, on the basis of lithology and subsurface stratigraphy, subdivide the Prairie du Chien Group in the Lower Peninsula into the Oneota dolomite, New Richmond sandstone, and Shakopee dolomite, in ascending order. Cohee (1945, 1947, and 1948) made numerous correlations to the strata in areas surrounding the Michigan Basin. Much of the nomenclature that he introduced is still used today. Using gamma-ray logs and similar lithologies between wells, Ells (1967) was able to prepare a stratigraphic cross-section of Cambro-Ordovician strata in the Upper and Lower Peninsulas of Michigan.

Syrjamaki (1977) made a regional study of the Lower Ordovician Prairie du Chien Group in the Lower Peninsula of Michigan. Based on well samples, and geophysical logs he was able to determine the Prairie du Chien boundary contacts and define the extent, distribution, and lithology of the Group in the Southern Peninsula. Syrjamaki divided the Oneota dolomite into a lower sandy dolomite unit and an upper argillaceous dolomite unit. Because of difficulties in recognizing individual units, Syrjamaki believed that the New Richmond sandstone and Shakopee dolomite should be combined in this area into the New Richmond-Shakopee Interval.

The Oneota dolomite is described (Syrjamaki, 1977) as a buff to brown, fine to coarsely-crystalline dolomite with white chert and floating sand grains. The Oneota is more argillaceous and sandy at its base where it is interbedded occasionally with green, red, and gray, mottled shales and sandstones. The New Richmond-Shakopee Interval is described as a fine-to-medium-grained, subrounded to rounded, frosted to slightly frosted to clear, gray sandstone, often stained pink, with silica and dolomite cement.

According to Syrjamaki (1977) the sandstones of the Interval are best developed in northwest Michigan and basinward are often associated with chert, green to gray shale, buff to tan siltstone, limestone, and dolomite. The dolomites are commonly buff to brown, very finely-to-finely-crystalline and sandy, alternating with beds of sandstone and thin shale. A brown, very fine-to-finely-crystalline, silty and argillaceous limestone is found basinward.

The Prairie du Chien group ranges in thickness from zero in southeast Michigan to approximately 1050 feet in the west central portion of the Lower Peninsula according to Syrjamaki (1977). However, more recent well data indicate that the Prairie du Chien Group is greater than 1300 feet in the middle-basin area (Figure 6, of this report).

At the time of Syrjamaki's work (1977) the Prairie du Chien Group as a whole had not proved to be a significant hydrocarbon producer. Overall, the Prairie du Chien sandstones and dolomites appeared to be too tight to have sufficient porosity for a good reservoir, although a few scattered porosity zones had been found toward the edges of the basin (Syrjamaki, 1977). However, his restored section of the Prairie du Chien north-south across the Lower Peninsula showing the increased quartz sand content apparently created considerable interest to the explorationists.

Stelzer (1982) reported on studies of samples from Missaukee County deep tests and suggested that hydrocarbon occurrences in the Prairie du Chien are related to clay mineral content of the sandy dolomite, with clay believed to coat quartz grains thereby curtailing silica overgrowth development which would tend to close pores decreasing porosity.

Bricker et al. (1983) have recently published a set of cross-sections indicating Upper Cambrian and Lower Ordovician correlations in the Michigan Basin based on the most up-to-date mechanical logs available.

Zwicker (1983) used over 200 well logs to analyze the distribution of Cambro-Ordovician sandstones, the deeper (Ordovician) structure of the Michigan Basin, and the possible relationship of the deeper petroleum occurrences to structure. Zwicker concluded that future exploration for Prairie du Chien (for "Knox Sandstone") gas is good and will depend not only on finding structural highs, but also on findings favorable zones of porosity.

STRUCTURE OF THE MICHIGAN BASIN

The Michigan Basin is a circular to ovate sedimentary basin located in the Central Interior physiographic province of the United States. It is approximately 122,000 square miles in areal extent and encompasses all of Michigan, and portions of the States of Wisconsin, Illinois, Indiana, Ohio, and the western portion of the province of Ontario, Canada. Geologically, the Michigan Basin is surrounded by several well-known framework structures (Figure 4) including: the Kankakee Arch to the south and southwest; the Findlay Arch to the southeast; the Algonquin Arch to the east; the Canadian Shield to the northeast and north; the Wisconsin Dome to the northwest; and the Wisconsin Arch to the west. Workers in the Michigan Basin have tried previously to relate the surrounding framework structures to the occurrence, origin, and predominant NW-SE trend of many smaller intra-basin structures (the producing anticlines and fractures) (Figure 5). It is believed that an understanding of the origin of the large framework structures may aid in understanding the origin and occurrence of the smaller intra-basin structures.

Robinson (1923) proposed that the structural features observed in the Michigan Basin are the result of vertically directed forces and not the result of horizontal compressional forces. He describes five types of folds that are the result of vertically acting forces:

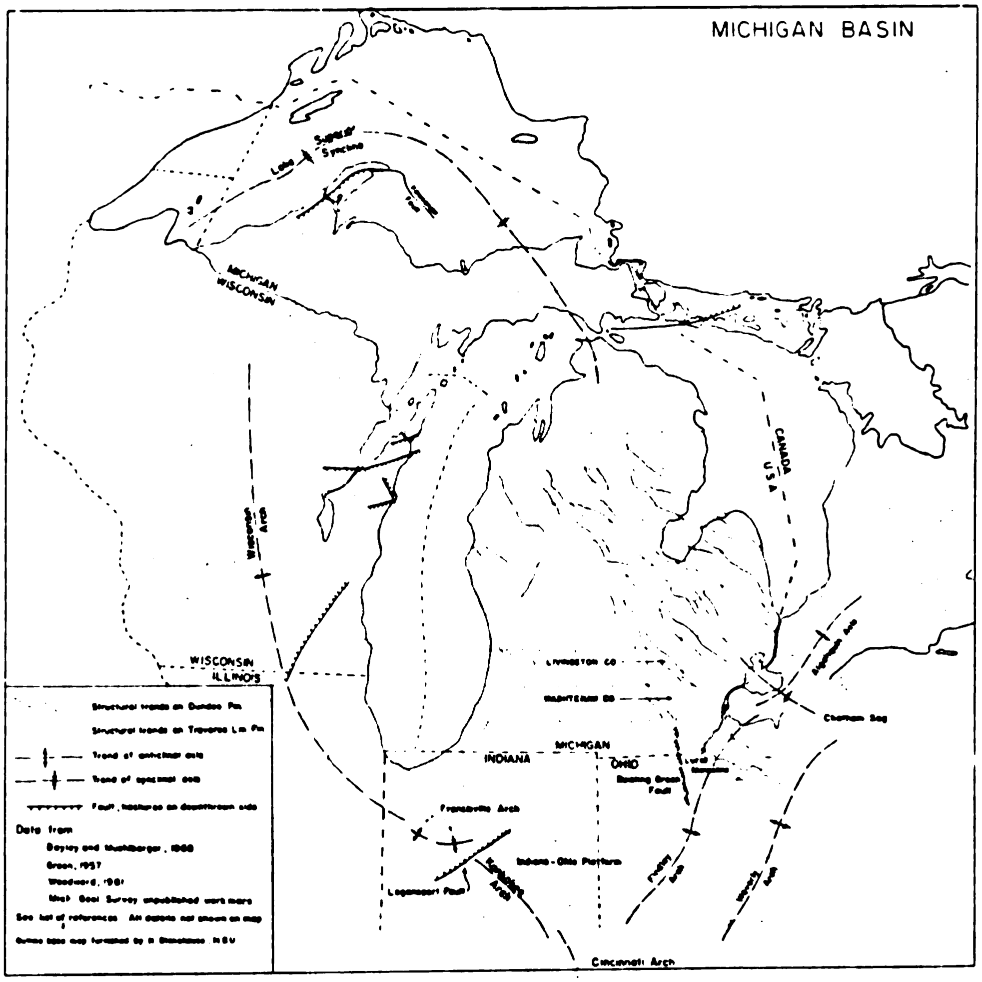


Figure 4. Michigan Basin and surrounding structural elements (from Ells, 1969).

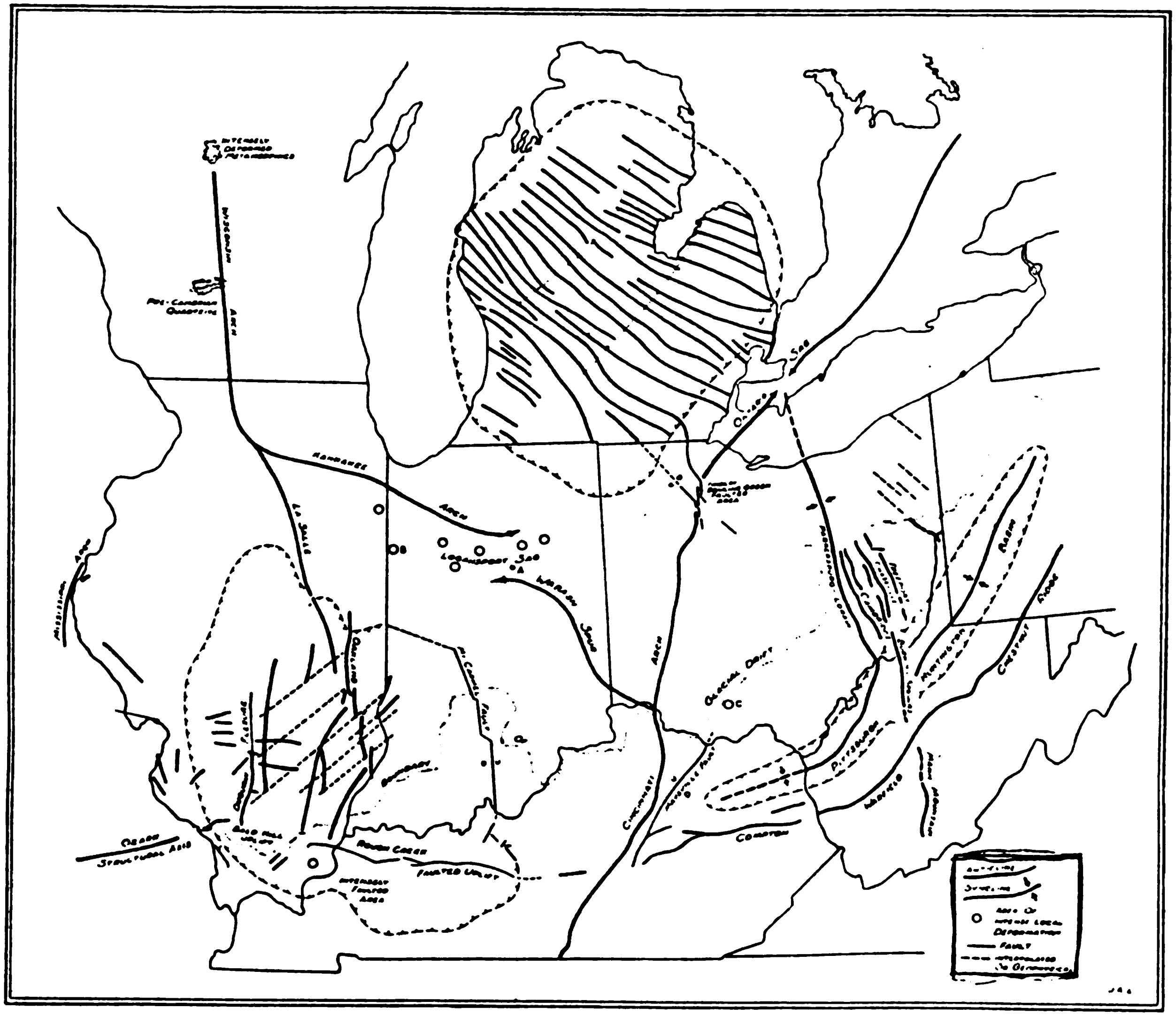


Figure 5. Structural trends in Michigan Basin and structural elements framing the Michigan Basin (after Lockett, 1948).

(1) domes and quaquaversal folds; (2) radial linear folds; (3) concentric terrace folds; (4) linear terrace folds; and (5) monoclinal folds related to deep-seated faulting. Of these five types only one, the dome or quaquaversal fold, is typically due to an upward acting force.

Pirtle (1932) believed that the Michigan Basin probably originated in Precambrian time and its sedimentary and structural history is closely related to the large framework structures surrounding it (the Cincinnati, Kankakee, and Wisconsin Arches).

Pirtle postulated that the Wisconsin and Kankakee arches are the remnants of large Precambrian mountains. These mountains were base-leveled before the Paleozoic with the sediment accumulating in a proto-Michigan Basin that paralleled the Precambrian mountains in an elongate, trough-like manner. He suggested that old lines of structural weakness in the basement (probably Precambrian in age), with accompanying vertical acting forces and subsequent periodic horizontal compressions through time, could account for the development of the folds in the Michigan Basin. These lines of weakness probably closely paralleled the trend of the adjacent Precambrian mountains and therefore produced sufficient basin subsidence in Precambrian time to accommodate sediment from erosion of the mountains.

Lockett (1947) also believed that the structural features surrounding the Michigan Basin are underlain by the cores of Precambrian mountains. He also stated that these features remained more or less positive and that the principal movement during the Paleozoic was the continued subsidence of the basin into which the sediments from erosion of these mountains were deposited. During the Paleozoic, three sides of Michigan Basin were more or less held stationary by the surrounding framework structures, however, the southeast side of the basin, in the vacinity of Lake St. Clair, continued to subside. Lockett considered that this condition produced a system of lines of weakness (or fractures) in the basement through the unsupported end of the basin parallel to the northeast and southwest sides which remained positive. With increasing sediment load, differential basin subsidence was initiated along these lines of basinal weakness. Sediment accumulation was believed to be greater on the basinal side of these faults forming a stepfaulting situation into the central portion of the basin. Lockett (1947) further considered that the parallel trends of structures in the Michigan Basin were due to movements along these lines of weakness in the basement under the basin and that the structures are to be considered the result of basinal subsidence. Compressional orogenic forces were believed to have played little or no role in the development of anticlinal structures or fractures in the Michigan Basin.

Rudman et al. (1965) postulated that much of the strata in the midwestern United States is underlain by basement that is highly faulted. They suggest that the prominent NW-SE trend of structures in the Michigan Basin is similar to trends of gravity anomalies in the basin, i.e., the mid-Michigan gravity anomaly, further indicating some kind of basement control over the development of these structures.

Fisher (1969) postulated that faults have controlled the development of many of the large structures in the Michigan Basin, including the Howell Anticline, Lucas-Monroe Monocline, and Albion-Scipio Field. He also suggested that the rectilinear fault pattern observed on the surface of the Canadian Shield could be a model for that of the basement of the Michigan Basin which may also exhibit this same type of rectilinear fault pattern and that this was probably developed during the Precambrian and was subjected to periodic movements through the Paleozoic era.

On the basis of systematic isopachous mapping of successive strata, Fisher (1969) postulated that the Michigan Basin was created in Ordovician time with the major subsidence occurring in the Middle Ordovician (Mohawkian Series) and Upper Ordovician (Cincinnatian Series) time. Catacosinos (1972) suggested that the Michigan Basin was initially created in Cambrian time, at least.

The data assembled in this study indicate that, indeed, a proto-basin was developed in early Ordovician time and was undergoing very active susidence. More than 1300 feet of Prairie du Chien sediments occupy the depocenter (Figure 6). This supports the suggestion of Catacosinos (1972) that the Michigan Basin was initiated by Late Cambrian time, at the latest. However, as pointed out by Fisher (1969), it was not until Middle Ordovician time that the basin configuration with which we are most familiar became evident (Figures 7 and 8). The position of the basin center during Ordovician time was northwest of the Saginaw Bay area (Figures 9, 10, and 11).

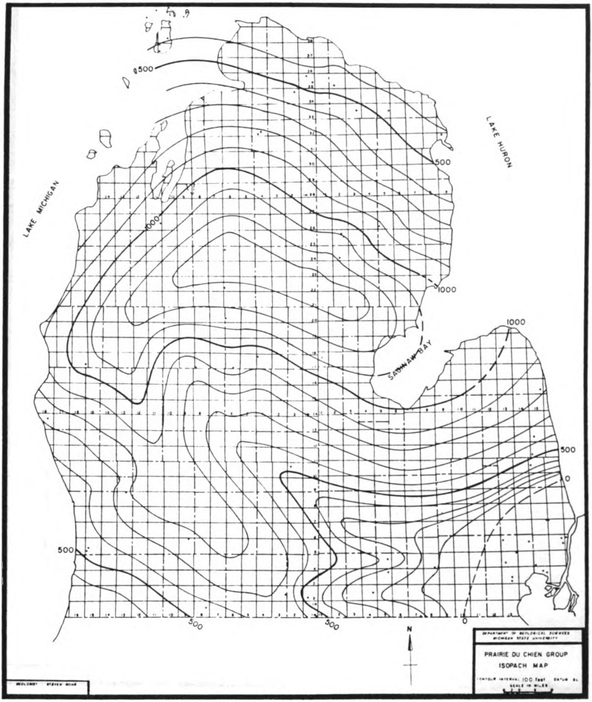


Figure 6. Isopach map of Prairie du Chien Group.

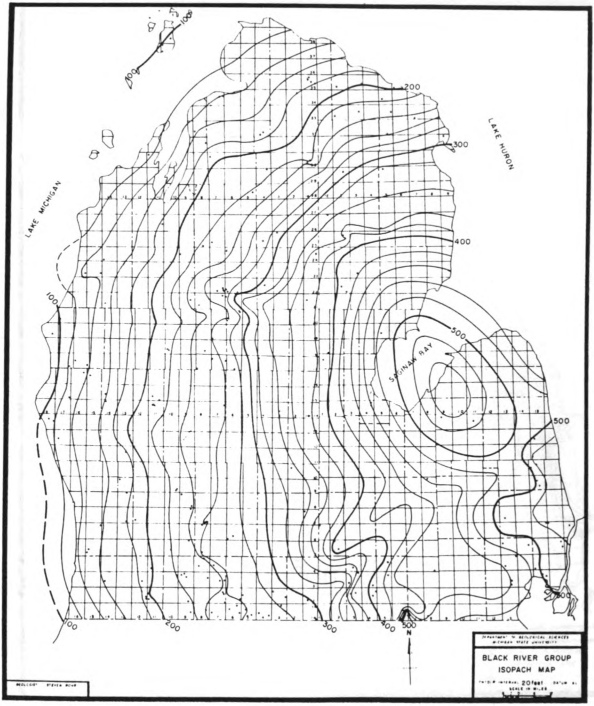


Figure 7. Isopach map of Black River Group.

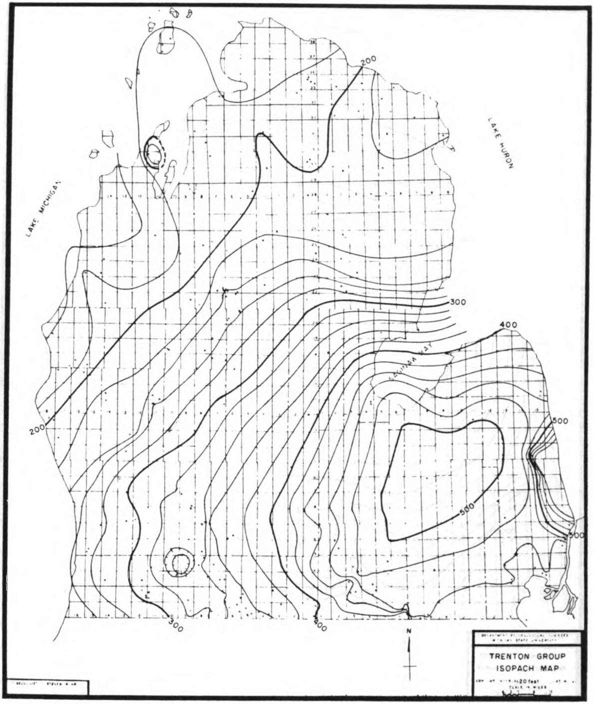


Figure 8. Isopach map of Trenton Group.

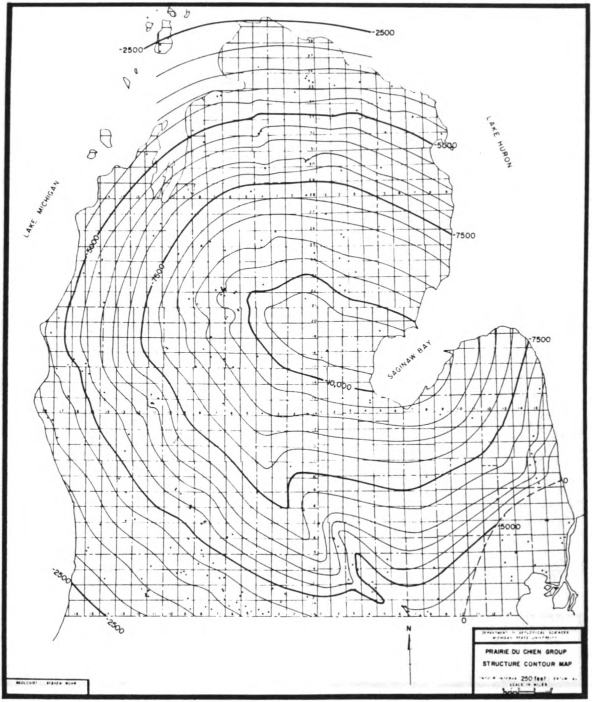


Figure 9. Structure contour map of Prairie du Chien Group.

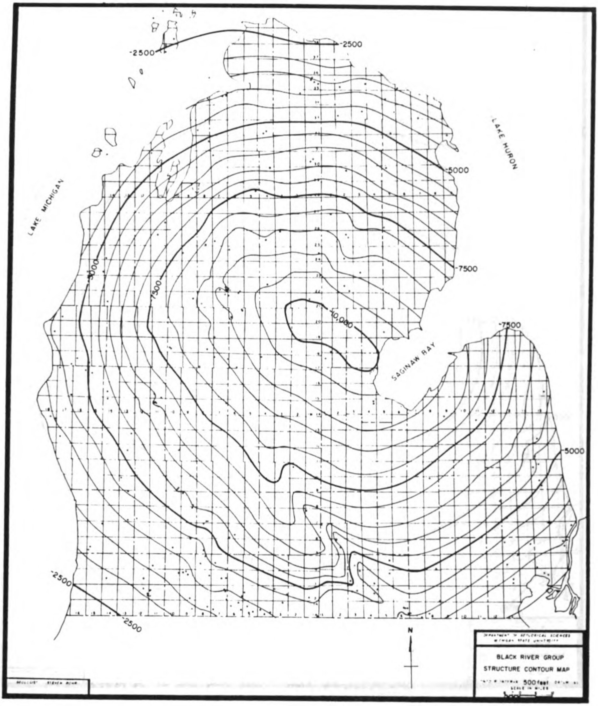


Figure 10. Structure contour map of Black River Group.

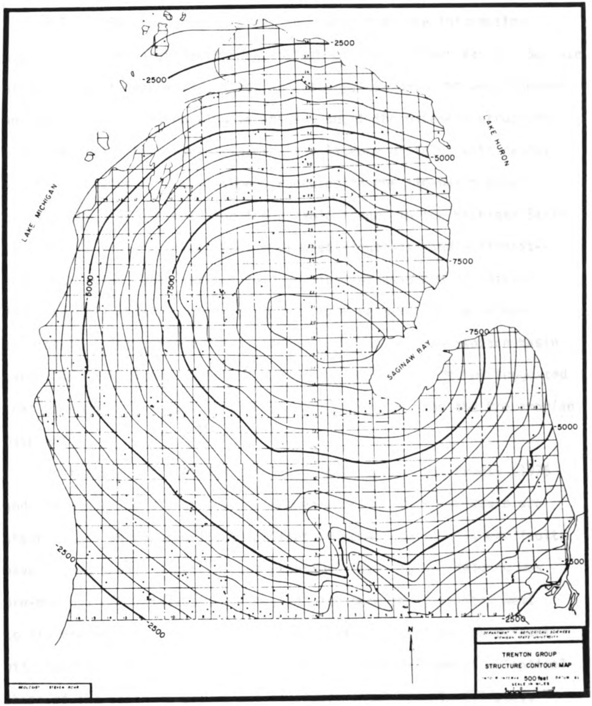


Figure 11. Structure contour map of Trenton Group.

Ells (1969) prepared an excellent summary of the information available on the architecture and origin of the Michigan Basin. Because of the lack of deep well control and geophysical data, he was, however, not able to draw any conclusive answers about the basement structure over the entire Michigan Basin, the persistence of folds with depth, and the presence of Howell-type structures in the mid-basin area.

Prouty (1970) summarized the notable trends in the Michigan Basin, including: (1) the predominant northwest--southeast and northeast--southwest folds, both sets of folds exhibiting evidence of lateral faulting; (2) a fairly definite radial fold pattern; (3) a rather persistent joint pattern; (4) a shift in structural and isopach basin center in each system up to the Mississippian System. He also suggested that basement lineations (fractures) are inherited from the Precambrian basement.

On the basis of LANDSAT satellite imagery studies, Prouty (1976 and 1980) concluded that: (1) lineaments in the Michigan Basin are shear faults which show lateral offset in some cases; (2) shear faults have formed shear folds; (3) the principal faulting and folding was pre-Marshall (Mississippian) time; (4) the depocenter shifted west to its present position in post-Osage Mississippian time, coincident with the time of the major compression; (5) north-northwest elliptical shape of the basin is the result of simple shear (strain ellipse); (6) faults were the channelways for the migration of hydrocarbons and ascending dolomitizing fluids; (7) basement shear fault patterns are attributed to stresses from a general east-southeast direction

(Appalachian orogen). Even more recently, Prouty (1984) showed that lineaments (shear fractures and faults) in the Presque Isle County, Michigan area have controlled the development of Karst topography and surface drainage patterns. Prouty's summary includes pre-LANDSAT detection of Michigan Basin structures, the development and use of LANDSAT imagery in mapping of intrabasin structures, and development of a simple shear model in the Michigan Basin which can account for the folds and fractures in the basin. Prouty believes that the wrenching model for the Michigan Basin is a valuable tool for future exploration of hydrocarbons in the Basin.

Other hypotheses about the origin of structures within the Michigan Basin also have been proposed in recent years. They include: (1) fault block tectonics with associated drape sediments over the blocks (Fisher, 1983) and (2) deep seated faulting produced during an episode of Keweenawan rifting in the Michigan area, now interpreted to be represented by the mid-Michigan gravity high (Chase and Gilmer, 1973). Like other hypotheses these must address the problems of: (1) channelways for petroleum migration and ascending dolomitizing fluids; (2) lateral offset observed along many folds and faults in Michigan, etc. As more drill data becomes available these theories may be further tested.

From the previous discussion it is evident that the hypotheses concerning the geology of the Michigan Basin have developed at a slow, methodical pace. Until 1980, deep drilling was a very rare occurrence in Michigan because of the belief that deep strata were economically unimportant as they were thought to be barren of hydrocarbons. However, with the recent natural gas discoveries in the deeper strata of the Michigan Basin more of these data will become available.

PRAIRIE DU CHIEN STRATIGRAPHY

Regional Stratigraphy

The regional stratigraphic nomenclature dealing with strata of Lower Ordovician (Canadian) age is fairly well accepted. Syrjamaki (1977) summarized the evolution of this nomenclature. Therefore, this report will only briefly discuss the regional stratigraphic correlates of the Michigan Basin Prairie du Chien Group.

Lower Ordovician sedimentation in the eastern half of the United States was dominated by widespread carbonate deposition. Lower Ordovician carbonate lithologies are observed from the Appalachians west to Missouri, northwest to Wisconsin and Michigan, and north to New York. Both dolomite and limestone lithologies are observed. Some structural control over lithofacies appears to be present in the Appalachian Valley and Ridge Province. Prouty (1948) demonstrated that the Chepultepec dolomite (basal formation of the Canadian Series in Virginia and Tennessee) is predominantly a limestone facies to the southeast of the Adirondack Arch. On the other hand, however, dolomite is the predominant lithology northwest of the Arch, and persists to the west, northwest, and north to Missouri, Wisconsin, and New York, respectively. The facies control by structure is also observed to the north along the Adirondack Arch into Pennsylvania. Prouty (1948) suggested that the area northwest of the Adirondack Axis was restricted from the circulating waters of the geosynclinal area to the southeast. The restriction of ocean waters west of the Adirondack Arch allowed evaporation to concentrate these waters. Penecontemporaneous replacement of the deposited limestone by dolomite therefore occurred. The area of restricted ocean waters is presumed to have extended throughout the eastern half of the United States, westward of the Adirondack Axis. This is suggested by the great volume of dolomite lithologies observed in Lower Ordovician strata.

The lithology of the Beekmantown Group (Lower Ordovician) of Virginia and Tennessee was described by Butts (1940) and Prouty (1948). The Beekmantown is described as a thick bedded, bluish-gray, fine to medium grain crystalline dolomite. Chert is abundant and is usually brown, soft, coarse, and cavernous. White chert, similar to the chert in the Oneota dolomite of Wisconsin (Prouty, 1985) is occasionally observed. Siliceous oolites and oolitic chert is common in the lower portion of the Beekmantown. Thin limestone units are occasionally seen in the lower Beekmantown also. Well-rounded grains are observed, and in some cases sandstones lenses are present, but rare. The Beekmantown weathers to a light to dark brown color.

Prouty (1948) described two thin sandstone beds near the contact of the Copper Ridge Formation (Upper Cambrian) and Chepultepec dolomite (Lower Beekmantown) in northwest Virginia and Tennessee. These sands are three to ten feet thick and separated by 15 to 20 feet of dolomite. Prouty observed a steady westward and northwestward increase in the median sand grain size of these two sandstones which suggested a west-northwest source for the sand, possibly the Wisconsin Dome area. A similar source has been suggested for the Upper Cambrian sandstones (Prouty, 1948). As suggested previously (Syrjamaki, 1977), the sands of the Prairie du Chien Group in the Michigan Basin also have a north-northwest source.

Several distinct fossil assemblages are observed in the Beekmantown Group, which are useful in stratigraphic correlation throughout the region. Generally, fossils in the dolomites of Lower Ordovician strata are completely obliterated by processes of dolomitization. However, some very well-preserved fossils are recovered from the cherts. Lecanospira beds have been correlated largely on the gastropod fauna with the Nittany dolomite of Pennsylvania, the Longview dolomite of Alabama, and the Roubidoux Formation of Missouri (Prouty, 1948).

Helicotoma uniangulata is the chief guide fossil for the Chepultepec dolomite of Alabama, Gasconade Formation of Missouri, Oneota dolomite of Wisconsin, and a cherty zone considered to be the top of the Little Falls dolomite in New York (Butts, 1940).

Other paleontologic evidence indicates that these strata are correlates. A Ceratopea zone in the Beekmantown has been shown to have common fossils in the Newala limestone of Alabama and southeast Tennessee; to the Jefferson City and Cotter formations of Missouri; to the Shakopee dolomite of the Upper Mississippi Valley; and to the Bellefonte (and possibly Axemann) formation of central Pennsylvania (Prouty, 1948).

The general stratigraphic correlations are shown in Table 2. Throughout the entire area, the Lower Ordovician lithologies remain strikingly similar which further supports these stratigraphic correlations.

Following Lower Ordovician time a eustatic drawdown of the Ordovician seas caused the development of a worldwide erosion surface. The post-Knox Unconformity, as it is often referred to, is developed on the Beekmantown and other regional correlates (Table 2). The post-Knox Unconformity is often marked by a very masked contact with the overlying Chazyan strata, extensive solution features and erosional relief of 200-300 feet in some instances (Cooper and Prouty, 1943, and Prouty, 1948). Locally up to 600 feet of strata are missing in parts of central Pennsylvania, where transitional beds may occur at the contact when the missing units are present (Chafets, 1967 and 1969). Following development of the post-Knox Unconformity, a massive transgression of Middle Ordovician seas brought about deposition of Champlanian sediments.

Michigan Basin Stratigraphy

Lower Ordovician stratigraphy in the Michigan Basin is fairly well established. The Prairie du Chien type section in Wisconsin (Bain, 1906) (Appendix A; after Stark, 1949) is divided into three units. In ascending order they are: the Oneota dolomite (McGee, 1891), New Richmond sandstone (Wooster, 1878), and Shakopee dolomite (Winchell, 1874). The Michigan Basin Geological Society (1964; Figure 1 of this report) accepts this terminology in the Michigan Basin.

Table 2. Generalized regional correlation chart for Lower Ordovician Series

		Illinois (Bricker et al. 1983)	Indiana (Bricker et al. 1983)	Michigan (Bricker et al. 1983)	Wisconsin	Missouri (Woodward, 1959)	Western Kentucky (Woodward, 1959)	Eastern Kentucky (Woodward, 1959)	Ohio (Bricker et al. 1983)	West Virginia (Woodward, 1959)	Central Pennsylvania (Woodward, 1959)	Tennessee (Prouty, 1948)	Virginia (Prouty, 1948)	Alabama
Middle Ordovician	Trent.	Galena Gr.	Trenton LS	Trenton-Black River Group	Trenton Gr.	Kimmswick	Trenton Gr.	Trenton Gr.	Trenton Gr.	Trenton Gr.	Trenton Gr.	Martinsburg	Martinsburg	Martinsburg
	Bl. R.	Platteville Gr.	Black River Group		Black River Group	Plattin	Black River Group	"Camp Nelson"	Black River Group	Black River Group	Bl. R. Gr.: Benner	Black River Group	Black River Group	Black River Group
											Hatter			
	Chazy	Ancel Gr.: Glenwood	Ancel Gr.: Glenwood	Glenwood	Glenwood	Joachim	Joachim		Chazy	Chazy LS	Loysburg	Cliffield Gr.	Cliffield Gr.	Lenoir LS
		St. Peter	St. Peter	St. Peter	St. Peter	Dutchtown	Dutchtown							Mosheim LS
						St. Peter	St. Peter							
Lower Ordovician		Prairie du Chien Group	Knox Dolomite Group	Prairie du Chien Group: Shakopee dol.	Prairie du Chien Group: Shakopee dol.	Beekmantown Group: Powell	Beekmantown Group: Powell	Upper "Knox" Dolomite	"Knox" Dolomite	Beekmantown Group	Beekmantown Gr.: Bellefonte	Beekmantown Gr.: Mascot Dol.	Beekmantown Group	Beekmantown Gr.: Odenville
				New Richmond sandstone	New Richmond sandstone	Cotter	Cotter				Axemann LS	Kingsport Dol.		Newala
				Oneota dol.	Oneota dol.	Jeff. City	Jeff. City				Nittany Dol.	Longview Dol.		Longview
						Roubidoux	Roubidoux				Stonehenge	Chepultepec dol.		Chepultepec
						Gasconade	Gasconade							
						Van Buren	Van Buren							
Upper Cambrian		Eminence	Trempealeau	Trempealeau	Trempealeau	Eminence	Eminence	Eminence	Copper Ridge	Trempealeau	Gatesburg	Copper Ridge	Copper Ridge	Copper Ridge
		Potosi				Potosi	Potosi	Potosi			Conococheague			

Carbonate lithologies of the Prairie du Chien have been known to be present in the Michigan Basin for some time (Cohee, 1945, 1947, and 1948). However, the lack of well data in the center of the Michigan Basin precluded Cohee from making the correlations of Lower Ordovician strata there. More recently, several deep tests showed that not only are the dolomite lithologies present, but a very thick, massive sand was also developed in the Prairie du Chien Group. This massive sand is probably equivalent to the New Richmond. This sandstone has become the target of many wells over the past few years, and more information about its distribution and character is, therefore, available.

A widespread transgression during New Richmond time resulted in a large amount of sand being deposited in the Michigan Basin. Concomitant with this sand influx, the Michigan Basin was undergoing an episode of active subsidence. The sediment influx kept pace with or slightly exceeded the rate of basin subsidence and, therefore, the sand spread into the southern portion of Michigan instead of being restricted to accumulation in the continually deepening basin. Over 1000 feet of sand plus sandy dolomites are observed in the Lower Ordovician depocenter (Figure 13 of this report). The deposition of the sand was the dominant sediment accumulating in the middle and northern Michigan Basin area through the end of Prairie du Chien time. However, carbonate and shale deposition was taking place contemporaneously in the southern part of the Basin as sand deposition thinned southward. A series of small scale transgressions and regressions produced an interfingering of sand, shale, and carbonate near the margin of the sand deposition. Elsewhere, carbonate and shale deposition took place exclusive to the deposition of sand.

The Prairie du Chien Group will differ lithologically depending on location within the Michigan Basin. Therefore, geologists must recognize the various lithologic characters of the different facies of the Prairie du Chien in order to identify top (and bottom) of this unit.

In the deep basin area, the top of the Prairie du Chien is placed below the Glenwood Shale or below the "Lower Glenwood" formation (Zone of Unconformity, Bricker et al., 1983) when it is present. The massive sand of the Prairie du Chien possesses a very distinct and distinguishable gamma-ray signature compared to the Glenwood and "Lower Glenwood" (Figure 12). Generally, the top of the Prairie du Chien is placed at the first clean sand below the Glenwood or "Lower Glenwood." In the south and southeast portion of the study area the assignment of the Prairie du Chien top is a bit more problematical. The carbonate and shale lithologies of the Group are more prevalent here than in the north and thus the contrast with the overlying Glenwood Shale is not as distinctive. However, as the Glenwood is found at the base of the Black River Group the top of the Prairie du Chien can still be identified with confidence directly below the Glenwood Shale (Figure 13).

Even though the Prairie du Chien Group and underlying Trempealeau Formation are similar lithologically, the bottom of the Praier du Chien is also identified with confidence. It is generally accepted that the top of the Trempealeau is placed below the lower most highly radioactive

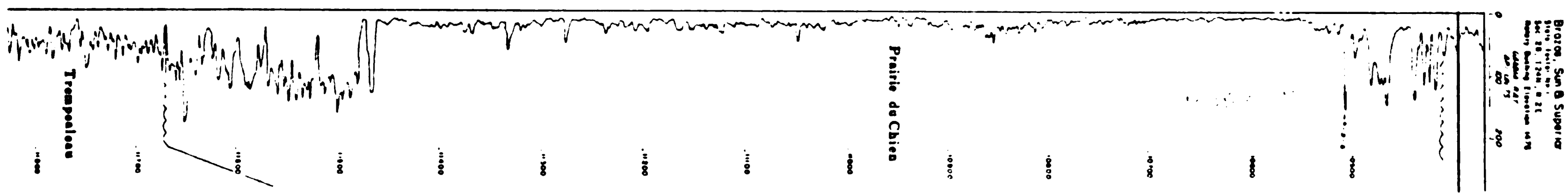


Figure 12. Gamma-ray log of State-Foster #1 (T24N R2E Sec. 28), Ogemaw County. This illustrates the characteristic log response of the Prairie du Chien Group sandstones in the middle Michigan Basin (from Bricker et al., 1983).

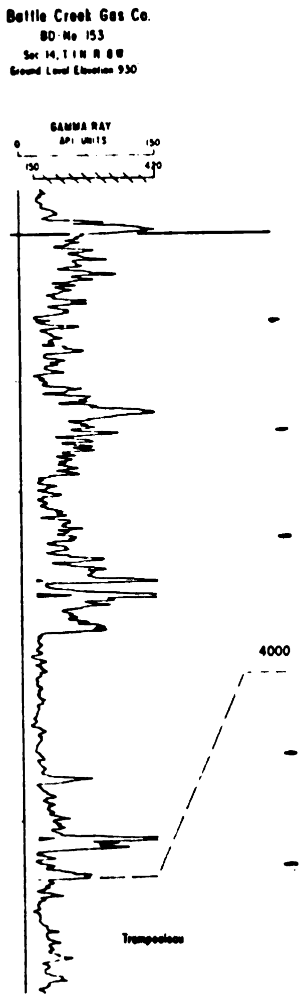


Figure 13. Gamma-ray log of Battle Creek Gas Company BD #153 (T1N R8W Sec. 14), Barry County. This illustrates the characteristic log response of the Prairie du Chien Group in the southern portion of the study area (from Bricker et al., 1983).

zone of the Prairie du Chien and above the cleaner and less radioactive sand of the Trempealeau (Lilienthal, 1978).

As mentioned previously, a eustatic lowering of sea levels occurred following Lower Ordovician time which produced the post-Knox erosional surface in eastern North America. The eustatic sea-level lowering may have been, in part, associated with the Blountian Disturbance in the southern Appalachians. The effect of this erosion is easily recognized in the Michigan Basin. It is generally accepted that the top of the Prairie du Chien is marked by the post-Knox Unconformity. In the southern portion of the Basin, cut and fill channel deposits are present in the Prairie du Chien carbonates. In one instance approximately 230 feet of sand has been observed to fill one of these channels (Nelson, John, oral comm., 1985).

The presence of the post-Knox Unconformity in the mid-basin region appears to be more problematic, however. In several of the cores described in this study (Appendix B), the position of the post-Knox Unconformity was not recognized by a clearly demarcated contact at the top of the Prairie du Chien sandstone. The transition always appeared gradational in the wells studied, with interfingering relations often observed. The lack of evidence for the presence of the post-Knox Unconformity in the mid-basin area suggests that: (1) the Michigan Basin was not sufficiently drained by the lowered sea-level to cause subaerial exposure with intense erosion of the Prairie du Chien; or (2) the deep basin topography was highly irregular with only higher provinces being affected by post-Knox erosion. In the southeast portion of the study area, intense erosion, coupled possibly with some small amount of tectonic activity along the northern portion of the Findlay Arch, did take place, totally removing the Prairie du Chien (Figure 7). A similar situation is reported for the Northern Ohio Platform area, where the Lower Ordovician strata has been totally removed by erosion and hydrocarbon production is related to the post-Knox Unconformity and Copper Ridge erosional "knobs" (Whiting, 1965; Stelzer, 1966; Benedict, 1967; and Dolly and Busch, 1972).

In the middle Michigan Basin area, a series of carbonate, shale, and sand facies exists between the Glenwood and Prairie du Chien. This body of sediments has been informally named the "Zone of Unconformity" by workers at the Michigan State Geological Survey, Petroleum and Subsurface Division (Bricker et al., 1983). This "Zone" is considered to represent sediments accumulated from the erosion of units on the basin rim during the development of the post-Knox Unconformity. The area of accumulation may not itself have been exposed to the erosional effects at the end of Prairie du Chien time. Rather, the drawdown of the seas in the Michigan Basin may not have occurred in the middle basin area where these sediments later accumulated. The nomenclature used by Bricker et al. (1983) does not, however, appear to be very useful and therefore should be rejected. The writer prefers the use of the term "Lower Glenwood" formation for the unit between the Glenwood Shale and Prairie du Chien. This nomenclature was also used by Zwicker (1983).

It is interesting to speculate about the actual stratigraphic relationship of the "Lower Glenwood" to the Glenwood Shale and Prairie du Chien Group. Does the "Lower Glenwood" represent the youngest Prairie du Chien strata or the oldest Glenwood? Because the presence of the Shakopee dolomite in the middle basin is problematic, Syrjamaki (1977) grouped the New Richmond sandstone and Shakopee dolomite into the New Richmond-Shakopee Interval because of difficulties in distinguishing between them on the geophysical logs. The writer concurs with this because strata with recognized Shakopee-type lithology was not found in every core described. The "Lower Glenwood" perhaps could represent atypical Shakopee sedimentation in a basin that was possibly slowly becoming very restricted and stagnant from the eustatic lowering of sea level that was beginning to occur towards the close of the Lower Ordovician. The "Lower Glenwood" depocenter was located to the northwest of Saginaw Bay. If this were the case, the post-Knox Unconformity might have occurred (timewise) between the "Lower Glenwood" and Glenwood formations. Transitional beds similar to these of the "Lower Glenwood" are observed on top of the Beckmantown Group of Pennsylvania (Chafetz, 1967 and 1969). He further concluded that this transitional zone represents continuous sedimentation between Lower and Middle Ordovician strata on the basis that no physical evidence was observed above, below, or within these transitional beds to mark the position of the post-Knox Unconformity. Another possibility is that the "transitional beds" represent uneroded beds of uppermost Prairie du Chien which are in other areas eroded along the Unconformity. Alternatively, however, the "Lower Glenwood" sediments may simply represent older Glenwood strata that filled erosional channels on top of the Prairie du Chien and post-Knox Unconformity.

Following the development of the post-Knox Unconformity Middle Ordovician seas advanced on the craton and began sedimentation of the St. Peter sandstone (in the southwestern part of the basin and farther west) and then Champlanian carbonates.

<u>Sand Source</u>

Syrjamaki (1977) believed that several areas might be the source of the Prairie du Chien sands. First, the Canadian Shield may be the principal source. The exposure of the gneissic and granitic rocks there would have permitted weathering and erosion to produce the sand. A second source could be the Wisconsin Dome which had rock similar to those of the Canadian Shield. A third source to be considered would be the exposed Precambrian and Cambrian sandstones in the Lake Superior and Upper Peninsula region (i.e., the Jacobsville Sandstone; Munising Formation, and possibly, Trempealeau Formation). These could have been eroded and reworked to form the sands of the Prairie du Chien.

Study of Recent sands as indicators of provenance (Blatt, 1967; Basu et al., 1975; Young, 1976) suggest that source rock determinations may be made on the nature of quartz grains, proportion of feldspar and rock fragments, and heavy mineral types. Sands derived from plutonic sources are believed to contain higher proportions of monocrystalline, non-undulose quartz grains, while sands from metamorphic sources are believed to contain significant amounts of polycrystalline, undulose quartz. Feldspar and rock fragment types may also be used as provenance indicators by use of composition and nature.

The sands of the Prairie du Chien Group appear to be multi-cycle in nature, derived possibly from pre-existing sandstones. The quartz grains are predominantly monocrystalline, non-undulose grains. However, undulose and polycrystalline quartz is also occasionally observed. Feldspar comprises less than 1% of the framwork grains. Rock fragments, likewise, make up less than 1% of the framwork grains. Unstable ferro-magnesian and other ingenous/metamorphic minerals are conspicuous by their absence from the non-quartz mineral suite. Some such grains are observed to possess a high degree of rounding. These characteristics indicate that a pre-existing sandstone was the most likely source for the Prairie du Chien sands. The Precambrian Jacobsville and Cambrian Munising and Trempealeau Formations of the Lake Superior/Upper Peninsula of Michigan are the most likely sources. The Wisconsin Dome and Canadian Shield may have contributed small amounts of sand to the Prairie du Chien sediments. Further work on this topic is still needed.

PRAIRIE DU CHIEN FACIES

There are two aspects with which to deal when considering the facies relationships of the Prairie du Chien sands. First, the gross lateral facies changes are important to understand in the southern portion of the Michigan Basin where sandstones thin, interfingering, or are replaced in their distribution by correlative shale and carbonate facies; and second, developed within the massive sand of the Prairie du Chien Group are smaller, micro-facies. These relationships should also be studied.

Gross Lateral Facies Relations

At the beginning of Lower Ordovician deposition in the Michigan Basin, a widespread regional carbonate shelf existed with deposition occurring from the Appalachians to Wisconsin. This inundation of the Canadian Shield, Lake Michigan and Lake Superior regions, and Wisconsin Highlands progressed to the north and northwest across the Michigan Basin area depositing the Oneota dolomite. A lowering of the sea level brought New Richmond sands to the southeast of the craton, followed by transgression toward the source area in Upper New Richmond and Shakopee time. Although this sand is not continuous across the continent, it is well developed in Wisconsin and in the Michigan Basin. The New Richmond sandstone in the Michigan Basin exists as a massive sand, in places appearing greater than 1000 feet thick (Figure 14). At the southern

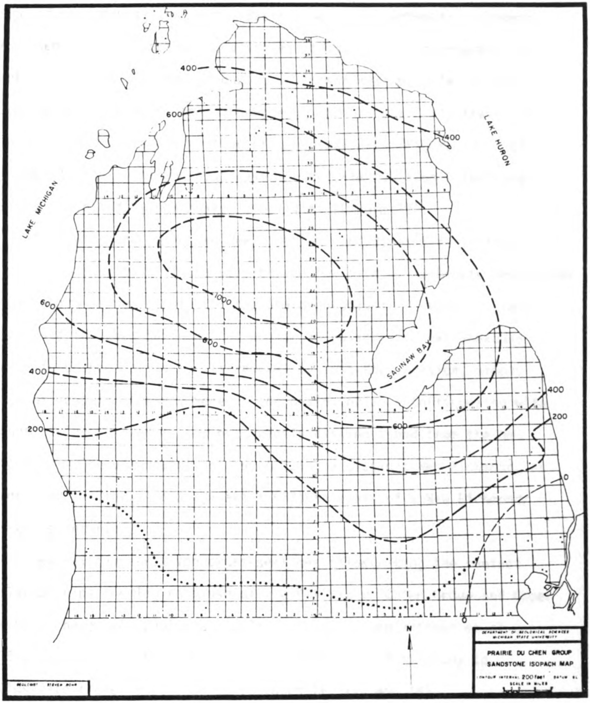


Figure 14. Sandstone isopach map of Prairie du Chien Group.

edge of sand deposition in the Basin, shale and carbonate sediments were deposited. Apparently, a series of small scale transgressions and regressions occurred producing an interfingering relationship between sands, shales, and carbonates. This is best illustrated in the south and southeast portion of the study area (Figure 15). Still farther to the south and southeast the Prairie du Chien lithologies become dominated by carbonate lithologies (Figure 15).

Following the extensive New Richmond sand deposition in the Michigan Basin, much of the area became the site of carbonate deposition again which is represented by the Shakopee dolomite. However, many places of the deep basin do not appear to possess typical Shakopee dolomite perhaps owing to its removal by post-Knox erosion, simply lack of deposition everywhere in the basin, or an interfingering with sands giving a mixed facies not readily distinguished from the New Richmond. The uncertainty of recognizing a distinct New Richmond, as mentioned earlier, led Syrjamaki (1977) to speak of a New Richmond/ Shakopee interval.

Several gamma-ray log cross-sections illustrating the contact relationships and log response of the Prairie du Chien Group and Upper Cambrian have been published (Lilenthal, 1978; and Bricker et al., 1983). Several of these sections are located in this study to illustrate these relationships (Figures 16, 17, and 18).

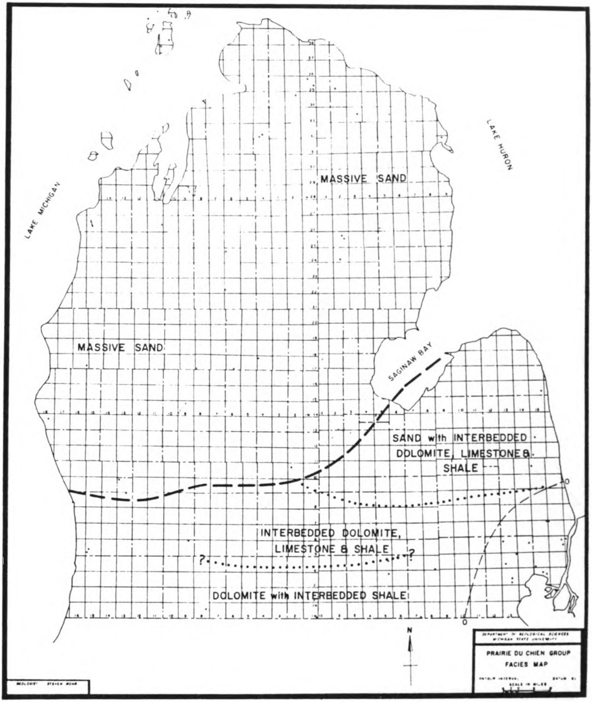


Figure 15. Facies map of Prairie du Chien Group.

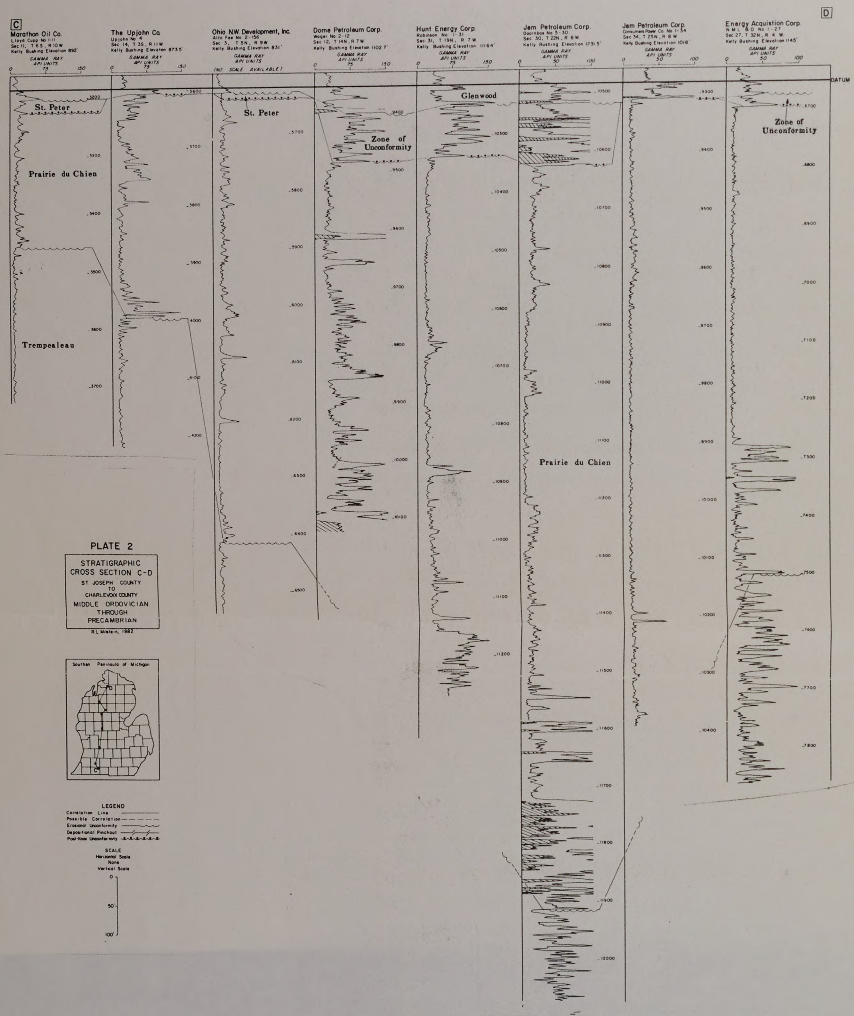


Figure 16. Gamma-ray cross-section in Michigan Basin. Illustrates lithologic changes in Prairie du Chien Group (from Bricker et al., 1983).

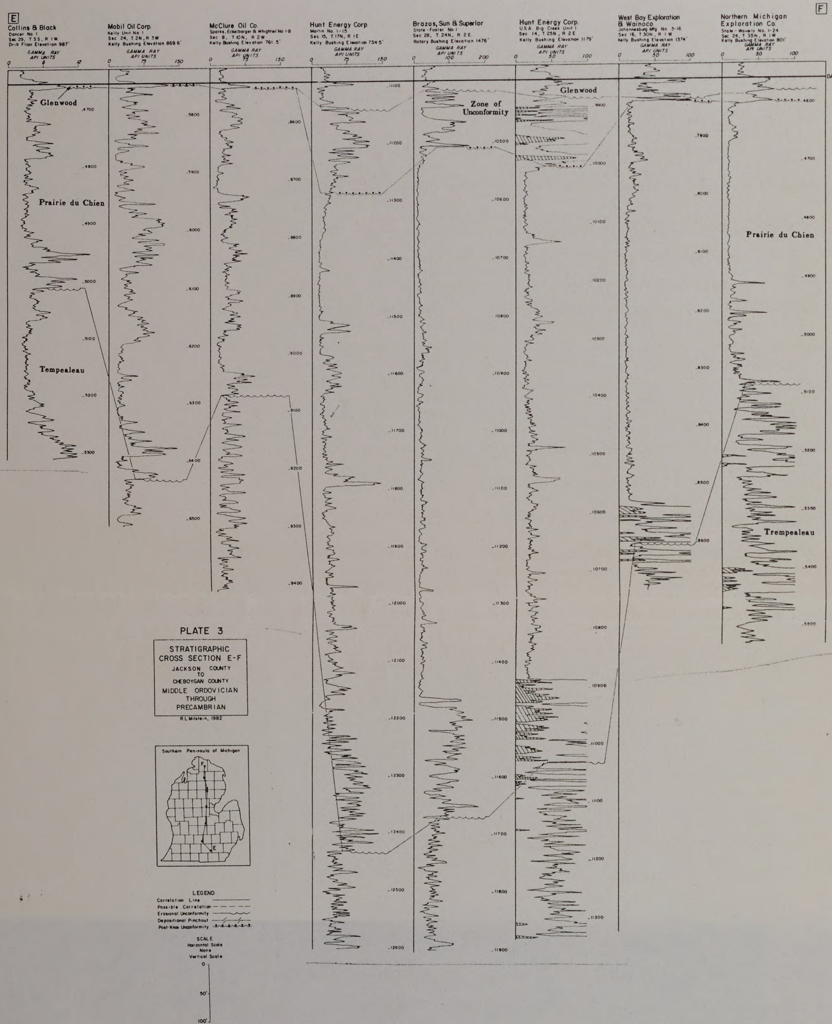


Figure 17. Gamma-ray cross-section in Michigan Basin. Also illustrates lithologic changes in the Prairie du Chien Group (from Bricker et al., 1983).

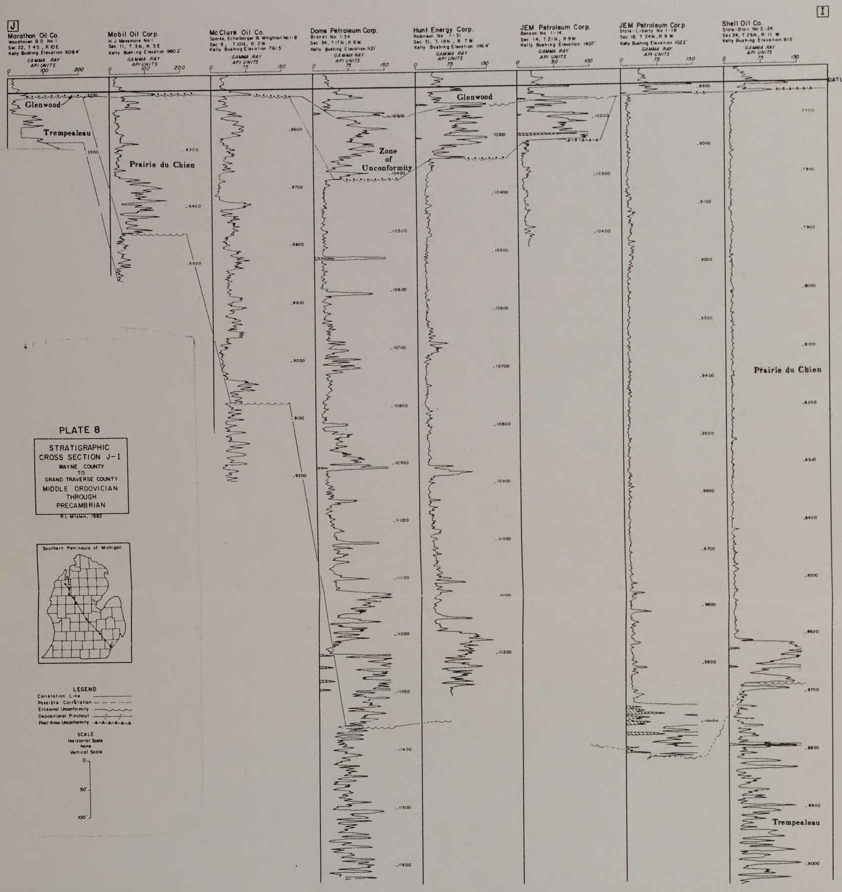


Figure 18. Gamma-ray cross-section in Michigan Basin. Again, illustrates the lithologic changes in the Prairie du Chien Group (from Bricker et al., 1983).

Facies Within the Prairie du Chien Sand

Elsewhere in the Michigan Basin the sandstones of the Prairie du Chien Group exhibit several interesting micro-facies developed within the massive sand sheet. Based on the characteristics of lithologies, sedimentary structure, trace fossils, etc., the most reasonable facies model for these micro-facies in the Prairie du Chien appears to be an offshore barrier-bar system.

During the extensive deposition of the New Richmond sandstone, sand influx into the Michigan Basin was very great. The currents were apparently strong enough to preclude the development of deltaic facies to the north closer to the sand source. Rather, a widespread massive sand sheet formed over the Michigan Basin.

Presumably sediment influx into the Michigan Basin kept pace with the subsidence of the Basin producing an equilibrium situation. Water depth was therefore probably fairly shallow with restricted to normal marine depositional environment indicators present in the Prairie du Chien sands. In some instances, the sands are extensively bioturbated, with the feeding movements of organisms completely obliterating any depositional sedimentary structures. These burrows are typically horizontal feeding burrows, but other burrow types are present. Vertical Scolithus burrows have been observed (Plate 1) and in one instance a Diplocraterion burrow (Plate 2) was observed. These vertical burrow types suggest that very shallow water organisms were present and in the case of Scolithus burrows an intertidal setting may be even suggested. On the other hand, horizontal burrows suggest deeper water

Plate 1. Scolithus burrows in Prairie du Chien sandstone. Sample is from Glide 1-25 well core, Missaukee County, from approximately 10,573' 6" in depth.

Plate 2. Diplocraterion burrow, in Visser 3-35 well core, Missaukee County. Approximate depth of sample is 10,879'. Also note Scolithus burrows and well indurated nature of the sample.

environments (Rhoads, 1975). Typically, the vertical burrows are more extensively cemented with silica overgrowths than the surrounding sand. These burrows are readily distinguished from the surrounding sediment by their lighter, whitish color and well indurated character.

Sedimentary structures also suggest that the sands were deposited in a shallow, restricted to normal marine depositional setting. In places, the Prairie du Chien sandstones are horizontally laminated while other sandstones possess low to medium angle cross beds. Shallow, high energy depositional environments could probably create these kinds of bed forms.

Figure 19 illustrates how the lithofacies observed fit into the suggested facies model for the Prairie du Chien sands.

Lagoonal Facies. Lagoonal Facies are consistently greenish to green-gray to green-brown sands. These sediments are usually greatly bioturbated, with *Scolithus* burrows commonly observed. The sediments are fine-to-coarse-grained owing to the low energy depositional environment plus spillover from barrier-bars. These sands are typically glauconitic, with some finely disseminated pyrite observed occasionally. The typical lithologies of the lagoonal facies are siltstones and silty-sandstones (Plate 3).

Near-shore Facies. The near-shore facies is fine-to-coarse-grained, also a consequence of normal sedimentation, sorting, and spillover from barrier-bars. However, they are light in color, usually white to yellow to beige and extensively indurated with silica cement.

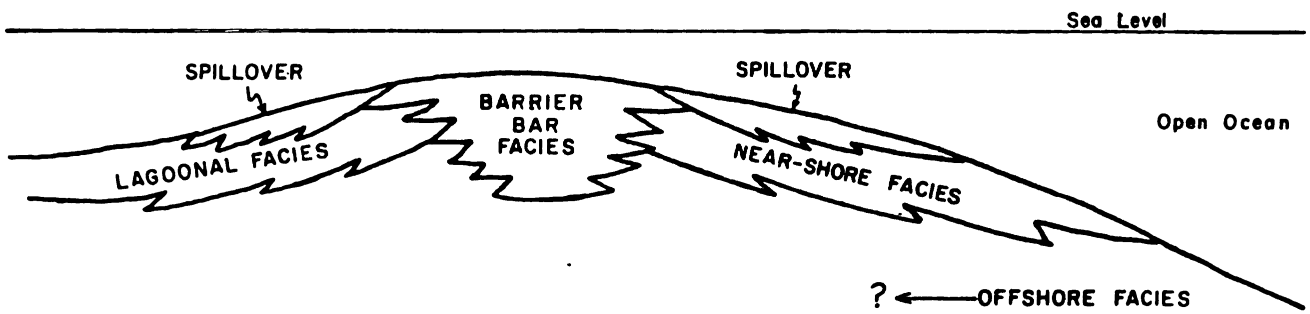


Figure 19. Illustration of offshore barrier-bar facies model (adapted from Selley, 1982).

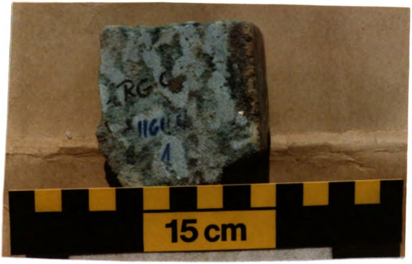


Plate 3. Glauconitic sandstone in Prairie du Chien Group. This sand is interpreted to represent a restricted lagoonal depositional environment. Note abundant Scolithus burrows and some pyrite. Sample from Roseville Gun Club "B" 1-17, Roscommon County from approximately 11,644' depth.

The light color and lack of glauconite suggests that they are not restricted lagoonal sediments, but rather they were deposited on the oceanward side of a barrier-bar in contact with open marine waters. Again, Scolithus burrows are observed and low to medium angle cross beds are present. The lithologies of the nearshore facies range from silty sandstones to quartz arenites. Orthoquartzities may also be observed (Plate 4).

Offshore Facies. This facies is believed to represent the typical Prairie du Chien sediment when it was deposited in the Basin prior to the effects of reworking and sorting. These sands are generally fine-to-medium-grained but some coarse grains are observed occasionally. These sediments are light colored, white to yellow to beige, and again, greatly indurated with silica. Sedimentary structures are generally absent but some sand laminations are present. Also, no trace fossils are evident in this environment. The lithologies of the offshore facies (Plate 5) range from silty sandstone to orthoquartzities.

Barrier-bar Facies. This facies is characteristically coarser than the offshore facies. The higher energy depositional environment has winnowed most of the fine sediments while reworking the coarse sediments. The residual sand is better rounded, sorted, and coarser than any other sediments. These sandstones are generally without traces of fossils. High-energy, medium-angle cross-beds are also observable in this facies. The lithologic composition includes quartz arenites.

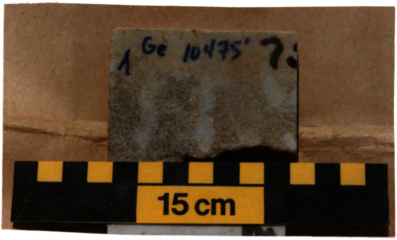


Plate 4. Near-shore sandstone in Prairie du Chien Group. This sand is interpreted to represent near-shore sedimentation of an open marine environment. Note <u>Scholithus</u> burrows. Sample from Gernaat 2-19, Clare County, from approximately 10,475' depth.

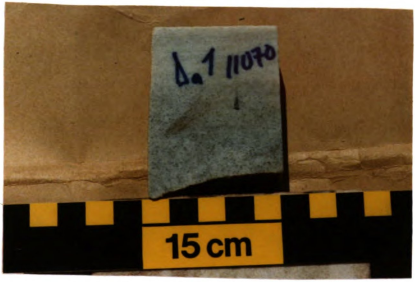


Plate 5. Tight, fine-grained sandstone of Prairie du Chien Group. This sand is interpreted to represent offshore, open marine sedimentation. Note small, black "dead" oil blobs. Sample from Dalrymple 1-16, Roscommon County, from approximately 11,070' depth.

It is interesting to note that there may be some sort of basin (tectonic) influence upon the development of certain types of Prairie du Chien sandstone facies. However, with the sparse amount of data present any discussion would be speculative in nature. As more data become available some relation between Prairie du Chien sandstone facies and structure might be tested.

PRAIRIE DU CHIEN PETROLOGY

Mineralogy and Lithology

The lithologies of the Prairie du Chien Group sandstones are highly variable ranging from siltstone, silty sandstones, quartz arenites, orthoquartzites, dolomitic sandstones to sandy dolomites. However, some outstanding petrologic characteristics can be described in the sands.

The sands of the Prairie du Chien are mineralogically dominated by the presence of quartz grains. The quartz grains are typically monocrystalline exhibiting unit extinction. However, some undulose quartz grains and occasional polycrystalline quartz grains are present. Overall, quartz ranges in abundance from 43% to 95%, this was determined through point counting of over 50 thin sections. The dolomitic sands and sandy dolomites contain floating quartz grains in a dolomitic matrix (Plate 6). On the other hand, many examples of orthoquartzites are observed. These sands contain greater than 90% quartz grains with silica cement completely closing pore space (Plates 7, 8, and 9). Other framework grains include feldspar plus gneissic and schistose rock fragments. These framework grains generally comprise less than 1% of the matrix.

Grain shapes are also highly variable in the Prairie du Chien sands. Grain sphericity ranges from oblong and ovate to nearly

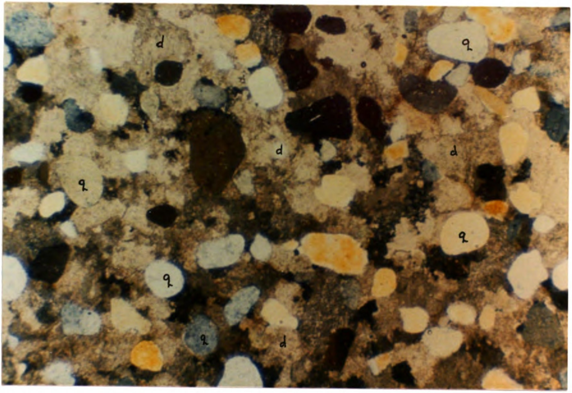


Plate 6. Photomicrograph of sandy-dolomite sample from McCormick 2-27 well core, Osceola County. From an approximate depth 9841'. Photograph frame is 2.5 mm x 3.8 mm. Some grains are identified as follows: q = quartz grain; d = dolomite matrix.

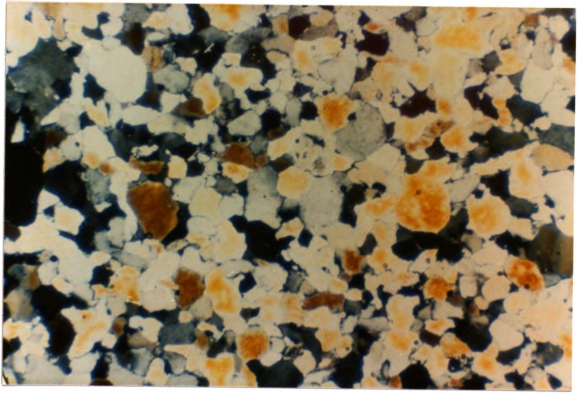


Plate 7. Photomicrograph of tight sandstone from Visser 3-35 well core, Missaukee County, and from approximately 10,843' 7" depth. Photograph frame is 2.5 mm x 3.8 mm.

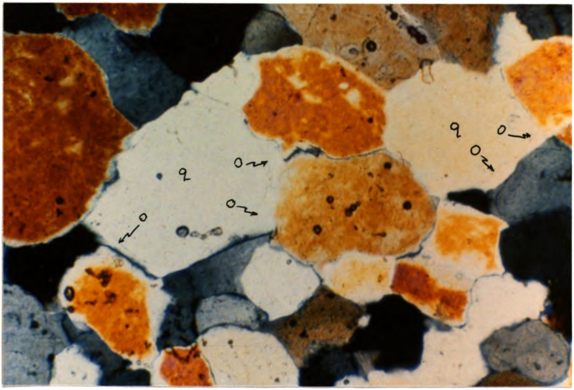


Plate 8. Photomicrograph of tight sand with syntaxial silica overgrowths from Fruedenberg 1-31 well core, Osceola County, and from approximately 9657' depth. Photograph frame is 1.0 mm x 1.5 mm. Labelled grains are indicated by: q = quartz grain; O = syntaxial silica overgrowth.

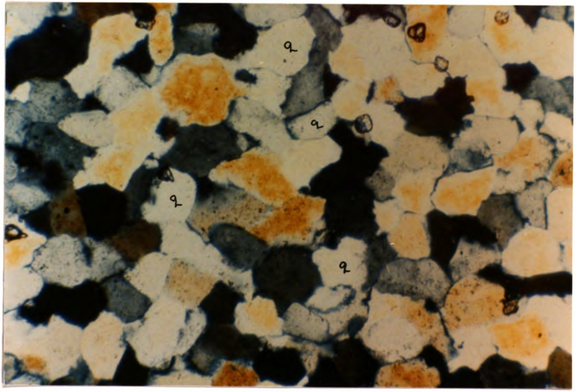


Plate 9. Photomicrograph of tight sandstone sample from Roseville Gun Club "B" 1-17 well core, Roscommon County, and from approximately 11,772' depth. Photograph frame is 1.0 mm x 1.5 mm. Quartz grains are indicated by the letter q.

spherical, with most grains ovate to nearly spherical. Grain roundness ranges from angular to rounded, with most from subangular to subrounded.

Grain sizes are also highly variable, depending on: (1) distance from source; (2) facies; and (3) diagenetic processes. As expected, farther south in the study area (Newaygo County) the sand grains are generally smaller than to the north. Here, the sand grains occur in the fine sand size fraction, however some medium size grains are also observed. To the north, however, grains are observed to range mostly from fine to medium sand sizes. In a few instances, some cross-bedded sandstones were observed to possess 2 mm sand grains.

The type of depositional facies, as described earlier, also appears to effect grain size through differences in energy of the depositional environment. The lagoonal and offshore facies described already generally have poorly sorted sediments with a wide range of grain sizes. These depositional environments characterized by lower energy conditions would not have been winnowed by strong water currents. On the other hand, the near shore and barrier-bar facies would leave coarser sediments reflecting their higher energy conditions.

Extensive silica cementation in the Prairie du Chien sandstones has produced grains which appear coarser because of syntaxial overgrowth.

Heavy minerals in the Prairie du Chien sands are infrequently observed. The most often observed heavy mineral is rutile, occurring in a needle-like form. Other observed heavy minerals include tourmaline and an occasional biotite flake.

Prairie du Chien sandstone matrix is also highly variable in abundance and mineralogy. Clay is present between the framework grains in many of the sandstones observed. The overall abundance of clay, determined by point counting, ranges from 0% to 35%. Typically, however, clay constitutes 5% to 10% of the clastic matrix. Clay is observed in some instances to be associated with presence of pressure solution and sutured framework grain contacts. In other instances, clay is observed as authigenic clay rims on framework grains.

Clay mineralogy is also variable. X-ray diffraction data reveal that several clay minerals are present in the Prairie du Chien sandstones. Clay separations were prepared from several of the porous and friable sand samples. In each sample, illite was present in some quantity. However, kaolinite and chlorite were sometimes observed to be present with the illite. The depths and temperatures from where the Prairie du Chien sandstone samples were taken preclude the existence of smectite and vermiculite type clay.

Several cement types are present in the Prairie du Chien sandstones. The most abundant cement type is syntaxial silica overgrowths (Plate 8 and 10). In many instances, silica cementation is very pervasive and produces very dense, tight sandstones. In these sandstones, effective porosity has been reduced essentially to zero. Typically, fine-grained poorly sorted, quartz sandstones have been observed to be more extensively cemented than are the coarser sandstones. The reasons for this are not altogether clear, but probably are related to the initiation of pressure solution in fine-grained lithologies, as previously suggested by Heald (1956) and Thomson (1959).

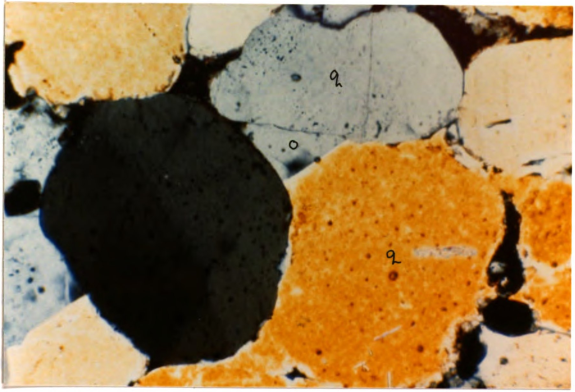


Plate 10. Photomicrograph of Prairie du Chien sandstone with syntaxial silica overgrowths. Sample from Dowker 2-21 well core, Otsego County, from approximately 7908' depth. Photograph frame is 1.0 mm x 1.5 mm. Labelled are: q = quartz grains; O = syntaxial silica overgrowths.

Clay minerals also appear to have acted as cement in some of the sandstones, but such sandstones are very friable and possess good porosity.

Dolomite cement is also present in the Prairie du Chien sandstones. Its distribution is erratic and somewhat problematic as it is usually observed in the upper portion of cores, close to the top of the Prairie du Chien. However, when dolomite cement is present it completely fills the pore spaces. Such dolomite cement is commonly coarsely crystalline, anhedral and is characterized by undulose extinction. The dolomite crystals are usually interlocking and very tight, with no observable porosity between them (Plate 11).

The distribution of dolomite cement in the Prairie du Chien sandstones suggests several possible origins for the dolomite. First, the dewatering of the overlying Glenwood and/or "Lower Glenwood" formations may represent a local source for the carbonate. Second, during sand deposition, some carbonate may have been forming also, filtering into the sands and becoming cement. And third, the dolomite cement may represent remnant Shakopee dolomite that was later significantly reduced in volume by pressure solution, and therefore is observed as dolomite between grains. Further work is needed here.

The porosity in the Prairie du Chien sandstones is highly variable. Overall, the growth of silica cement has the most influence on the loss of sandstone porosity. The porosity observed in the sandstones is exclusively intergranular and appears associated with the presence of clay minerals. Pores are typically less than 0.25 mm in diameter.

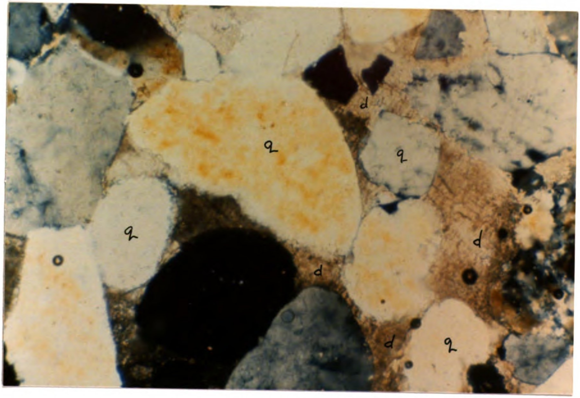


Plate 11. Photomicrograph of Prairie du Chien sandstone with dolomite cement, from Gilde 1-25 well core, Missaukee County, from approximately 10,547' depth. Photograph frame is 1.0 mm x 1.5 mm. Dolomite cement is indicated with the letter d, while q indicates quartz grains.

Lithologic Descriptions

A number of selected representative thin section descriptions are presented in Appendix C of this report. These demonstrate a wide variety of lithologies present in the Prairie du Chien Group sandstones. Four types of sandstones based on these thin sections are described below: (1) a sandstone tight with syntaxial silica overgrowths; (2) a sandstone showing pressure solution; (3) a sandy dolomite; and (4) a sandstone with some porosity.

Sandstones tight with syntaxial silica overgrowths are a very common lithology in the Prairie du Chien Group. A representative sample of this is illustrated in Plate 12. This sample is from the Roseville Gun Club "B" 1-17 well core, Roscommon County, from a depth of approximately 11,772'. Quartz is the predominant framework grain and comprises over 95% of the sample. Other framework grains include feldspar and rock fragments, but together they account for less than 1% of the sand. The remaining portion of the sample is silica cement. Mean grain size is 0.20 mm. Grain shapes range from subangular to subrounded. A rounded tourmaline grain is observed. Abundant silica cement is observed. This sample has no observable porosity.

The effects of pressure solution are also observed in some of the sandstones of the Prairie du Chien (Plates 13 and 14). This sample is from a depth of 10,166' 8" in the Bruggers 3-7 well, Missaukee County. Quartz predominates the framework grains comprising 90% of the sample, and is observed to be mostly monocrystalline, non-undulose in nature. Rock fragments and feldspar make up less than 1% of the framework

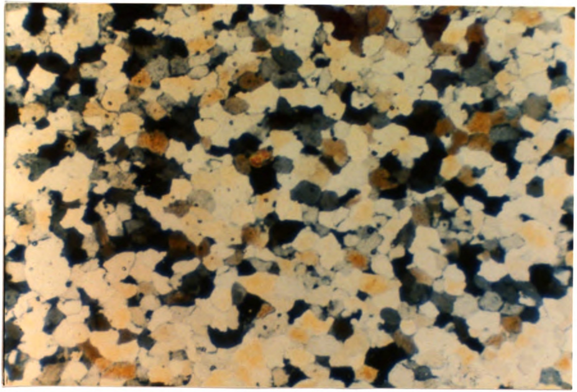


Plate 12. Photomicrograph of sandstone tight with syntaxial silica overgrowths from Roseville Gun Club "B" 1-17 well core, Roscommon County, from approximately 11,772' depth. Photograph frame is 2.5 mm x 3.8 mm. The grains are predominantly quartz, with one tourmaline grain observed in the center of the photomicrograph.

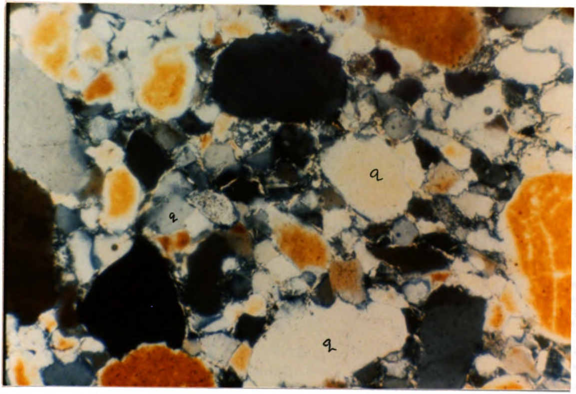


Plate 13. Photomicrograph of sandstone in the Prairie du Chien Group illustrating pressure solution. Sample from Bruggers 3-7 well core, Missaukee County, from approximately 10,167' depth. Photograph frame is 1.0 mm x 1.5 mm. Note clay between grains and the sutured grain contacts of framework grains. Quartz grains are indicated by the letter q.

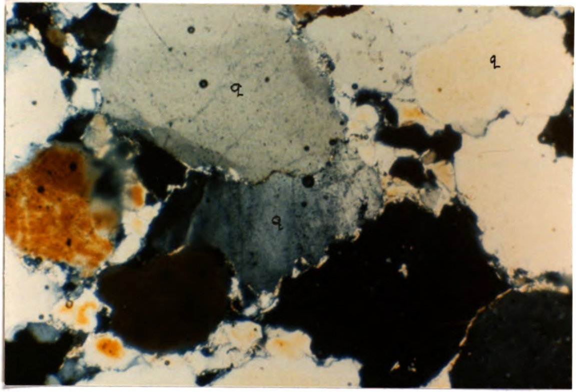


Plate 14. Photomicrograph of Prairie du Chien sandstone framework grains with sutured contacts because of pressure solution. Sample from Brinks 1-3 well core, Missaukee County, from approximately 10,785' depth. Photograph frame is 1.0 mm x 1.5 mm. The letter q indicates quartz grains. Note clay between framework grains.

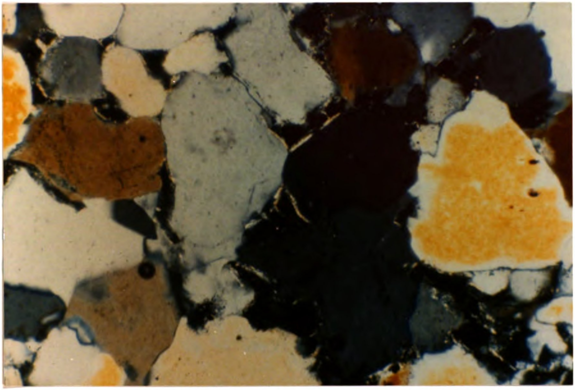
grains. Mean grain size is 0.32 mm, and the sorting is considered to be poor. Sand grains are subangular to subrounded. There is no observable porosity. Clay is abundant, constituting 10% of the sample. Grain edges appear sutured probably due to pressure solution.

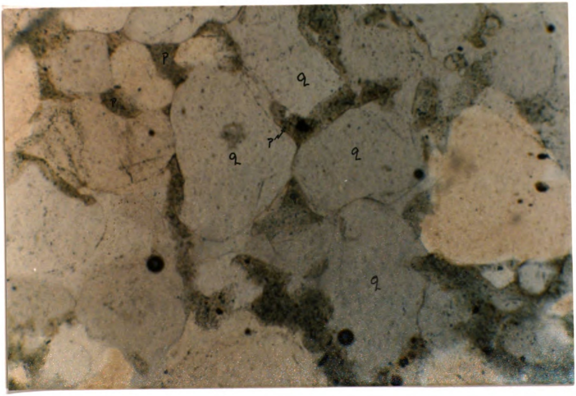
The most interesting lithologies in the Prairie du Chien sandstones are the sandy dolomites (Plate 6). A good example of this is from 9841' depth in the McCormick 2-27 well, Osceola County. Monocrystalline, non-undulose quartz is the most abundant grain type. However, these grains are "floating" in a dolomite matrix. Quartz makes up only 34% of this sample. The mean grain size is 0.26 mm, and they are subangular to subrounded in shape. The dolomite is medium to finely-crystalline, anhedral, and tightly interlocking, with no observable porosity present. This lithology might be interpreted by some to represent typical Shakopee dolomite of the Prairie du Chien Group. The only other examples of this type lithology were observed in the Fruedenberg 1-31 and Gray 1-31 well cores (also in Osceola County). Cuttings samples of the Anderson 1-8A and Michigan Consolidated Gas Co. 1-9 (Newaygo County) indicate that dolomite lithologies are also present.

Porous sandstones are also observed in the Prairie du Chien Group. Plate 15 is an example of this. This sample is from 10,831' in the Workman 1-31 well core, Missaukee County. Quartz is the predominant framework grain making up 93% of the sample and is observed to be mostly monocrystalline, and non-undulose. Mean grain size is 0.35 mm. The sorting is considered to be fair. Grains are subangular and subrounded. Porosity is measured by point counting to be 3%, however,

Plate 15A. Example of isolated, clay-lined pores in Prairie du Chien sandstones. Sample is from Workman 10-31 well core, Missaukee County, from approximately 10,831' depth. Photograph frame is 1.0 mm x 1.5 mm.

Plate 15B. Same as above, except under uncrossed nicols. Labelled are: q = quartz grains, p = pore. Note clay rims on framework grains.




P
q
P
q
q
q

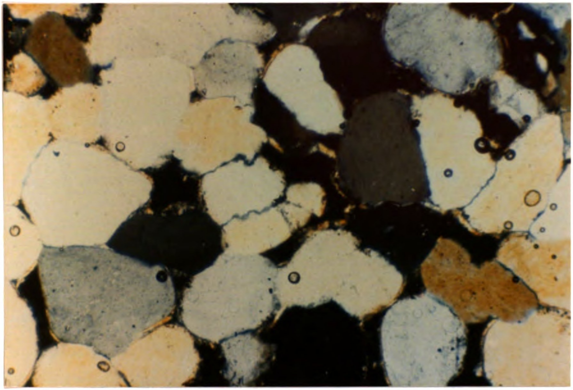
this figure appears to be low. Pores appear to be clay-lined. Some dolomite cement is observed in this sample. Plate 16 illustrates clay-line pores and this sample is also from the Workman 10-31 well core, but from approximately 10,963' depth.

Sedimentary Structures

Many sedimentary structures are observed in the Prairie du Chien sandstones. These features include: (1) low angle cross-beds (Plate 17); (2) laminations (Plate 18); (3) cross-laminated sandstone (Plate 19); and (4) some graded bedding.

Plate 16A. Example of isolated, clay-lined pores in Prairie du Chien sandstones, from Workman 10-31 well core, Missaukee County, from approximately 10,963' depth. Photograph frame is 1.0 mm x 1.5 mm.

Plate 16B. Same as above, except under uncrossed nicols. Labelled are: q = quartz grains, p = pore. Note clay rims on framework grains.



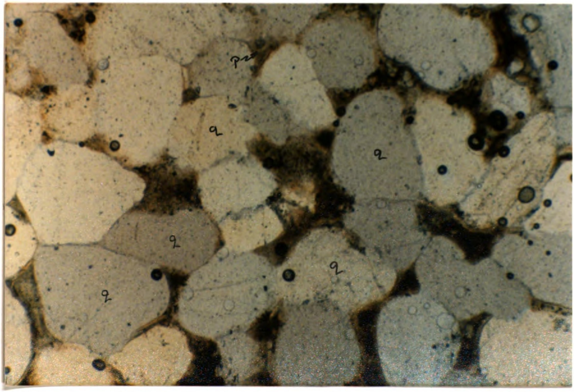

pz
q
q
q
q
q

Plate 17. Example of low angle cross beds from the Prairie du Chien Group. Sample is from Gilde 1-25 well core (Missaukee County), and from approximately 10,636' depth.

Plate 18. Example of laminated sandstone in the Prairie du Chien Group. Sample is from Gilde 1-25 well core (Missaukee County), and from approximately 10,598' depth.

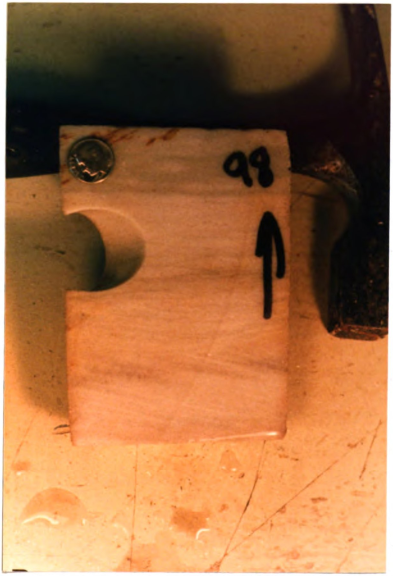


Plate 19. Example of cross-laminated sandstone in the Prairie du Chien Group. Sample is from Gilde 1-25 well core (Missaukee County), and from approximately 10,598' depth.

PRAIRIE DU CHIEN SANDSTONE POROSITY

Sandstone diagenesis has been the topic of much study in recent years, with most emphasis being placed on porosity retention, destruction, and development in relation to hydrocarbon reservoirs. Schmidt, McDonald, and Platt (1977) and Schmidt and McDonald (1979a, 1979b, and 1980) have stated that the amount of primary porosity in sandstones has been greatly overestimated because of the lack of recognition of secondary porosity in sandstones. The recognition of porosity types is of utmost importance in petroleum geology in order to understand reservoir history characteristics and quality.

The origin of porosity in the sandstone facies of the Prairie du Chien Group in the Michigan Basin is extensively debated at present. Because little previous work has been done on these sands, opinions concerning the Prairie du Chien sandstone porosity have been divided between two groups [Montgomery (ed.), 1984]. One group believes that the sandstone porosity is entirely retained depositional (primary) porosity. The primary porosity has escaped the detrimental effects that some types of diagenetic processes (compaction, pressure solution, and cementation) have on sedimentary rock pores. Another group, however, believes that secondary porosity development has produced the Prairie du Chien hydrocarbon reservoirs. Secondary porosity is here defined (Schmidt, McDonald, and Platt, 1977; Schmidt and McDonald, 1979a and 1980) as porosity produced by the removal of soluble rock constituents (mostly carbonate minerals) by acidic surface and ground water before effective burial began or after effective burial ended.

Between the above two groups, several theories concerning how the Prairie du Chien sandstone porosity was developed, have remained relatively untested. It is hoped that this study might be able to develop some conclusive information to explain the porosity of these sands, and from this an improved exploration strategy might be developed and implemented.

The first theory states that the porosity is secondarily developed and is directly related to the downward leaching effects of surface waters during the development of the post-Knox Unconformity [Montgomery (ed.), 1984].

The second theory (Syrjamaki, 1977) states that basinal fluids ascending along fractures also produced secondary porosity through leaching of the Prairie du Chien sands.

A third theory, somewhat similar to the first (above), contends that porosity may be secondarily developed by descending leaching fluids during the post-Knox erosional event but that production is limited to erosional "knobs" similar to the Copper Ridge (Cambrian) production in Morrow County, Ohio (Whiting, 1965; and Dolly and Busch, 1972).

These three theories require the presence of soluble sedimentary rock constituents and the movement of fluids with sufficient acidity to dissolve these constituents.

A fourth theory (Stelzer, 1982) postulated that porosity in the Prairie du Chien sands is retained depositional (primary) porosity which was preserved by the presence of clay minerals presumably inhibiting the nucleation and/or growth of pore-occluding silica cement.

A fifth theory [Montgomery (ed.), 1984] suggests that detrital chlorite rims (girders) hold apart the quartz sand grains thereby reducing the effects of silica cementation by pressure solution.

In order to establish which theory (or theories) is/are correct and to ascertain what geologic factors controlled the origin of the present porosity, it is necessary to first characterize the porosity as either primary or secondary. Following this, one may attempt to explain porosity development and distribution using geological phenomena which is considered to be most reasonable.

Discussion of Secondary Porosity

In recent years, secondary porosity has been considered more prevalent in sandstones than previously thought. In some instances secondary porosity forms the predominant type of porosity in hydrocarbon reservoirs. Schmidt and McDonald (1979a and 1980) have classified secondary sandstone porosity types into five classes, each of which can be recognized in thin-section. The five genetic-textural classes of secondary sandstone porosity can be differentiated on the basis of process of origin and textural relations (Schmidt and McDonald, 1980; Figure 20 of this report):

1. porosity created by fracturing--this type includes any newly formed fractures including those created by stresses resulting from the shrinkage of rock constituents or whole rocks;
2. shrinkage porosity--this porosity type is formed through the dehydration and/or recrystallization of a number of minerals such as glauconite and hematite. Shrinkage fractures are not included here, but in the above textural class. Shrinkable constituents occur in rocks as framework grains, parts of grains, matrix, authigenic cement, or authigenic replacement. It perhaps should be mentioned here that shrinkage porosity which occurs in the epigenetic dolomitization process of limestone according to some workers is not under consideration here as the Prairie du Chien dolomite (matrix here) is considered early diagenetic in origin and therefore preconsolidation where any potential shrinkage would not be manifest as voids in the non-rigid carbonate muds;
3. porosity created by dissolution of sedimentary material--this type of porosity results from the selective removal of soluble grains and/or soluble matrix. The dissolution of carbonate constituents is by far the most common form of this type of secondary sandstone porosity;
4. porosity originating from dissolution of authigenic cement--this type of porosity is possibly the most important textural class of secondary porosity developed in sandstones. The majority of dissolved cements consist of the mineral calcite, dolomite, and siderite;

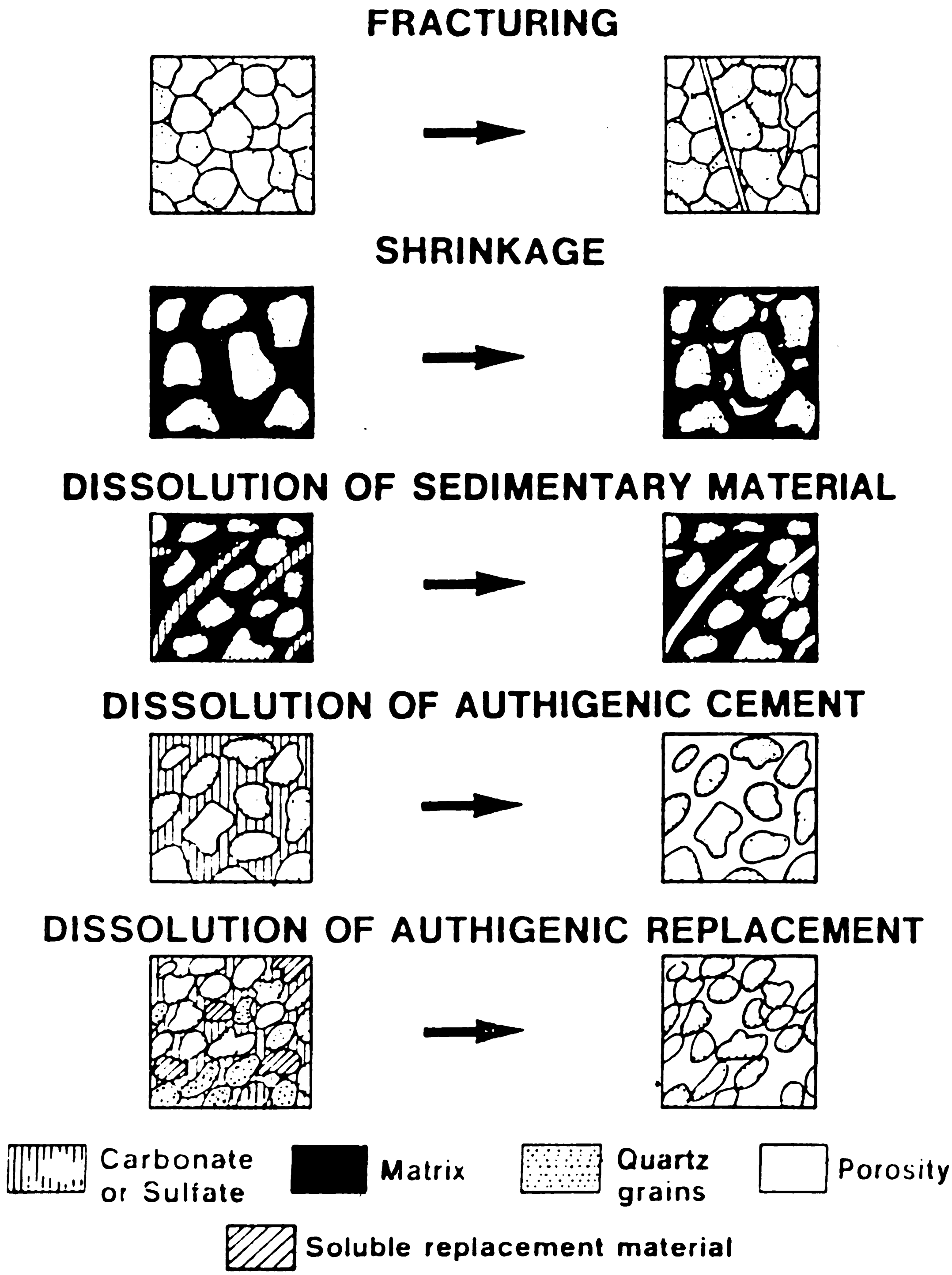


Figure 20. Genetic classes of secondary sandstone porosity (after Schmidt and McDonald, 1980).

5. porosity resulting from dissolution of authigenic replacive minerals--this type also forms a significant portion of secondary porosity in sandstones. It is formed by the selective dissolution of soluble minerals, dominantly calcite, dolomite, and siderite that previously had replaced sedimentary framework constituents, matrix, and/or authigenic cements.

Combinations, or hybrids, of these pore classes may also occur in sandstones (Figure 21; Schmidt and McDonald, 1980).

Schmidt and McDonald (1979a and 1980) further recognize five types of secondary sandstone porosity textures. These pore textures can be differentiated in sandstones and was based, in part, on the nomenclature used to describe carbonate pore textures (Choquette and Pray, 1970). These groups include the following (Schmidt and McDonald, 1979a and 1980):

1. intergranular pore textures--this includes pores between grains. The pores may be lined by cement. Three types of intergranular pore texture are observed: (a) regular intergranular; (b) reduced intergranular; and (c) enlarged intergranular.
2. oversized pore textures--this includes pores that are larger than adjacent grains by a factor of 1.2. This does not include fracture porosity. Two types of oversized pore textures are described: (a) oversized fabric-selective; and (b) oversized cross-cutting.

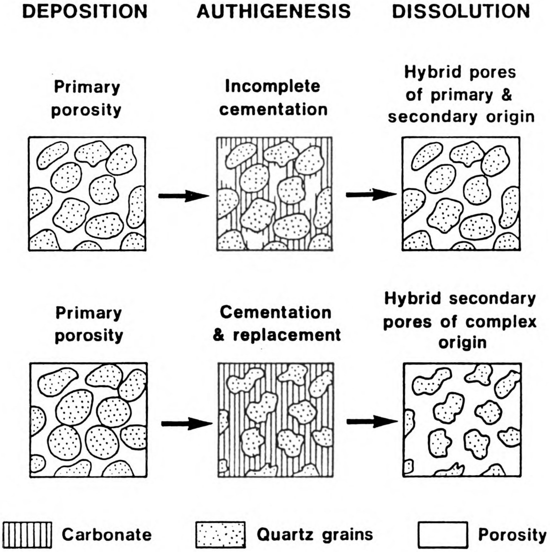


Figure 21. Textural development of hybrid pores (from Schmidt and McDonald, 1980).

3. moldic pore textures--this pore class shows the outline of dissolved rock constituents. Three types of moldic pore textures are recognized: (a) grain molds; (b) cement molds; and (c) replacement molds;
4. intra-constituent pore textures--this includes all pores contained within the sedimentary rock constituents. Four types have been recognized: (a) intragranular; (b) intra-matrix; (c) intra-cement; and (d) intra-replacement;
5. fracture pore textures--this includes all parting or separation by fracturing of a rock. Three types of fracture pore textures are recognized: (a) open rock fractures; (b) open grain fractures; and (c) open intergranular fractures.

Recognition of secondary sandstone porosity is very critical in determining what factors controlled porosity development. However, as stated previously, secondary porosity has been little recognized in sandstones possibly owing to its misidentification as primary porosity (Schmidt, McDonald, and Platt, 1977; and Schmidt and McDonald, 1979a, 1979b, and 1980). As a consequence, Schmidt and McDonald developed a list of criteria used to recognize secondary sandstone porosity (Figure 22; Schmidt and McDonald, 1980). To help in recognition of these criteria, Schmidt and McDonald recommend vacuum impregnation of sandstone samples with blue stained epoxy.

The carbonate minerals calcite, dolomite, and siderite are the most commonly affected sedimentary rock constituents. Feldspar dissolution also occurs but plays a subordinate role by volume to the

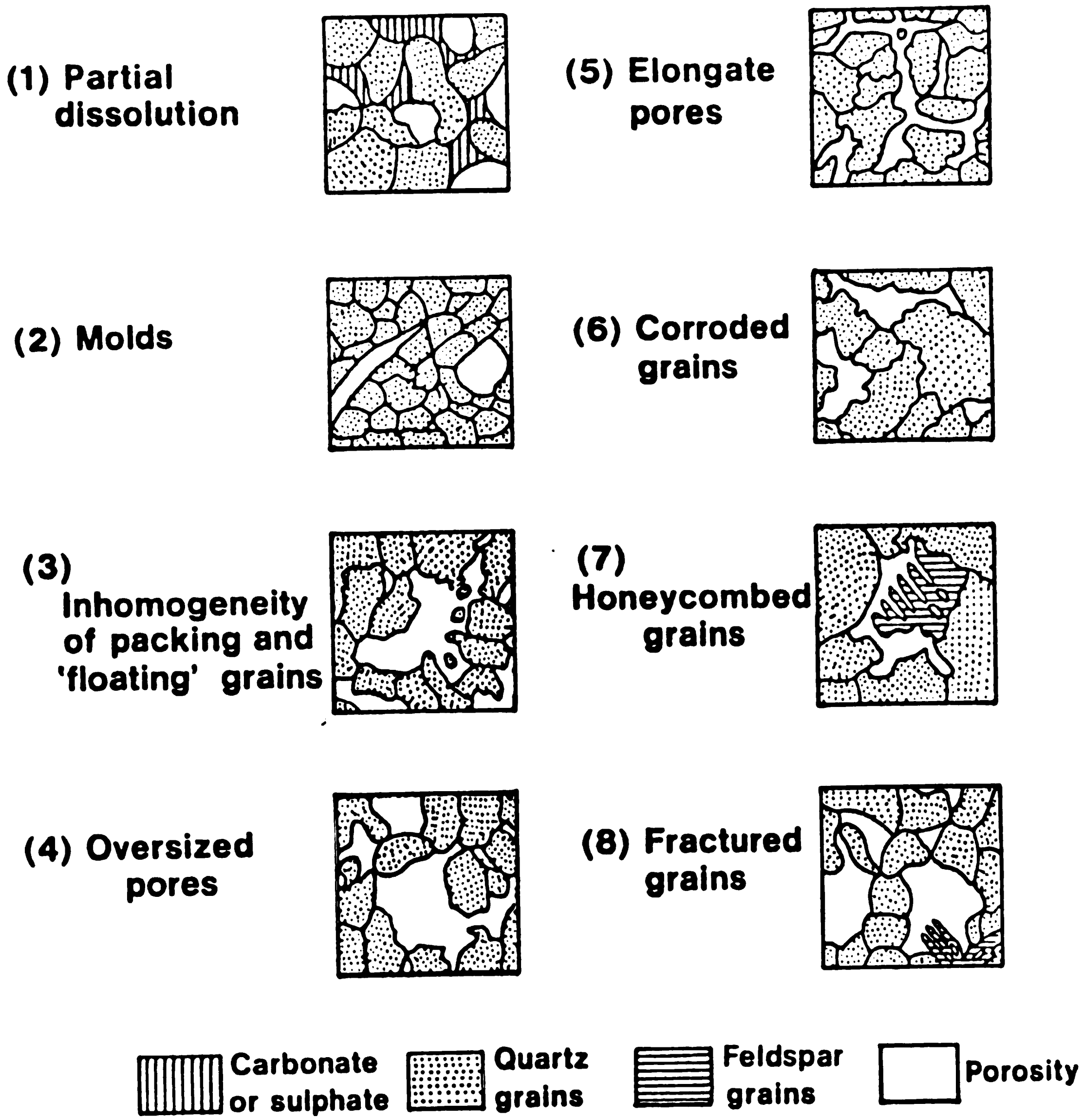


Figure 22. Petrographic criteria for recognition of secondary sandstone porosity (after Schmidt and McDonald, 1980).

amount of carbonate dissolution in secondary sandstone porosity. Most other minerals are not dissolved significantly enough to produce an appreciable amount of secondary sandstone porosity (Figure 23; Schmidt and McDonald, 1980).

Secondary sandstone porosity may occur anywhere in the Earth's crust. Following the nomenclature of Choquette and Pray (1970), Schmidt and McDonald (1979a and 1980) described three diagenetic environments, which include: (1) diagenesis before effective burial in the environment of deposition (eogenetic); (2) diagenesis of any depth of burial above the zone of metamorphism (mesogenetic); and (3) diagenesis during exposure following a period of burial (felogenetic). Further, Schmidt and McDonald (1979a, 1979b, and 1980) pointed out that most secondary sandstone porosity is developed during the deep burial of rocks (mesogenetic environment) and is possibly closely related to the maturation and migration of hydrocarbons. It has been shown empirically (Tissot and Welte, 1978) that during hydrocarbon generation, significant amounts of carbon dioxide may also be produced. Additional CO_2 in subsurface brines would adjust solution pH's significantly enough to cause the dissolution of carbonate and feldspar minerals. In this way, the migration of hydrocarbons and development of secondary sandstone porosity may occur simultaneously.

To test the role that secondary sandstone porosity may have played in the development of Prairie du Chien Group reservoirs, one must first determine sandstone petrology. This subject has been discussed in the previous section. Then, after rock constituents are identified and

DIAGENETIC PROCESSES		PORTION OF SECONDARY POROSITY
	ROCK FRACTURING	* MINOR
	GRAIN FRACTURING	MINOR
	SHRINKAGE	* MINOR
DISSOLUTION OF	CALCITE	MAJOR
	DOLOMITE	MAJOR
	SIDERITE	MAJOR
	SULFATE	* MINOR
	OTHER EVAPORITES	* MINOR
	SILICATE	VERY MINOR
	OTHER NONSILICATE	VERY MINOR

* MAY BE OF MAJOR IMPORTANCE IN INDIVIDUAL STRATIGRAPHIC UNITS

Figure 23. Diagenetic processes creating secondary sandstone porosity (from Schmidt and McDonald, 1980).

their abundances determined (identifying constituents that would have most likely been affected by dissolution, shrinkage, or fracturing), it may be able to assess the significance of secondary sandstone porosity development. Using the criteria for the recognition of secondary porosity it should be possible to determine if secondarily formed pores are present and what relations pores have with surrounding rock constituents. If these criteria cannot be observed, i.e., those which indicate the presence of secondary sandstone porosity, then some alternative geologic interpretation must be considered to explain porosity in the sands, suggesting what factors may have controlled porosity development.

Discussion of Data

The presence of secondary porosity in the Prairie du Chien sandstones was evaluated in this study in order to test several of the theories concerning porosity in these sands (already discussed). Several of these theories were based on the presumption that porosity is secondarily formed by either descending or ascending fluids leaching dissolvable rock constituents. Rock constituent shapes, grain edges and contacts, and observable diagenetic effects were observed to test the possibility of secondary porosity development in the Prairie du Chien sands.

The framework constituents of the Prairie du Chien sands are predominantly quartz grains with minor amounts of feldspar grains. No detrital carbonate clasts were observed. These framework grains are observed to vary in roundness from angular to rounded; however, most occur in the range of subangular to subrounded. These grain shapes appear to be the result of: (1) transportation; (2) compaction; (3) pressure solution; and (4) silica cementation. These processes also have affected grain sphericity ranging from bladed and oblong to oval.

Several diagenetic processes are observed to affect the Prairie du Chien sands. The most pervasive process is the cementation of sand grains with syntaxial silica overgrowths. Silica cementation is observed in many instances and appears to be the process that has the most destructive effects on Prairie du Chien sandstone porosity. Other diagenetic processes include cementation by dolomite cement with occasional embayment of quartz grains by dolomite, and formation of authigenic clay rims of framework grains. No dissolution phenomena were observed to have affected the framework grains of the sands. In all instances, grain edges are very distinct forming sharp contacts with the surrounding rock constituents.

In several instances, dolomitic sands and sandy dolomite lithologies were observed. The dolomite crystals are anhedral, tightly interlocking and coarsely, crystalline with undulose extinction. Overall, these lithologies are very tight with no visible porosity. Dissolution of the dolomite was not observed.

Several cement types are observed in the Prairie du Chien sands. As previously mentioned, silica cementation has produced in some lithologies, a very dense, tight sandstone. In many instances, the sandstone porosity has been completely occluded by silica cement.

Dolomite cement is also observed in the sands; however, it is secondary in abundance to silica cement. Dolomite cement, when present, is also observed to completely occlude sandstone porosity. A third cement type is clay cement. Some lithologies contain a significant amount of clay between grains with little or no silica or dolomite cement present. Clay mineral species observed in the Prairie du Chien sands include illite (glauconite), kaolinite, and chlorite. The clay cement is presumed to be authigenic in nature. Again, dissolution is not observed to have affected the cements in the Prairie du Chien sands.

The amount of porosity in the Prairie du Chien sands is highly variable. Point counting reveals that porosity ranges from 0 to 8%. However, on compensated neutron porosity logs sand porosity is observed to be as high as 20%. Intergranular porosity is the only type observed in thin-section. The pore shapes and sizes are controlled by compactional effects and the shapes of surrounding framework grains and the presence of clay minerals and other types of cements. Pores appear to be clay lined (Plates 15 and 16). Pore size is variable, however usually less than 0.25 mm in diameter.

From the grain shape, grain edge, pore geometry and pore location data, secondary sandstone porosity does not appear to be important in the development of the Prairie du Chien sandstone reservoirs. The Prairie du Chien sand constituents are dominated by the presence of quartz framework grains, with significant amounts of syntaxial overgrowths present. These two constituents are not soluble enough to appreciably dissolve forming secondary porosity. Carbonate cement, when present, shows no evidence of dissolution. Also the dolomitic sands and sandy dolomites likewise show no secondary porosity development. Overall, porosity in the Prairie du Chien sands does not appear to have been formed by the dissolution of sandstone constituents. It appears that the presence or non-presence of syntaxial silica overgrowths in the Prairie du Chien sands is what determines whether the sands are dense, tight and non-porous or friable and porous. As porosity is found entirely as intergranular porosity, and appears to be closely associated with the presence of clay minerals, the data suggest that the Prairie du Chien sand porosity is retained primary (depositional) porosity that escaped the pore occluding effects of silica cementation (Stelzer, 1982). Stelzer believed that clay minerals inhibited the growth of silica cement.

Several factors have apparently acted to destroy or retain primary porosity in the Prairie du Chien sandstones.

First, compactional effects in the Michigan Basin cannot be overlooked. As overburden stresses increased from sediment loading, the sandstones of the Prairie du Chien were subjected to mechanical and chemical porosity reduction processes. Mechanical compaction, pressure solution and cementation are processes that can significantly alter the amount of primary porosity retained or destroyed in a sandstone (Houseknecht, 1984). Primary porosity may be reduced through mechanical compaction by one-third in some quartzose sandstones from an original porosity of 35% to 50% (Pryor, 1973). The two processes of mechanical compaction that reduce porosity are the reorientation and repacking of competent (brittle) framework grains and the plastic deformation of ductile grains like lithic fragments. As the sediment load increases, pressure solution and cementation may close pores, further reducing effective porosity to nearly zero. The process of pressure solution is well documented by Sibley and Blatt (1976).

Pressure solution has been studied extensively for some time. Taylor (1950) showed that the number of grain contacts increased with increasing depth of burial as a result of pressure solution. Heald (1956) illustrated that laminae of fine-grained clastic sands are more susceptible to pressure solution than are laminae of coarser-grained sands. It was suggested further that a small amount of clay between framework grains may promote the process of pressure solution (Heald, 1956; and Thomson, 1959). Maxwell (1964) suggested a decrease in quartzose sandstone perosity, with increasing burial depth and further suggested that the porosity loss was in part due to intergranular pressure solution.

Pressure solution had been considered for years to be a viable source of silica that precipitated as cement in some sandstones. However, Sibley and Blatt (1976) demonstrated that only one-third of the volume of silica cement in the Tuscarora sandstone of Pennsylvania can be accounted for by pressure solution. On the basis of that study, many workers have considered pressure solution to be a small contributor of silica to the cementation of sands, and therefore, many have looked elsewhere for cement sources.

As observed in many of the samples of the Prairie du Chien sandstones, the sandstones are highly indurated with silica cement in the form of overgrowths. Still, some effective porosity is observed in some of the sandstones.

Compactional differences, even from the sparse sample distribution in this study, can be suggested for the Prairie du Chien snads based on the depth of burial. The sandstones of the Jennings Petroleum discovery well (Anderson 1-8A) in Newaygo County show less compactional effects than those sandstones in the deeper basin. Porosity is reported to reach 20% in the Anderson 1-8A, with 240 milidarcies permeability [Montgomery (ed.), 1984]. Stuart Jennings (oral communication, 1985) has suggested that silica cementation (and perhaps pressure solution) is less pervasive in the sands of Newaygo County compared to the deeper basin sands. These differences may not be so much related to burial pressure as to the temperature and time of burial. Houseknecht (1984) postulated that for a given grain size, porosity is higher in sandstones of lower thermal maturity. As the Newaygo County Prairie du Chien sands are shallower than the deeper basin sands they should be expected to be less thermally mature (this is of course, assuming a fairly constant geothermal gradient over the Michigan Basin). The effect of pressure solution in these sands is presumed here to account for the difference observed in deeply buried versus shallower sands. It has been proposed (Houseknecht, 1984) that temperature exerts a fundamental influence on the occurrence of pressure solution in sandstones and, hence, porosity loss. Thus, a dichotomy of opinion could exist when this last observation is contrasted to the observation of Schmidt and McDonald (1979a, 1979b, and 1980) mentioned previously that secondary sandstone porosity is developed during deep burial. In any event the silica produced by pressure solution may remain locally in the sand and become a source for the silica overgrowths observed in the Prairie du Chien sandstones. Pressure solution effects are frequently observed in the Prairie du Chien sandstones (Plates 13 and 14) and may represent the silica source for the syntaxial overgrowths also observed in the sandstones (Plate 8).

Grain size, is a second factor that must be considered important for pore retention in the Prairie du Chien sandstones. Houseknecht (1984) has proposed that at any given sample locality, coarser sands will retain higher amounts of primary porosity than finer-grained sands, even though the coarser-grained sands contained a greater volume of cement. In general, this appears to be the case in the Prairie du Chien sands. The offshore facies recognized in this study are generally characterized by fine-to-medium-grained sands which have porosity greatly reduced by pressure solution and silica cementation. On the other hand, the coarser-grained lithologies, like barrier-bar facies and some lithologies of near-shore facies are less cemented, more friable and less indurated with silica.

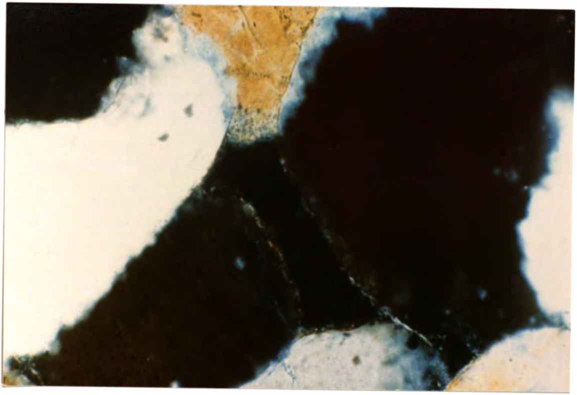
If less thermally mature, coarser-grained sandstones are more porous than thermally more mature or finer-grained sandstones, an ideal region in which to explore for good Prairie du Chien reservoir rocks would be in the northwest portion of the study area. In this region, the sandstones are closer to their source and, therefore, coarser than distal sands, and they are less deeply buried and therefore less thermally mature. The sands in this area would be expected to have retained a significant portion of their primary porosity, escaping some of the pore reduction effects of pressure solution. Also, the southwest portion of the study area offers an excellent area in which to explore for Prairie du Chien reservoirs based on present production in the area and that these sandstones are also expected to be thermally less mature than deeper buried sandstones.

A third factor that has apparently played a role in retaining porosity, especially in the deep basin sandstones, is the presence of authigenic clay rims on the sand grains. As noted before, porosity appears closely associated with the presence of clay minerals. On the basis of x-ray diffraction data illite, chlorite, and kaolinite are found to be the only clay minerals present. Clay usually appears as clay rims on framework grains. Stelzer (1982) was the first to conclude that the porosity observed in the Prairie du Chien sandstones was related to the presence of clay minerals, and this report concurs with that conclusion. The clay rims have apparently acted to preclude the pore reduction effects of silica concentration by inhibiting the nucleation and/or growth of silica overgrowth (Plates 20 and 21).

Fourthly, the presence of hydrocarbons in the sands has also acted to inhibit the pore destroying effects of silica cementation. As the clay rims "coated" framework grains, hydrocarbons also "coated" some grains and inhibited the nucleation and/or growth of silica overgrowths (Plates 22 and 23). The early migration of hydrocarbons along shear fractures (Prouty, 1970, 1976, 1980, and 1984) into shear folds in the basin might account for production being limited to the uppermost

Plate 20A. Close-up photomicrograph of isolated clay lined pore in Prairie du Chain sandstone. Sample is from Dalrymple 1-16, Roscommon County, and from approximately 11,155' depth. Photograph frame is 0.39 mm x 0.60 mm.

Plate 20B. Same as above, except under uncrossed nicols. Frame is slightly rotated compared to above photomicrograph.



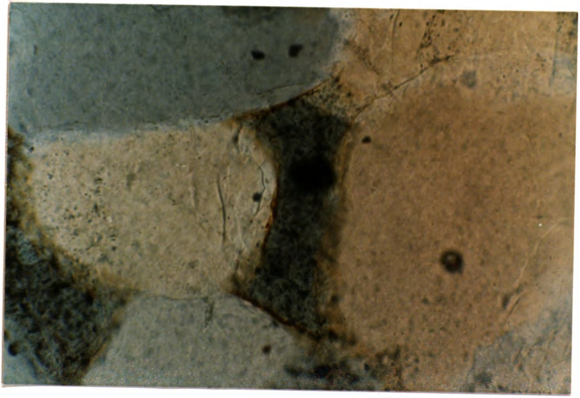
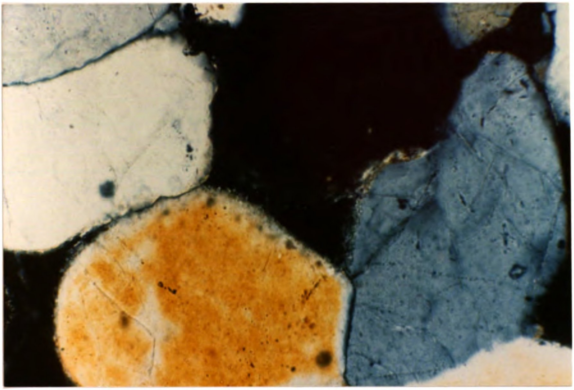


Plate 21A. Close-up photomicrograph of isolated clay-lined pore in Prairie du Chien sandstone. Sample is from Dalrymple 1-16 well core, Roscommon County and from approximately 11,155' depth. Photograph frame is 0.39 mm x 0.60 mm.

Plate 21B. Same as above, except under uncrossed nicols.



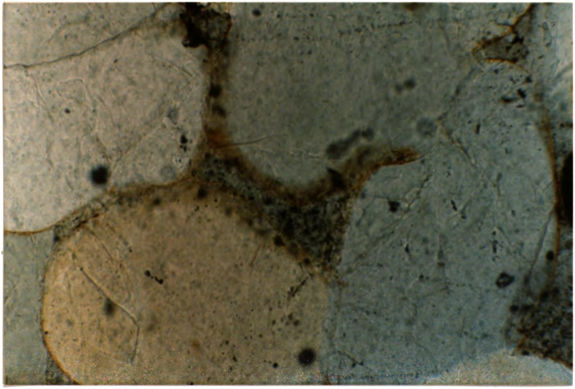
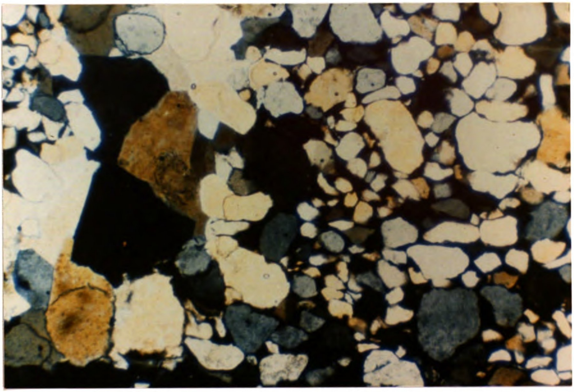


Plate 22A. Example of inhibiting effects on diagnesis of the presence of hydrocarbons in Prairie du Chien sandstones. Sample is from Dalrymple 1-16 well core, Roscommon County, from 11,057' 4" depth. Note the high degree of angularity of some of the grains, likely brecciated along a fault and offering a porous reservoir rock for the hydrocarbons. Photograph frame is 2.5 mm x 3.8 mm.

Plate 22B. Same as above, except under uncrossed nicols. The hydrocarbon is located beneath sand grains on the right hand side of the photomicrograph.



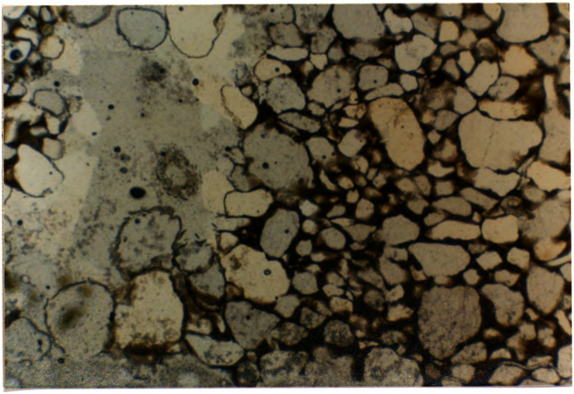
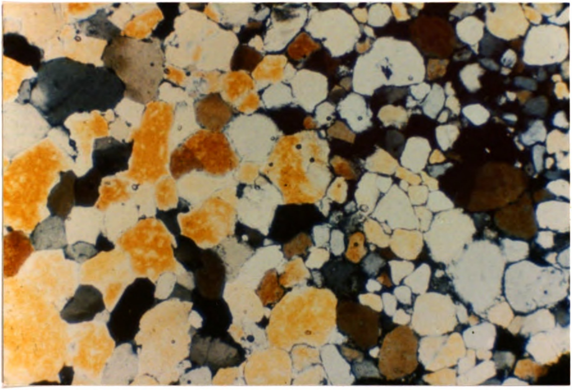
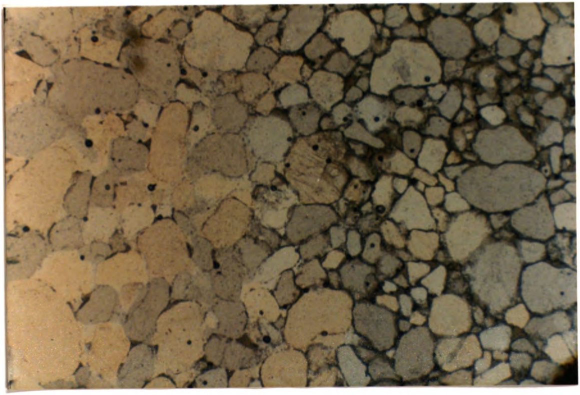


Plate 23A. Example of hydrocarbon inhibition on diagenesis of Prairie du Chien sandstone. Sample is from Roseville Gun Club "B" 1-17, Roscommon County, from approximately 11,723'. Note brecciated zone of angular fragments also a "reservoir rock" for hydrocarbons as observed in Plate 22A and B. Photograph frame is 2.5 mm x 3.8 mm.

Plate 23B. Same as above, except under uncrossed nicols. The hydrocarbon between grains is best observed in the upper right hand portion of the photomicrograph.





150 feet of the Prairie du Chien sandstones [Bricker et al., 1983 and Montgomery (ed.), 1984]. The hydrocarbons may have migrated into these structures before the time of extensive pressure solution and silica cementation of the Prairie du Chien sandstones in other areas.

As this study represents a reconnaissance study of the few available samples of the Prairie du Chien sandstones of the Michigan Basin, it is not intended to provide definitive answers regarding the porosity of the Prairie du Chien sandstones.

SUMMARY AND CONCLUSIONS

The theories about the origin of porosity in the Prairie du Chien sandstones can be tested by observing petrographic character of pore types and geometry, framework grains and their margins, and rock matrix and cement. On a larger scale the observation of cores can also help examine these theories.

From these observations it appears that secondary sandstone porosity does not play a principal role in the development of porosity in the Prairie du Chien sands.

In the Gilde 1-25 well (the only producing-well core studied), the post-Knox Unconformity was not observed. No clear cut discontinuity was seen between the Prairie du Chien and overlying "Lower Glenwood" formation. Therefore, there does not appear any support for the concept that sandstone reservoir porosity is related to the post-Knox erosional event here, or secondary porosity development by leaching of descending fluids.

To date, Prairie du Chien production has been restricted to the uppermost 150 feet of the sand, and is closely associated with structure (Figures 24, 25, and 26). However, porosity is not restricted to structure as previously thought. In 13 of the 14 cores examined, good zones of porosity were observed. The possibility that these sands might also have been hydrocarbon producers if on structure must be considered.

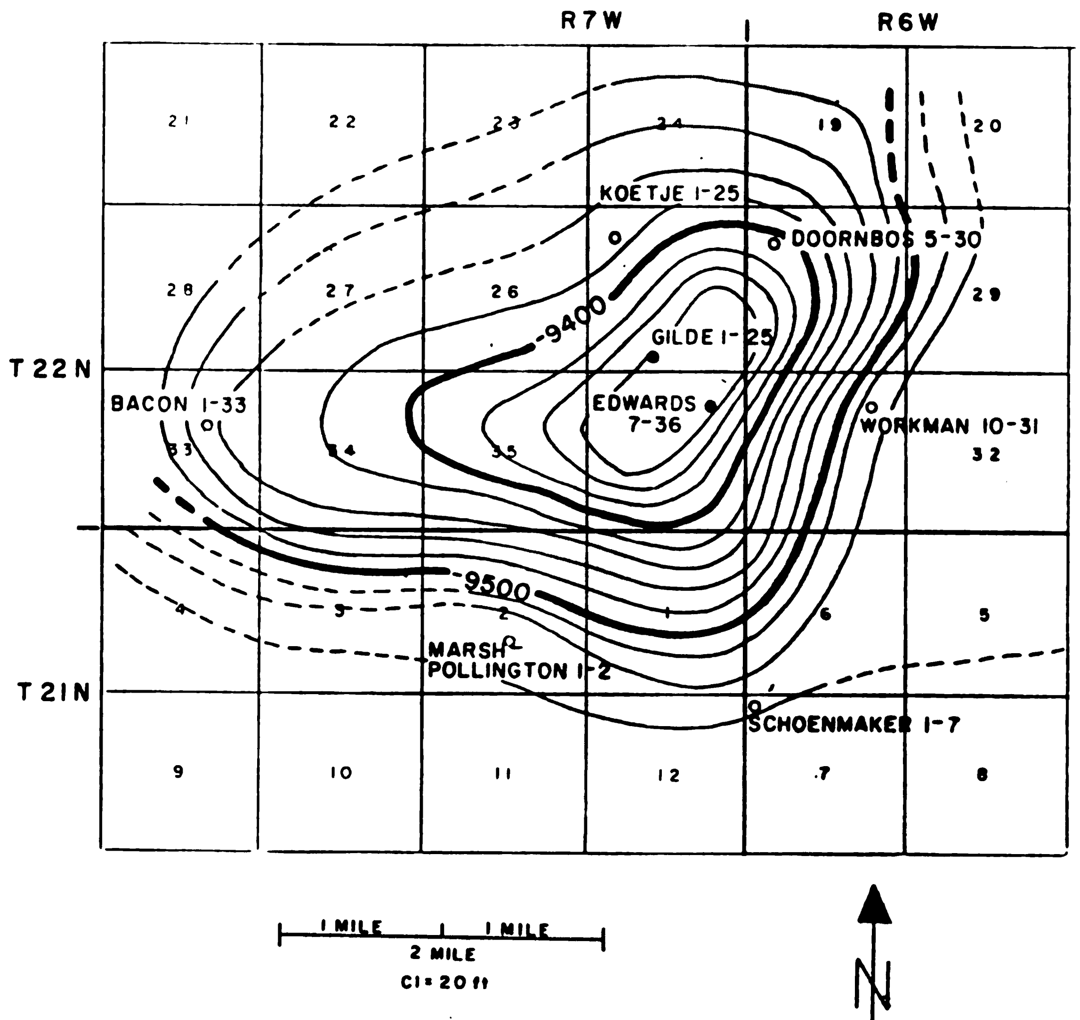


Figure 24. Structure contour of Prairie du Chien in Falmouth Field, Missaukee County.

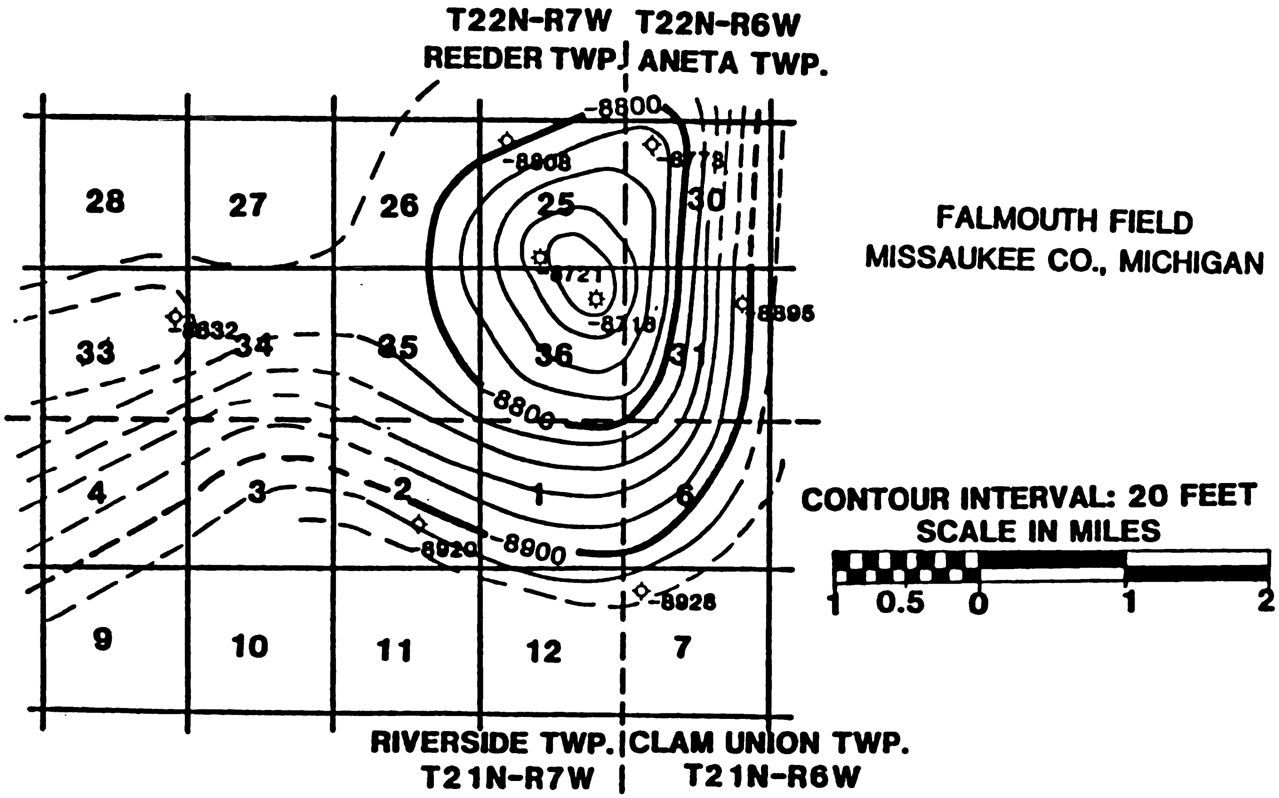


Figure 25. Structure contour of Trenton in Falmouth Field, Missaukee County (from Zwicker, 1983).

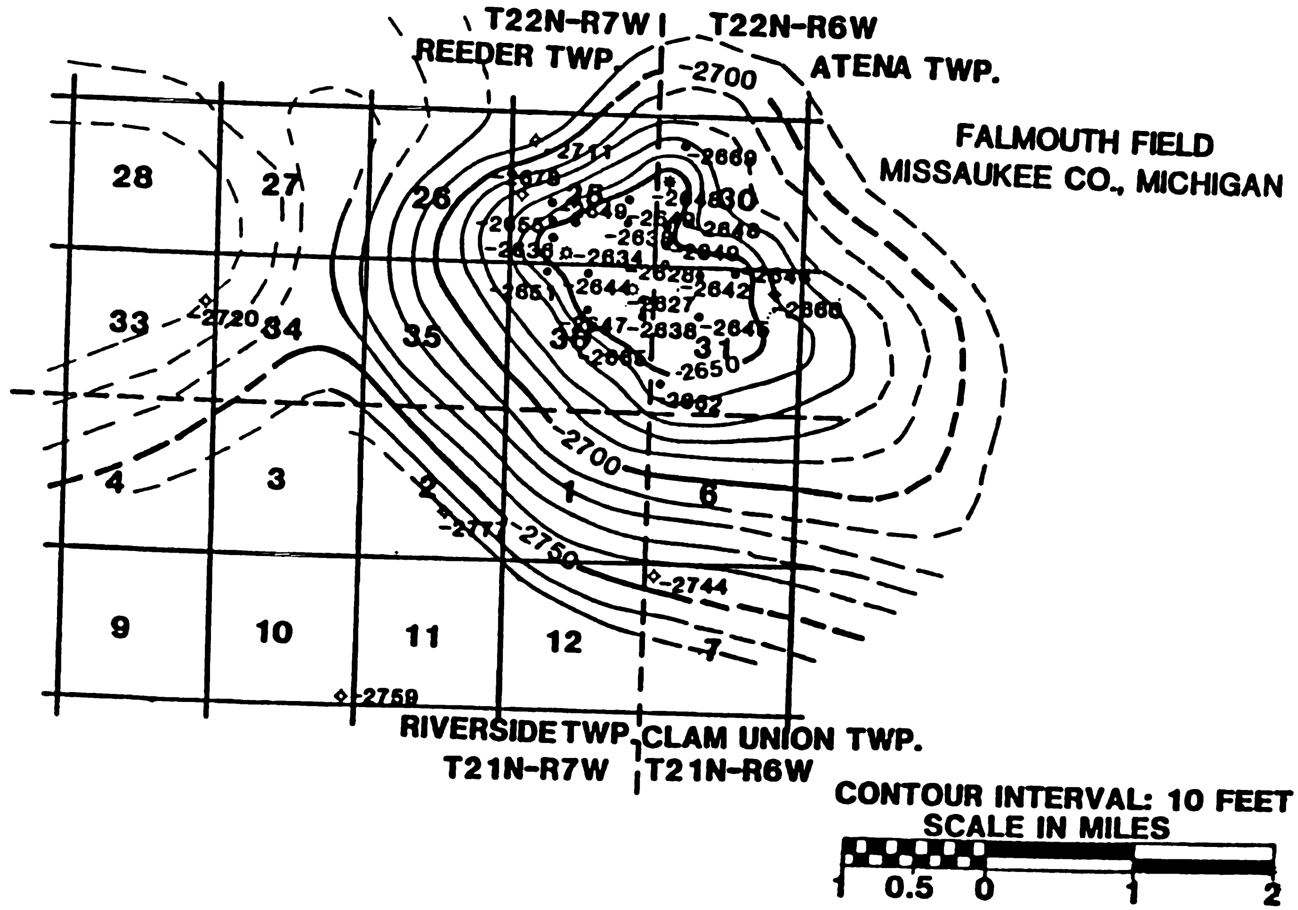


Figure 26. Structure contour of Dundee in Falmouth Field, Missaukee County (from Zwicker, 1983).

The porosity observed in the Prairie du Chien sands appears to be retained primary depositional porosity that escaped the detrimental, pore destroying effects of silica cementation. Porosity appears entirely intergranular and is closely associated with the presence of clay minerals, like illite, chlorite, and kaolinite. The clay is observed as authigenic clay rims on framework grains. This association suggests that clay minerals have inhibited the nucleation and/or growth of pore-occluding silica cement, as first suggested by Stelzer (1982). This report strongly supports Stelzer's work. Other factors that may have affected the retention of porosity in the Prairie du Chien sands include compactional effects, grain size, and the presence of hydrocarbons.

In conclusion, the hydrocarbon potential of the Prairie du Chien sandstones of the Michigan Basin appears good. More data will continue to accumulate with further testing of these strata. Deeper testing of shallow producing structures will remain the exploration strategy employed by explorationists until more data have accumulated to develop another technique.

APPENDICES

APPENDIX A

A DETAILED DESCRIPTION OF THE TYPE PRAIRIE DU CHIEN GROUP

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A DETAILED DESCRIPTION OF THE TYPE PRAIRIE DU CHIEN GROUP

A detailed measured section after Stark, 1949 is shown in Michigan Basin Geological Society Annual Field Excursion, 1960, C. E. Prouty (ed.)

A description of the Prairie du Chien Group type section, exposed in a quarry on north side of County Highway X in the NW¼ NW¼ Sec. 31, T. 6 N., R. 6 W., Elkader Quadrangle, Wisconsin.

Description modified after George Stark, 1949, Master's Thesis, University of Wisconsin.

Canadian Series
Prairie Du Chien Group
Shakopee dolomite

	Feet	Inches
Dolomite gray massive dolomite with some stringers of sandstone; gnarled appearance; in well developed one foot beds	10	--
Dolomite, gray, massive, brecciated throughout	--	11
Dolomite, gray, very fine grained, in thin beds separated by green shale partings	1	--
Dolomite, gray with buff mottling, in beds six inches thick and separated by gray shale	4	6
Dolomite, fine grained, light gray with orange-stained areas	--	11
Dolomite, gray, fine grained, thinly bedded and with green shale partings; floating grains of quartz sand	12	--
Dolomite, green, glauconitic, coarse grained	--	6
Dolomite, gray to reddish, fine grained; weathers to irregular surface	7	--

New Richmond sandstone:	Feet	Inches
Sandstone, white, weathers brown, in beds 4 inches to 1½ feet thick with interbedded fine grained dolomite	4	4
Oneota dolomite:		
Dolomite, light buff with dark specks throughout, in beds 3 to 6 inches thick separated by green clay partings	2	2
Dolomite, gray, fine grained, weathers to irregular surface; some algal structures	2	--
Dolomite, buff, relatively soft; algal structures profusely developed; in beds 3 to 4 feet thick with stringers of chert throughout; basal foot is weathered chert	29	4
Dolomite, conglomeratic with dark gray pebbles embedded in buff colored matrix; well bedded with some green shale partings and some clean white quartzose beds several inches thick	20	--
Sandstone, white, clean quartz grains of medium size; some green specks	1	8
Dolomite, gray, non-cherty, relatively soft, very massive; encloses some areas up to 15 feet in diameter of fine grained, gray-buff dolomite	54	--
Dolomite, very fine grained, undulating beds; includes white, gray, and black chert; cavernous	3	4
Dolomite, gray to buff, coarse grained; in 4 inch beds	1	6
Dolomite, gray to buff to orange colored, massive; includes some white chert and near the top some clay pockets	25	2

APPENDIX B

PRAIRIE DU CHIEN SANDSTONE

CORE DESCRIPTIONS

APPENDIX B

PRAIRIE DU CHIEN SANDSTONE
CORE DESCRIPTIONS

Brinks 1-3
PN 36786
Sun Exploration
T21N R6W Sec. 3 CNNENE

Very sharp contact exists between Prairie du Chien and overlying "Lower Glenwood" formation; top of the Prairie du Chien is picked in the core at 10,783' 5".

10,783' 5" to 10,818' 3"
sandstone, green to green-gray to gray to orange to orange-brown; fine to coarse grained; quartz sand; silica cement present; friable sand with some porosity; scattered glauconite (?) throughout, but very glauconitic at 10,787' 11" to 10,790' 8", 10,794' 7" to 10,799' 3", and 10,812' 11" to 10,814' 1"; laminated in places; vertical burrows observed; iron staining throughout; pyrite is observed at top of Prairie du Chien sand probably associated with erosional event.

Bruggers 3-7
PN 34078
JEM Petroleum Corp.
T24N R6W Sec 7 NESWNE

Top of Prairie du Chien picked in core at 10,157'. The contact with the overlying "Lower Glenwood" formation is gradational.

10,157' to 10,160'
sandstone, gray to black to brown to orange; fine to medium grained; coarse grained in places; quartz sand; tight with silica cement; no observable porosity; vertical burrows present; pyrite in top 1 inch of sand.

10,160' to 10,166' 6"
sandstone, gray to gray-pink to tan to brown; fine to medium grained; quartz sand; tight sand with silica cement; no observable porosity; vertical burrows present.

10,166' 6" to 10,170' 4"
sandstone, green to green-gray to gray to brown; fine to medium grained; quartz sand; silica cement; glauconitic (?); laminated; vertical burrows present; shale partings also present.

10,170' 4" to 10,202"
sandstone, green to green-gray to gray to pink to orange; fine to medium grained quartz sand; tight with silica cement; little observable porosity; finely disseminated glauconite (?) in places; laminated and cross bedded sand; some shale partings; vertical burrows and bioturbations present; iron staining also observed.

Dalrymple 1-16
PN 34537
JEM Petroleum Corp.
T22N R4W Sec. 16 NWNESE

11,012' to 11,052'
sandstone, green to green-gray to gray to white to pink to tan; fine to coarse grained; quartz sand; little cement; fair porosity; very glauconitic (?) from 11,012' 9" to 11,046' (corresponds to gamma-ray Kicks on log); some sand lamination present; some shale partings; burrowed and bioturbated sand; possible dead oil present.

11,052' to 11,157'
sandstone, white to yellow to tan to pink to rust/red to maroon; fine to medium quartz sand; well indurated with silica cement; little porosity; no observable clay; good cross bedding observed; some sand laminations also present; burrowed sand; heavily iron stained in places.

Dowker et al. 2-21
PN 35922
Reef-West Bay-Wainoco
T30N R1W Sec. 21 NWSWSE

Top of Prairie du Chien picked at 7891' in core, but has gradational contact with overlying "Lower Glenwood" formation.

7891' to 7902'
sandstone, green to gray-green to yellow to orange to tan; fine to medium grained; quartzose sand; tight sand (in places) with silica cement; fair porosity elsewhere; some clay present; laminations observed, also some low angle cross beds are present; bioturbation is observed.

7902' to 7928'
sandstone, white to white-yellow to yellow to tan; fine to medium grained; quartz sand; tight with silica cement, however some scattered porosity is observed; laminated and cross bedded.

<u>Fruedenberg 1-31</u>
PN 34558
JEM Petroleum Corp.
T17N R8W Sec. 31 SENENE

Top of Prairie du Chien picked in core at 9589' 11" (9590'); however, this is not a sharp contact, rather it appears very gradational with the overlying "Lower Glenwood" formation.

9590 to 9595'
sandstone, green to green-gray; fine to medium grained; quartz sand; little cement; friable sand; some porosity; glauconiteic (?) (corresponds well with gamma-ray Kicks on logs); some lamination present; burrowed and bioturbated; disseminated dead oil observed.

9595' to 9647'
sandstone to dolomitic sand to sandy dolomite, white to yellow-white to gray to brown; fine to coarse grained, very coarse in places; quartz sand; little porosity; fairly tight, clean sand; very well indurated with silica cement; scattered porosity appears associated with the presence of clay (glauconite ?); cross bedded and laminated in places; vertical burrows throughout and better cemented than surrounding sediment; some dead oil observed; dolomitic sand in places.

9647' to 9693' 3"
sandstone, green to green-gray to green-pink to pink; fine to medium quartz sand; little cement, friable sand; porosity throughout; clay present (glauconite ?); laminated sand; some burrows; traces of iron staining present.

9693' 3" to 9703' 8"
sandstone, pink to pink-green to green; very fine grained lithology, sandy in places; sand is quartzose; cement type is undifferentiable; no porosity is observed; scattered glauconite (?) and glauconitic chips; laminated in places.

9703' 8" to 9726'
sandstone, white to yellow-white to tan-yellow; fine to coarse grained; quartz sand; no observable porosity; fairly tight, clean sand; very well indurated with silica cement; cross bedded and laminated; vertical burrows observed.

Gernaat 2-19
PN 35781
ROM Energy
T20N R6W Sec. 19 SWSWNE
Prairie du Chien top 10,434' on drillers log

10,435' to 10,438' 6"
siltstone, black to gray-black to gray; very fine grained; bioturbated in places; shale partings in places.

10,438' 6" to 10,471'
sandstone, gray to gray-green to tan mottled sand; fine to coarse grained; quartz sand; not very indurated, friable sand; some silica cement; scattered porosity, associated with glauconite (?); glauconitic (?) from 10,445' 6" to 10,449'; bioturbated and well indurated burrows; shale interbeds and partings present.

10,471' to 10,533'
sandstone, yellow to brown to pink, white and gray; fine to medium grained; quartz sand; fairly tight sand with silica cement; some low angle cross beds; laminated in places; well indurated burrows.

Gilde et al. 1-25
PN 35899
Patrick Petroleum
T22N R7W Sec. 25 SESESW

10,540' to 10,542' 4"
sandstone, green-gray to gray to grapy-ink; fine to medium grained; quartz sand; tight with silica cement; no observable porosity; finely disseminated glauconite (?); bioturbated; patchy iron staining; possible pressure solution seams.

10,542' 4" to 10,545'
sandstone, green-gray to gray to pink-gray to pink to tan; fine grained; quartz sand; finely disseminated glauconite (?); bioturbated.

10,545' to 10,545' 5"
sandstone, green to green-pink to pink-gray to pink; fine to coarse grained; quartz sand; silica cement; disseminated glauconite (?); bioturbated.

10,545' 5" to 10,547'
sandstone, gray-green to gray to gray-black; fine to medium grained; occasionally coarse grained; quartz sand; silica cement; tight, with no observable porosity; disseminated glauconite (?), sometimes patchy; bioturbated; some iron staining observed.

10,547' to 10,547' 11"
sandstone, gray to brown; coarse grained; quartz sand; friable sand with little silica cement; good porosity; vertical burrows are well indurated.

10,547' 11" to 10,549' 4"
sandstone, green to green-gray to pink; fine to medium grained quartz sand; silica cement; fair porosity; glauconitic (?); burrowed and bioturbated.

10,549' 4" to 10,550' 9"
sandstone, gray to gray-brown to borwn; medium to coarse grained; quartz sand; silica cement; good porosity; vertical burrows are tightly indurated with silica.

10,550' 9" to 10,551' 5"
Absent section.

10,551' 5" to 10,552' 10"
sandstone, green to green-gray to gray; fine to medium grained quartz sand; silica cement; tightly indurated, no visible porosity; glauconitic (?) in places (especially from 10,552' to 10,552' 11"); bioturbated and burrowed.

10,552' 10" to 10,553' 1"
sandstone, green to green-gray to green-orange; medium grained; quartz sand; silica cement; tightly indurated with no observable porosity; disseminated glauconite (?); bioturbated; finely disseminated iron staining observed.

10,553' 1" to 10,554'
same as above, but green to green-gray to gray.

10,554' to 10,556' 7"
sandstone, gray; fine to coarse grained; quartz sand; very tightly induated with silica; friable in places; no observable porosity; finely disseminated glauconite from 10,555' 8" to 10,556' 2"; vertical burrows; iron staining observed.

10,556' 7" to 10,565'
sandstone, green to green-gray to orange-green to pink; fine to medium grained; quartz sand; fairly tightly indurated with silica cement; no observable porosity; disseminated glauconite (?); burrowed and bioturbated.

10,565' to 10,568' 6"
sandstone, gray to brown-gray to brown; fine to coarse grained; quartz sand; silica cement; fair porosity; slightly glauconitic (?); vertical burrows are well cemented with silica; bioturbated also; iron stain occurs as blobs.

10,568' 6" to 10,575' 10"
sandstone, gray to brown; medium to coarse grained; quartz sand; silica cement; good porosity in places; vertical burrows are observed; disseminated iron staining.

10,575' 10" to 10,576' 6"
sandstone, green to green-orange; fine to medium grained quartz sand; tightly indurated with silica cement; slightly glauconitic (?); laminated sand; bioturbated.

10,576' 6" to 10,589'
sandstone, green to green-orange to gray to pink-gray to pink; medium to coarse grained; quartz sand; silica cement; some porosity; patchy glauconite (?); burrowed and bioturbated.

10,589' to 10,596'
sandstone, green to gray-green to gray to gray-pink to pink to brown; medium to coarse grained; quartz sand; silica cement; tightly cement in places, friable and porous elsewhere; disseminated glauconite (?); laminated; burrowed.

10,596' to 10,658'
sandstone, white to yellow-white to yellow to orange to pink to pink-gray; fine to medium grained; quartz sand; silica cement; very tightly indurated; no observable porosity; finely disseminated glauconite (?); laminated and cross bedded; vertical burrows observed.

<u>Gray 1-31</u>
PN 35800
Willmet Oil and Gas
T17N R8W Sec. 31 NENWNW

9564' to 9586'
dolomite sand to sandy dolomite; gray to gray-green to pink to white; fine to medium grained; quartz grains; no observable porosity; bioturbated and burrowed; disseminated dead oil observed.

<u>Koetje 1-25</u>
PN 34927
JEM Petroleum Corp.
T22N R7W Sec. 25 SENWNW

Prairie du Chien top picked at 10,653' in core with gradational contact with overlying "Lower Glenwood" formation.

10,653' to 10,679'
sandstone, green to green-gray to yellow to pink; fine to medium grained quartzose sand; some silica cement; some porosity observed; glauconite (?) present; bioturbated with well induated burrows.

10,679' to 10,692'
sandstone, white to yellow-white to yellow to tan; fine to medium grained; quartz sand; tightly cemented with silica; no observable porosity; finely disseminated glauconite; laminated sand; some iron staining present.

McCormick 2-27
PN 34536
JEM Petroleum Corp.
T18N R8W Sec. 27 SWSENW

9725' to 9773'
sandstone, green to green-gray to gray to black to pink; fine to medium quartzose sand; little cement present; friable sand; glauconitic (?) (corresponds well with gamma-ray log response); some shale partings; burrowed and bioturbated; some disseminated dead oil present.

9773' to 9878'
sandstone to dolomitic sand to sandy dolomite, green to gray-green to gray to white to yellow-white to tan to pink; fine to medium grained; quartz sand; generally tightly indurated with silica cement but some scattered porosity is observed; some dolomite observed; slightly glauconitic (?); solution seams observed; laminated and cross bedded; some shale partings present; burrowed and bioturbated.

Roseville Gun Club "B" 1-17
PN 37409
Newport Petroleum
T21N R1W Sec. 17 ESSWNW

11,631' to 11,704' 6"
sandstone, green to green-brown to green-gray to gray; fine to coarse grained sand; very coarse in places; quartz sand; little cement; generally friable; good porosity; abundant clay (glauconitic ?); some low angle cross beds; bioturbated and burrowed; disseminated pyrite; some dead oil present; very glauconitic (?) from 11,636' 8" to 11,640' 6" and 11,644' to 11,645.

11,704' 6" to 11,772'
sandstone, yellow to white to yellow-white to yellow-green; fine to medium grained; quartz sand; heavily cemented with silica; very tight sand (little or no porosity); little observable clay, however some glauconite scattered, with associated porosity low and medium angle cross beds; some laminations present; very intensely burrowed; some bioturbation.

Visser 3-35
PN 34606
JEM Pet., Woods Pet., & Joutel Pet.
T22N R6W Sec. 35 NWSESE

10,836' 1" to 10,967'
sandstone, white to white-yellow to yellow-tan to tan-gray to pink; fine to medium grained; some coarse grained sections; quartz sand; tight sand; well indurated with silica cement; no observable porosity; scattered occurrence of glauconite (?); some laminations and cross beds; vertical burrows and bioturbation; Diplocraterion burrow observed at 10,879'; some shale partings present; finely disseminated iron staining throughout.

Weingartz 1-7
PN 34611
JEM Petroleum Corp.
T17N R4W Sec. 7 NENENE

10,747' to 10,795'
sandstone, green to green-black to tan; fine to medium grained; quartz sand; generally friable; spotty porosity with silica cement; glauconitic in places, especially from 10,776 to 10,787; laminated; some shale partings present; burrowed.

10,795' to 10,848'
sandstone, white to pink; fine to medium grained; quartz sand; heavily cemented with silica; little or no porosity, tight sand; some shale partings; bioturbated and burrowed.

10,848' to 10,855'
sandstone, green to green-gray to tan-gray to gray; fine to medium grained; quartz sand; friable porous sand; little silica cement; glauconitic in places; burrows present and well cemented with silica.

Workman 10-31
PN 34357
JEM Petroleum Corp.
T22N R6W Sec. 31 SWNENE

Top of Prairie du Chien picked in core at 10,738'. Contact with overlying "Lower Glenwood" formation.

10,728' to 10,733'
sandstone, green to green-gray to pink-gray; fine to medium grained; quartz sand; fairly tight with silica cement; finely disseminated glauconite (?); burrowed; some finely disseminated iron staining observed.

10,733' to 10,783'
Absent section.

10,783' to 10,838'
sandstone, gray to yellow to tan to pink; fine to medium sand; quartz sand; fiarly tight and dense with silica cement; porous and friable section from 10,801' 6" to 10,810'; few shale partings observed; some lamination present; vertical burrows and some bioturbation.

10,838' to 10,842'
Absent section.

10,842' to 10,956'
sandstone, white to gray-white to gray-yellow to yellow to pink-gray to pink; fine to medium grained; quartz sand; silica cement present; highly variable porosity in this section; fairly friable and porous sands; laminated sands; some thin shale partings; vertical burrows observed; finely disseminated iron staining.

10,956' to 10,971'
same as above but becomes very rust colored.

10,971' to 11,018'
sandstone, same as above, however, loses rust color becoming yellow to white to yellow-green again; some cross-bedding.

APPENDIX C

DESCRIPTION OF REPRESENTATIVE THIN SECTIONS OF PRAIRIE DU CHIEN GROUP SANDSTONES OF THE MICHIGAN BASIN

APPENDIX C

DESCRIPTION OF REPRESENTATIVE THIN SECTIONS OF PRAIRIE DU CHIEN GROUP SANDSTONES OF THE MICHIGAN BASIN

Well: Brinks 1-3 Sample Depth: 10,785' 3"

Grain Mineralogy: predominantly quartz with unit extinction; monocrystalline

Grain Size: $\overline{X}$ = .54 mm σ = .23 mm

Sorting: poor

Rounding: subangular to subrounded (mostly subangular)

Porosity: no observable porosity

Sedimentary Structures: some compactional alignment of grains

Accessory Minerals: clay present between grains

Comments: tight sand; pressure solution effects present; silica overgrowths observed; sutured grain contacts; small amount of dolomite cement present; possibly some "dead" oil; less than 1% feldspar + rock fragments; 92% quartz grains (+ silica) + 8% clay.

Well: Brinks 1-3 Sample Depth: 10,793'

Grain Mineralogy: quartz predominantly, with unit extinction; monocrystalline

Grain Size: $\overline{X}$ = .24 mm σ = .10

Sorting: poor to fair

Rounding: subangular to subrounded

Porosity: fair porosity

Sedimentary Structures: vague lamination, possibly compactional in nature

Accessory Minerals: some clay present

Comments: small amount of dolomite cement present; silica overgrowths observed; clay in pores appears to have inhibited silica cementation; 84% quartz (+ silica) + 6% clay + 3% dolomite cement + 7% porosity.

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Well: Bruggers 3-7 Sample Depth: 10,166' 8"

Grain Mineralogy: quartz predominates with unit extinction; monocrystalline

Grain Size: $\overline{X}$ = .32 mm σ = .19

Sorting: poor

Rounding: subangular to subrounded

Porosity: no observable porosity

Sedimentary Structures: none evident

Accessory Minerals: some clay present

Comments: some pressure solution observed; few silica overgrowths; less than 1% feldspar + rock fragments; 90% quartz grains (+ silica) + 10% clay.

Well: Dalrymple 1-16 Sample Depth: 11,057' 4"

Grain Mineralogy: quartz predominates; unit extinction; monocrystalline

Grain Size: $\overline{X}$ = .38 mm σ = .21

Sorting: --

Rounding: subangular to subrounded

Porosity: no observable porosity

Sedimentary Structures: none evident

Accessory Minerals: none observed

Comments: very tight sand; silica overgrowths present; some pressure solution with sutured grain contacts; very small amount of "dead" oil observed, appears to have inhibited silica cementation; less than 1% rock fragments; 100% quartz grains + silica.

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Well: Dowker et al. 2-21 Sample Depth: 7897'

Grain Mineralogy: quartz predominantly; unit extinction and monocrystalline

Grain Size: $\overline{X}$ = .13 mm σ = .08

Sorting: poor

Rounding: angular to subrounded

Porosity: no observable porosity

Sedimentary Structure: vague lamination, possibly due to compaction

Accessory Minerals: lots of clay present

Comments: clay appears to choke pores; less than 1% feldspar; possible "dead" oil along solution seam; 65% quartz grains + 35% clay.

Well: Fruedenberg 1-31 Sample Depth: 9596'

Grain Mineralogy: predominantly quartz grains with unit extinction; monocrystalline

Grain Size: $\overline{X}$ = .48 mm σ = .34

Sorting: poor to fair

Rounding: subangular to subrounded

Porosity: no observable porosity

Sedimentary Structures: none evident

Accessory Minerals: none observed

Comments: sandy dolomite lithology, possible "dead" oil present; most often quartz grains are observed to be "floating" in a dolomite matrix; 47% quartz grains + 53% dolomite matrix.

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Well Gilde 1-25 Sample Depth: 10,598' 11"

Grain Mineralogy: quartz grains predominate; monocrystalline quartz with some undulose grains

Grain Size: $\overline{X}$ = .45 mm σ = .15

Sorting: --

Rounding: subangular to rounded

Porosity: tight sand, no observable porosity

Sedimentary Structures: none evident

Accessory Minerals: no clay observed

Comments: very tight sand; highly compacted; quartz overgrowths present; less than 1% feldspar; 99% quartz grains (+ silica) + 1% rock fragments.

Well: Gray 1-31 Sample Depth: 9566'

Grain Mineralogy: quartz grains, with unit extinction; monocrystalline

Grain Size: $\overline{X}$ = .25 mm σ = .10

Sorting: fair

Rounding: subangular to subrounded

Porosity: no observable porosity

Sedimentary Structures: none evident

Accessory Minerals: none observed

Comments: sandy dolomite to dolomitic sand lithology; 58% quartz grains + 42% dolomite matrix.

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Well: McCormick 2-27 Sample Depth: 9766'

Grain Mineralogy: quartz predominates, with unit extinction and monocrystalline

Grain Size: $\overline{X}$ = .41 mm σ = .31

Sorting: fair to poor

Rounding: subangular to subrounded

Porosity: some porosity observed

Sedimentary Structures: some compactional alignment of grains

Accessory Minerals: small amount of clay

Comments: some dolomite cement present; some silica overgrowths observed, with possible pressure solution and suturing of grains; overall, sand appears fairly porous; 90% quartz grains (+ silica) + 6% dolomite cement.

Well: McCormick 2-27 Sample Depth: 9841'

Grain Mineralogy: quartz; monocrystalline, unit-extinction

Grain Size: $\overline{X}$ = .26 mm σ = .11

Sorting: poor to fair

Rounding: subangular to subrounded

Porosity: no observable porosity

Sedimentary Structures: none observed

Accessory Minerals: none evident

Comments: dolomitic sand to sandy dolomite; 34% quartz grains + 66% dolomite matrix.

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Well: Roseville Gun Club "B" 1-17 Sample Depth: 11,772'

Grain Mineralogy: quartz exclusively; unit extinction; monocrystalline quartz

Grain Size: $\overline{X}$ = .20 mm σ = .10

Sorting: --

Rounding: subangular to subrounded

Porosity: no observable porosity

Sedimentary Structures: compactional lamination

Accessory Minerals: tourmaline grain

Comments: very tight sand; silica overgrowths observed; sutured grain contacts, less than 1% feldspar plus rock fragments; less than 1% tourmaline; 99% quartz (+ silica) + 1% feldspar.

Well: Workman 10-31   Sample Depth: 11,083' 10"

Grain Mineralogy: predominantly quartz, with unit extinction; monocrystalline

Grain Size: $\overline{X}$ = .35 mm σ = .14

Sorting: fair

Rounding: subangular to subrounded

Porosity: fair amount of porosity

Sedimentary Structures: none evident

Accessory Minerals: some clay present, in the form of rims on framework grains

Comments: some pressure solution observed; sutured contacts; silica overgrowths present; small amount of dolomite cement observed; 90% quartz grains (+ silica) + 2% clay + 5% dolomite cement + 3% porosity.

APPENDIX D

WELL LOG DATA

O_{TR}	Depth to top of Trenton Group
O_{BR}	Depth to top of Black River Group
O_{GW}	Depth to top of Glenwood shale
O_{LGW}	Depth to top of "Lower Glenwood" formation
O_{PdC}	Depth to top of Prairie du Chien Group
O_{Tr}	Depth to top of Trempealeau formation

*Indicates producing well.

PN	Well Name	Operator	T	R	Sec.	¼ ¼ ¼	Elev.	O_{TR}	O_{BR}	O_{GW}	O_{LGW}	O_{PdC}	O_{Tr}
						Alcona County							
34931	State Mitchell 1-31	Gulf	26N	5E	31	CNNENE	986	8,679	8,930	9,285	9,311	9,419	10,345
						Alegan County							
21865	Noteboom 1	Strake & Basin Oil	2N	11W	18	NESWNW	823	3,762	4,064	4,263	--	4,277	
31991	Schipper 1-18	Miller Bros.	2N	11W	18	SWNENW	818	3,768	4,070	4,272	--	4,300	
23361	Green 1	Republic	2N	11W	30	SSWSW	826	3,688	3,992	4,186	--	4,201	
23685	Simpson 1	Continental	2N	12W	10	NWNESE	827	3,754	4,062	4,237	--	4,262	
24323	Marshall 1	Smith, R.C.	2N	12W	24	NWSWSW	836	3,694	4,004	4,194	--	4,204	
21684	Boss 1	Strake	2N	12W	25	SENWNE	847	3,717	4,024	4,215	--	4,224	
32870	Hoffmaster 1-22	Michigan Oil Co.	3N	12W	22	NENESW	739	3,791	4,104	4,290	--	4,303	
21930	Robinson 1	Taggart	3N	14W	20	NWSENE	678	3,380	--	3,849	--	--	
32648	Dehaan 1	Michigan Oil Co.	4N	11W	29	NESESW	772	4,098	4,418	4,613	--	4,624	
						Alpena County							
36758	Snowplow 1-5	Brown, H.L.	29N	5E	5	SESWNW	792	6,538	6,742	7,080	7,098	7,187	
25690	Ford Motor 1-5	Panhandle East. Ppl.	31N	9E	5	CNSENE	697	4,802	5,023	5,310	--	5,339	5,804
29571	Sheldon-State Wellington 1-34	Shell	32N	5E	34	SWSWSW	756	5,367	5,609	5,865	5,892	5,921	
						Antrim County							
35702	Visser 1-27	Shell	30N	7W	27	SWNENE	731	6,774	6,954	7,151	--	7,173	
10004	Chamberlain 1	Ohio Oil Co.	31N	8W	14	SSWSE	738	5,754	--	6,076	--	6,093	
22639	Wolgamo 1	Lindsay, Forrest	32N	8W	19	NWNWSE	878	5,393	5,578	5,737	--	5,755	
						Arenac County							
34973	Hagley 1-21	N.R.M. Pet.	19N	5E	21	CNSESE	629	10,236	10,573(?)	--	--	11,058(?)	
						Barry County							
22170	Sharkey-Mustard 1	Peak Petroleum	1N	7W	19	NWNWNE	900	4,207	4,530	4,775	--	4,790	
153BD	Fee BD 2	Battle Creek Gas Co.	1N	8W	14	SESENE	942	4,196	4,515	4,756	--	4,767	5,352
27731	Willison 1	Miller Bros.	1N	9W	23	NESENE	964	4,043	4,373	4.590	--	4,597	
28494	Pennoch 1	Kelly Oil	2N	7W	11	ESWSE	844	4,523	4,864	5,111	--	5,117	
28493	Hollister 1	Kelly Oil	2N	7W	13	NWNESW	917	4,567	4,898	5,156	--	--	
21999	Schantz 1	McClure	2N	7W	22	CNNENW	969	4,567	4,907	5,152	--	5,162	
29092	Kopf 1	Peninsular Oil & Gas	2N	7W	36	SESESE	959	4,497	4,841	5,081	--	5,091	
20732	Hibbard 1	McClure	2N	9W	34	NESWNE	976	4,198	4,523	4,732	--	4,753	
21987	Bahs 1	Benedum-Trees Oil	3N	7W	22	CNNENE	908	4,843	5,211	5,420	--	5,444	
23589	Brooks 1	Indiana Farm Bureau	3N	7W	24	NWSWNE	950	4,917	5,268	5,518	--	5,527	
30137	Timm-Kennedy 1-14	Amoco	3N	8W	14	SENWNW	927	4,739	5,078	5,314	--	5,322	
18526	Robertson 1	Rex Oil and Gas	3N	9W	4	SESWSW	818	4,435	--	--	--	5,007	
7873	Kidder 1	Sun Oil	3N	9W	8	NWNWNW	796	4,387	--	--	--	4,960	
9618	Mead 1	Sun Oil	3N	9W	10	SWSWSW	817	4,473	4,835	5,020	--	5,031	

PN	Well Name	Operator	T	R	Sec.	¼ ¼ ¼	Elev.	0_{TR}	0_{BR}	0_{GW}	0_{LGW}	0_{PdC}	0_{Tr}
					Barry County--Continued								
24504	Afman 1	Sun Oil	3N	10W	12	NENENE	776	4,308	4,639	4,860	--	4,872	
23572	Schaibly 1	McClure	4N	7W	20	SESENW	882	5,047	5,392	5,635	--	5,643	
23363	McClellan 1	McClure	4N	8W	3	NWSESE	882	5,037	5,376	5,614	--	5,653	
23573	Allerding	McClure	4N	8W	20	SESESE	864	4,822	5,160	5,388	--	5,397	
					Bay County								
5441	Bateson 1	Gulf	14N	4E	2	SSESE	599	9,400	--	10,338	--	10,361	
37779*	Prevost 1-11	Shell	14N	4E	11	SENENE				Tight Hole			
				Reported a producing well									
					Charlevoix County								
34824	N.M.L.O. Corp. 1-27	Energy Acquis.	32N	4W	27	NWSENW	1145	6,295	6,493	6,656	6,680	6,697	7,501
36260	Bradfield 1	Sun Oil	32N	4W	33	SESWNW	1195	6,290	6,493	6,650	6,668	6,690	7,502
29079	Hand 1	Benedum & MGU Devel.	34N	7W	13	NENENE	743	4,625	4,802	4,950	4,969	4,984	
29119	Clark 1	Benedum & MGU Devel.	34N	7W	14	CNSENW	717	4,602	4,790	4,930	--	4,948	
23478	State Beaver Island 2	McClure	37N	10W	6	NESWSE	743	3,007	3,204	3,305	3,316	3,325	
23681	Goddard et al. 1	McClure	37N	10W	19	SWNENE	661	3,054	3,254	3,358	3,369	3,380	3,820
23435	State Beaver Isand 1	McClure	38N	10W	27	NENENW	680	2,876	3,073	3,177	3,187	3,194	
					Cheboygan County								
35060	Salling-Hanson 1-11	Sun Oil	34N	2W	11	SWSENW	813	4,440	4,623	4,804	4,825	4,841	5,392
33156	Sand Mold Sys. Inc. 1-9	Mutch, J.O.	35N	1W	9	SSENE	904	4,188	4,375	4,550	4,572	4,588	
37730	Sand Mold Sys. Inc. 1-15	Mutch, J.O.	35N	1W	15	NESESE	895	4,348	4,579	4,678	--	4,702	
29611	Whitener 1-16	Hilliard	35N	1W	16	SENWSW	840	4,339	4,524	4,656	4,676	4,692	
30682	State Waverly 1-24	Northern Mich. Expl. Co.	35N	1W	24	NESWNE	801	4,189	4,375	4,555	4,580	4,600	5,081
					Clare County								
34611	Weingartz 1-7	JEM Pet. Corp.	17N	4W	7	NENENE	1004	9,965	10,260	10,590	10,633	10,767	11,772
34790	Brandt 1-34	Dome Pet.	17N	6W	34	SWNW	1121	9,687	9,377	10,250	10,298	10,407	11,356
36666*	Lease Mngmt. et al. 1-12	Hunt Energy	20N	6W	12	SWNWNW	1163	10,020	10,273	10,575	--	10,690	
			708 Mcfgd + 31 bwpd Initial Production										
35781	Gernaat 2-19	ROM Energy	20N	6W	19	SWSWNE	1166	9,793	10,047	10,307	10,357	10,457	
33680*	Winterfield Deep A-1	Hunt Energy	20N	6W	30	NESENW	1158	9,902	10,158	10,444	10,477	10,580	11,742
				190 Mcfgd Initial Production									

PN	Well Name	Operator	T	R	Sec.	¼ ¼ ¼	Elev.	0_{TR}	0_{BR}	0_{GW}	0_{LGW}	0_{PdC}	0_{Tr}
						Clinton County							
27811	Fox 1	McClure	7N	1W	6	SWSESW	773	6,812	7,253	7,750	--	7,756	
						Crawford County							
35587	State Beaver Creek 1-5	Miller Bros.	25N	3W	5	CN2NE	1277	9,572	9,787	10,075	10,109	10,173	
28110	State Beaver Creek C 4	Union Oil of Calif.	25N	4W	21	WNESW	1239	9,380	9,754	9,883	9,916	9,958	
						Eaton County							
27766	Whittum 1	Trolz and Assoc.	1N	3W	3	WSWSE	907	4,857	5,230	5,513	--	5,523	
29059	Holcomb 1	Peninsular Oil & Gas	1N	4W	19	SESFSE	945	4,555	4,914	5,183	--	5,193	
35258	Coats 1-26	Trendwell	1N	4W	26	SENESE	947	4,611	4,973	5,250	--	5,258	
28163	Sheets 1	Bag Mining Co.	1N	5W	17	NENWNE	883	4,502	4,854	5,116	--	5,176	
28263	Scheeberger-Murphy 1	M.I.O. Expl.	1N	5W	27	NENENE	920	4,482	4,836	5,095	--	5,105	
30291	Snow 1-28	Fortuna & Sokolowski	1N	5W	28	NWSESW	910	4,405	4,735	5,013	--	5,024	
22487	Hickok 1	Kelly Oil	1N	5W	30	NWNWNW	885	4,400	4,748	5,003	--	5,015	
22497	Palmer-Miller 1	Fulk, Perry	1N	6W	2	SESESW	948	4,554	4,904	5,160	--	5,168	
22541	Black 1	Lawton & Hack Drlg.	1N	6W	17	CNSWNW	954	4,408	4,752	4,995	--	5,006	
27898	Yeomans 1	Fortuna Oil	1N	6W	24	SENWSW	875	4,376	4,748	4,965	--	4,989	
27628	Koch 1	Perry, C.A. & Son	1N	6W	25	NWNWSW	921	4,382	4,705	4,982	--	4,993	
36319	Jones Unit B 3	Amoco	2N	3W	7	NWSENW	923	4,997	5,467	5,712	--	5,719	
29117	Kelly 1	Mobil	2N	3W	24	WNENW	870	5,067	5,449	5,743	--	5,751	6,429
22672	Lamont 1	Petrolia Corp.	2N	5W	18	SWSESW	925	4,754	5,108	5,370	--	5,380	
30214	Ripley 1-25	Wenner Pet.	2N	6W	25	NWNENE	926	4,690	5,043	5,303	--	5,315	
						Genesee County							
24079	Hutchinson 1	Dugger, Herring and Wells	9N	8E	4	ESWSW	827	7,473	7,952	8,450	--	8.456	
						Gladwin County							
35090	Martin 1-15	Hunt Energy	17N	1E	15	NENWNE	735	10,347	10,703	11,090	11,139	11,305	12,432
37582*	Letts Unit 2-36	Amoco	18N	1W	36	SESESW	756	10,323	10,667	11,043	11,090	11,255	
			4.4 Mmcfgd + 72 bcpd Initial Production										
						Grand Traverse County							
34132	Weber-Sheren 6-9	Shell	25N	11W	9	SWSWSE	1101	7,690	7,865	8,045	--	8,064	
34292	State Blair 2-24	Shell	26N	11W	24	SWSENE	915	7,294	7,462	7,645	--	7,662	8,683
						Gratiot County							
29739	Sparks et al. 1-8	McClure	10N	2W	8	NESWNW	762	7,792	8,193	8,528	--	8,539	9,070

PN	Well Name	Operator	T	R	Sec.	¼ ¼ ¼	Elev.	O_{TR}	O_{BR}	O_{GW}	O_{LGW}	O_{PdC}	O_{Tr}
					Huron County								
29191	Volmering 1	Mobil	15N	15E	26	NENENE	711	6,371	6,822	7,285	--	7,290	8,180
					Ingham County								
29416	Hasbrook 1	Mobil	1N	1W	35	SESESE	984	4,915	5,280	5,631	--	5,638	
29672	Reeve 1	Mobil	1N	1W	36	CNSESW	977	4,913	5,318	5,637	--	5,645	
22607	Basore	Ketchum, Ralph	1N	2E	13	NWNWNW	963	4,577	5,017	5,430	--	5,437	
24470	Wild 1	Ambassador Oil Corp.	1N	2E	31	CNSENE	944	4,978	5,430	5,769	--	5,777	
28607	Krantz 1	Mobil	2N	1W	29	NE	939	5,213	5,611	5,913	--	5,920	6,400
24518	Harkness 1	Pure Oil	2N	2W	16	NENENE	916	5,217	5,571	5,912	--	5,917	
28929	Seibly 1	Hibbard Oil Corp.	2N	2W	33	SSWSE	937	5,023	5,376	5,707	--	5,717	
					Ionia County								
23482	Troyer 1	McClure	5N	8W	28	SWSENE	816	5,055	5,390	5,633	--	5,642	
27700	Possehn 1	Hunting Oil Co.	6N	6W	31	CNSWSW	873	5,625	5,978	6,242	--	6,248	
27441	Sprague 1	Moore, Joe, Inc.	6N	8W	4	WNWNE	705	5,472	5,806	6,048	--	6,056	
25025	Burtle 1	Ambassador Oil Corp.	6N	8W	4	CNNENE	718	5,496	5,830	6,073	--	6,080	
24619	Ten-Cate 1	Ambassador Oil Corp.	7N	8W	34	CNSESW	775	5,551	5,886	6,132	--	6,141	
26990	Essington 1	An-Son Corp.	7N	8W	35	CNNWSW	819	5,659	6,017	6,242	--	6,248	
					Kalkaska County								
33596	Borgen 1-30	Strickler	25N	7W	30	NENENE	1091	9,302	9,496	9,733	--	9,765	
34208	Consumers Pwr. 1-34	JEM Pet.	25N	8W	34	NWSWSW	1018	8,867	9,059	9,282	--	9,308	
34613	State-Blue Lake 3-23	Shell	28N	5W	23	NENWNW	1315	8,643	8,841	9,063	--	9,093	
					Kent County								
BD156	Alto 2-156	Ohio NW Devel. Inc.	5N	9W	3	NNENE	830	5,064	5,398	5,623	--	5,644	6,054
11540	Sherk 1	Smith Pet.	5N	10W	21	CNSESE	758	4,550	--	--	--	5,112	
26946	Wingeier 1	An-son Corp.	7N	9W	2	CNSENW	857	5,742	6,068	--	--	6,328	
9166	Riddering 1	Producer Committee	7N	12W	30	ESESE	739	4,614	--	--	--	5,132	
24826	Ten Have 1	Ambassador Oil Corp.	8N	9W	6	CNNWSE	867	5,913	6,243	6,478	--	6,487	
24627	Francisco 1	Ambassador Oil Corp.	8N	9W	35	CNNWNE	872	5,829	6,160	6,397	--	6,404	
26908	Parmeter	An-son Corp. et al.	9N	10W	26	CNSESE	911	5,994	--	6,564	--	6,570	
27296	Goss 1	Beacon Resources	9N	10W	35	CNSENW	944	5,967	6,287	6,517	--	6,543	
					Lapeer County								
37408	Jager 1-25	Shultz, Frank	8N	12E	25	SENENE	813	5,847	6,337	6,844	--	6,852	
					Leelanau County								
22627	Kirt 1	Lindsay, Forrest	30N	11W	6	NWSWSE	925	5,387	5,610	5,725	--	5,740	
					Livingston County								

PN	Well Name	Operator	T	R	Sec.	¼ ¼ ¼	Elev.	O_{TR}	O_{BR}	O_{GW}	O_{LGW}	O_{PdC}	O_{Tr}
31961	American Agg. 1-13	Arbuckle	1N	6E	13	NWNESW	940	4,646	5,053	5,554	--	5,564	
26999	Kish 1	Texaco	1N	6E	14	SWNWSW	936	4,539	4,980	5,335	--	5,343	
24771	Lopez 1	Strake	1N	6E	14	NESENW	929	4,634	5,073	5,484	--	5,493	
34878	Wech 1-14	Sukenik, John T.	1N	6E	14	NWSWSW	913	4,687	5,129	5,578	--	5,587	
27720	American Agg. 1	Texaco	1N	6E	15	CNNWNE	910	4,590	5,050	5,526	--	5,537	
31695	Reed 1-25	Arbuckle	1N	6E	25	SENWSE	931	4,569	4,978	5,478	--	5,486	
36447	Cameron 1-10	Kullen and Schmidt	2N	3E	10	NESWSE							
28752	Kleinschmidt 1	Patrick Pet.	2N	3E	17	NWNWNE	960	5,056	5,504	5,891	--	5,899	
16067	Wilson-Bush 1	Panhandle East. Ppl.	2N	4E	12	SENWNE	934	4,834	5,172	5,735	--	5,742	
25868	Kizer 1	Brazos	2N	4E	14	SWSWNE	938	5,342	5,807	6,218	--	6,227	6,450
29051	Ganton 1	Musk, Rousek, Mutch	3N	3E	1	NWSWSW	920	4,798	5,212	5,654	--	5,660	
23374	Soule 1	Humble Oil	3N	3E	2	CNNENE	939	4,744	5,231	5,600	--	5,604	
31900	Rhodes 1-30	North. Nat. Gas	3N	3E	30	NENENE	927	5,767	6,204	6,580	--	6,586	
2179	McPherson 1	Panhandle East. Ppl.	3N	4E	35	NENENW	914	4,981(?)	--	--	--	5,890(?)	
27986	Messmore 1	Mobile	3N	5E	11	NENWNE	980	5,290	5,765	6,197	--	6,207	6,443
22642	Scepka	White, Joe B.	4N	3E	28	NENWNE	899	5,116	5,592	5,946	--	5,975	
37893	Laier 1-23	Yohe Ent.	4N	5E	23	NENWNE	935	5,713	6,205	6,644	--	6,653	7,023
						Macomb County							
36238	Cusamano and Divito 1-22	Patrick Pet.	3N	13E	22	SWNWSW	618	3,604	4,077	4,468	--	--	4,481
22825	Nitaro 1	Mich. Cons. Gas Co.	3N	13E	34	NESWNE	600	3,620	4,061	4,528	--	--	4,536
26214	Halmich 3-1	Consumers Power Co.	4N	13E	1	SWNWSE	690	4,220	4,680	5,128	--	--	5,141
29008	Pellerito 1	Cowen and Gordon	4N	13E	29	NESWNW	668	4,104	4,512	5,062	--	--	5,075
29024	Pellerito 2	Cowen and Gordon	4N	13E	29	NESWNW	671	4,111	4,570	5,038	--	--	5,045
22439	Heide 1	Panhandle East Ppl.	5N	13E	7	NESWSE	785	4,730	5,200	5,689	--	--	5,696
33737	Grierson 1-24	Energy Acquis.	5N	14E	24	SENWSW	739	4,174	4,625	5,053	--	--	5,067
						Manistee County							
35882	USA, State, Norman et al. 1-29	Gulf	21N	14W	29	SWSENW	756	6,356	6,538	6,692	--	6,706	
34277	Maidens 5-25	Shell	23N	15W	25	NENWSW	764	6,032	6,206	6,349	--	6,365	
30502	State-Springdale 5-31	Miller Bros.	24N	14W	31	NWNE	748	5,996	6,171	6,323	--	6,331	
						Mason County							
29503	Kissel & Gahr 1	Van Raalte	17N	16W	18	SWSWSE	718	5,495	5,671	5,800	--	5,836	
18905	Sippy 17	Superior Oil	17N	16W	25	NESWSW	726	5,605	5,796	5,933	--	5,952	6,983
32020	Schultz and Lundberg 1-35	Kirby Expl.	17N	17W	35	CNWNW	685	5,236	5,413	5,524	--	5,537	
17789	Dow-Brazos-Taggart 1	Brazos	19N	18W	27	SENENE	647	5,093	5,254	5,354	--	5,360	
32224	Carnagel Oil & Ass. 2-30	Miller Bros. & Total	20N	17W	30	SWNENE	669	5,216	5,376	5,490	--	5,495	

PN	Well Name	Operator	T	R	Sec.	¼ ¼ ¼	Elev.	0_{TR}	0_{BR}	0_{GW}	0_{LGW}	0_{PdC}	0_{Tr}
32471	Carnagel Oil & Ass. 3-30	Miller Bros	20N	17W	30	NWNESE	668	5,156	5,316	5,426	--	5,433	
						Mecosta County							
35259	Wager 2-12	Dome Pet.	14N	7W	12	SESWNW	1103	8,783	9,095	9353	9,398	9,484	
						Missaukee County							
36786	Brinks 1-3	Sun Expl.	21N	6W	3	CNNENE	1198	10,120	10,370	10,685	10,724	10,768	
34964	Schoenmaker 1-7	Page Pet and KEP Res.	21N	6W	7	NWNWNW	1184	10,110	10,356	10,633	10,666	10,743	
35021	Marsh-Pollington 1-2	Petromax Oil & Gas	21N	7W	2	SWNWSE	1188	10,107	10,347	10,624	10,656	10,734	
36173	Kuipers "A" 1-29	Cities Service Co.	21N	8W	29	CNNWSE	1446	9,896	10,113	10,369	10,399	10,482	
34376	Doornbos 5-30	JEM Pet.	22N	6W	30	SENWNW	1232	10,005	10,245	10,483	10,518	10,626	11,913
34357	Workman 10-31	JEM Pet.	22N	6W	31	SWNENE	1206	10,102	10,347	10,622	10,654	10,737	
34606	Visser 3-35	JEM, Woods, Joutel	22N	6W	35	NWSESE	1177	10,170	10,415	10,703	10,743	10,822	
34927	Koetje 1-25	JEM Pet.	22N	7W	25	SENWNW	1239	10,047	10,282	10,552	10,590	10,664	
35899	Gilde et al. 1-25	Patrick Pet.	22N	7W	25	SESESW	1215	9,936	10,172	10,413	--	10,554	
34511	Bacon 1-33	Hobson Pet.	22N	7W	33	NESENE	1210	10,042	10,278	10,545	10,577	10,655	
33963*	Edwards 7-36	JEM Pet.	22N	7W	36	SWNENE	1209	9,925	10,165	10,418	10,442	10,548	
			12.3 Mmcfgd Initial Production										
34078	Bruggers 3-7	JEM Pet.	24N	6W	7	NESWNE	1289	9,655	9,871	10,095	10,122	10,153	11,470
						Montmorency County							
34648	State-Albert 1-10	Shell	29N	2E	10	CNSWSE	1200	7,757	7,962	8,255	8,264	8,311	
						Muskegan County							
18666	Nelson 1	Taggart	12N	17W	20	NESWNW	666	4,387	4,504	4,723	--	4,737	
						Newaygo County							
22918	Seaman 1	Miller, Gene, Inc.	11N	13W	15	NWSENW	817	5,687	5,957	6,125	--	6,140	
13816	Bradley 4	Turner Pet.	12N	13W	11	NESWSE	822	5,976	6,169	6,380	6,403	6,461	
35656	Anderson 1-8	Jennings Pet.	14N	11W	8	NENENE	1081	7,209	7,466	7,680	7,704	7,823	
36622*	Anderson 1-8A	Jennings Pet.	14N	11W	8	NENESE	1081	7,135	--	7,586	--	7,721	
			10 Mmcfgd + 26 bcpd Initial Production										
37671	Mich. Cons. Gas Co. 1-9	Jennings Pet.	14N	11W	9	SWNESW	1078	7,156	7,414	7,618	--	7,633	
38192	Mich. Cons. Gas Co. 1-9A	Jennings Pet.	14N	11W	9	NWSESW	1078	7,200	7,458	7,672	--	7,679	
26662	Thompson 1	Thunder Hollow	15N	14W	20	SENESW	829	6,045	6,269	6,427	6,437	6,487	

PN	Well Name	Operator	T	R	Sec.	¼ ¼ ¼	Elev.	O_{TR}	O_{BR}	O_{GW}	O_{IGW}	O_{PdC}	O_{Tr}
						Oakland County							
32628	Mich. Smls. Tube 1-30	Wenner Pet.	1N	7E	30	SENENW	920	4,497	4,967	5,407	--	5,415	
19055	Gowen 1	Collin, C.W.	1N	7E	35	NWSESE	1020	4,437	4,881	5,330	--	5,340	
19086	Leone 1	Gray and Whyte	1N	8E	29	SESWNE	961	4,467	4,935	5,395	--	5,407	
36303	Standard Ind. 1-36	Winn-Lott Inc.	2N	8E	36	NESESE	975	4,618	5,078	5,544	--	5,550	
28258	Huntoon 1	Texaco	4N	8E	35	CNNWSW	1048	5,398	5,868	6,319	--	6,323	
						Oceana County							
33134	Schiller 1-10	Amoco	13N	18W	10	SWNWSE	752	4,351	4,548	4,660	--	4,702	
28182	Whitte 1	Chapman and Tribal	13N	18W	13	NENWNE	699	4,516	4,721	4,839	--	4,878	
24087	Peters 1	Pure Oil	15N	17W	36	CNSENE	733	5,119	5,310	5,450(?)	--	5,500(?)	
32517	Snow 1-17	Energy Acquis.	16N	15W	17	SWSENW	940	6,028	6,234	6,383	--	6,448	
22801	Skidmore 1	Peake Pet. & Harvey	16N	16W	11	SWNWSW	984	5,686	5,878	6,014	--	6,013	
17549	Lauber 12	Carter Oil	16N	17W	6	CNSESE	651	4,944	5,120	5,220	--	5,233	
						Ogemaw County							
31338	Rau 1-21	Amoco	22N	2E	21	NWNENW	970	9,878(?)	10,108(?)	--	--	10,612(?)	
12898	Reinhardt Con. 1	Ohio Oil Co.	22N	2E	35	SENWNW	903	9,847(?)	--	--	--	10,475(?)	
28456	A.B.G. Hunt Club 1	Amoco	23N	3E	28	NWNE	878	9,446	9,680	10,100	10,115	--	
25099	State Foster 1	Brazos	24N	2E	28	SWSESE	1477	9,766	9,995	10,414	10,440	10,506	11,668
						Osceola County							
37274	Clark, Rose 1	BWAB	17N	7W	7	NESWSW	1125	9,356	9,620	9,884	--	10,022	
34558	Fruedenberg 1-31	JEM Pet.	17N	8W	31	SENENE	1117	8,962	9,222	9,470	9,504	9,596	10,483
35800	Gray 1-31	Willmet	17N	8W	31	NENWNW	1154	8,964	9,222	9,423	9,500	9,570	
34536	McCormick 2-27	JFM Pet.	18N	8W	26	SWSENW	1055	9,126	9,374	9,627	9,658	9,724	
12802	Stedman 3	Ohio Oil Co.	18N	10W	29	CNNWNW	1133	8,319(?)	8,543(?)	--	--	8,851(?)	
35482	Robinson 1-31	Hunt Energy	19N	7W	31	SESESE	1116	9,697	9,945	10,213	10,222	10,337	
						Oscoda County							
34494	Consumer Pwr. 1	Hunt Energy	25N	2E	10	NENESW	1176	9,436	9,649	10,023	10,053	10,134	11,171
34070	USA Big Creek 1	Hunt Energy	25N	2E	14	NENESW	1179	9,283	9,494	9,854	9,887	10,002	11,028
						Otsego County							
25873	Lake Horicon Corp. 1	Simpson, C.J.	29N	4W	2	CNNWNW	1413	7,695	7,900	8,090	8,115	8,137	
35113*	Johannesburg Mfg. 3-16	West Bay-Wainoco	30N	1W	16	SWSWSE	1374	7,411	7,606	7,796	7,823	7,835	8,601
			625 Mcfg + 30 bcpd + 3 bwpd Initial Production										
35922	Dowker et al. 2-21	Reef-West-Bay Wainoco	30 N	1W	21	NWSWSE	1367	7,424	--	7,856	7,876	7,907	

PN	Well Name	Operator	T	R	Sec.	¼ ¼ ¼	Elev.	O_{TR}	O_{BR}	O_{GW}	O_{LGW}	O_{PdC}	O_{Tr}
						Ottawa County							
BD	Brine Disposal 3	Parke Davis and Co.	5N	15W	20	SWSWSW	604	3,483	3,759	3,913	--	3,930	4,468
34268	Hirdes 1-1	OMNI Pet.	6N	15W	1	NWNESW	638	4,002	4,276	4,429	--	4,450	
25800	Fenske 4-A	Swanson and Babcock	7N	13W	34	NWSENW	654	4,373	4,661	4,841	--	4,865	
34885	Umlor et al. 1-3	Gulf	8N	13W	3	NWNWNE	891	5,130	5,429	5,603	--	5,646	6,429
						Presque Isle County							
34999	State-Allis 2-30	Shell	33N	2E	30	NENWNE	829	5,312	5,516	5,750	5,773	5,804	
33487	State-Allis 2-30A	Shell	33N	2E	30	NWSENW	829	5,560	5,765	5,995	6,018	6,046	
35085	Moll 1-14	Jennings Pet.	33N	3E	14	SWNWSW	904	5,215	5,430	5,660	5,667	5,702	6,250
29372	Taratuta 1-13	Shell	33N	5E	13	SWNWSE	776	4,747	4,972	5,206	5,212	5,261	5,748
24999	Weide 1	Fain-Porter Drig. Co.	33N	7E	33	CNSWNW	815	4,836	5,059	5,303	5,320	5,357	
22638	Sellke 1	Lindsay, Forrest	34N	5E	20	NESESW	842	4,577	4,819	5,035	5,044	5,088	
27199	Draysey 1	Pan American Pet.	35N	2E	29	SESESE	809	4,255	4,446	4,634	4,662	4,685	5,168
27725	State Ocqueoc 1	McClure	35N	3E	24	SENWNW	730	4,159	4,365	4,567	4,590	4,615	
20194	Fee 1	Mich. LS Div,; U.S. Steel	35N	6E	31	NESWNE	669	3,892	4,127	4,340	4,353	4,391	
						Roscommon County							
37409	Roseville Gun Club B 1-17	Newport Pet.	21N	1W	17	E2SWNW	1240	10,871	11,146	11,492	11,540	11,632	
34537	Dalrymple 1-16	JEM Pet.	22N	4W	16	NWNESE	1141	10,323	10,576	10,886	10,930	11,015	
37134	Wahl Unit 1	Amoco	24N	1W	14	NWSENE	1202	9,597	9,834	10,205	10,230	10,298	
						St. Clair County							
25780	Puzzuoli 1	Bernhardt Oil & Gas	2N	16E	17	NENENE	579	3,050	3,493	3,995	--	4,102	
23796	Bidal-Faucher Levrau 1	Collin, C.W.	3N	15E	10	SENESW	595	3,483	3,942	4,446	--	--	
30376	Osterland 1-14	Mich. Cons. Gas Co.	3N	15E	14	NENENE	603	3,424	3,880	4,300	--	--	4,316
139BD	Consumer Pwr. BD 1	Consumer Pwr. Co.	4N	15E	31	SWSWSE	616	3,546	3,988	4,486	--	--	
22002	Roney 1	Panhandle East. Ppl.	5N	16E	11	NESESE	629	3,726	4,183	4,700	--	--	
196	Hurst 1	St. Clair Oil & Gas	5N	16E	26	SENW	620	3,625	--	--	--	--	
151BD	Consumer Pwr. BDW 1-7	Consumer Pwr. Co.	5N	17E	7	CNNWNW	676	3,584	4,058	4,579	--	--	
152BD	Consumer Pwr. BDW 2-7	Consumer Pwr. Co.	5N	17E	7	NENENW	632	3,573	4,057	4,561	--	--	
26086	Conrad 1	North American Drlg.	6N	15E	1	NWNENE	709	4,260	4,772	5,297	--	--	
25024	Baldwin 1	Goll, Graves, Mechli.	6N	16E	6	CNNWNW	681	4,233	4,747	5,272	--	--	5,275

PN	Well Name	Operator	T	R	Sec.	¼ ¼ ¼	Elev.	0_{TR}	0_{BR}	0_{GW}	0_{LGW}	0_{PdC}	0_{Tr}
						Sanilac County							
25357	Hoppinthal 1	Humble Oil	9N	15E	16	CNNENE	769	5,665	6,165	6,668	--	6,680	
26480	Spencer 1	Hallwell, Inc.	9N	15E	27	NWNWNE	759	5,183	5,717	6,225	--	6,245	
25939	Hontar 1	Simpson, C.I.	10N	15E	9	CNSESE	775	5,562	6,122	6,655	--	6,663	
33999	Woodruff 1-19	Mid-American Oil and Gas	10N	15E	19	NENWNE	765	6,114	6,603	7,103	--	7,109	7,560
35779	Frostic 1-30	Traverse Oil Co.	11N	15E	30	SESESE	775	5,694	6,250	6,775	--	6,783	7,306
30974	Hewitt and Shadd 1-20	McClure and M.N.R.	12N	15E	20	CNSWSE	785	6,370	6,853	7,357	--	7,369	
						Shiawasee County							
22379	Ferris 1	Lee, C.A.	5N	2E	5	CNSENE	856	5,885	6,341	6,718	--	6,725	
27907	Jelinek-Ferris 1	Mobil	5N	2E	5	SESENW	843	6,108	6,556	6,952	--	6,957	
23376	Dysinger 1	Hodson Oil and Gas	5N	2E	22	CNSWSW	906	6,336	6,807	7,226	--	7,233	
30727	Hasselbring 1-5	Mich. Oil Co.	6N	1E	5	N N N	783	6,694	7,135	7,505	--	7,510	
						Tuscola County							
23890	Sattleberg 1	Simpson, C.J. and Sun	13N	9E	8	NENENE	678	8,885	9,365	9,914	--	9,922	
25609	Novesta Twp. 1	Simpson, C.J.	13N	11E	16	CNSWSW	738	8,118	8,614	9,138	--	9,149	
						Wexford County							
34612	Benson 1-14	JEM Pet.	21N	9W	14	NWSWSW	1412	9,684	9,897	10,142	10,167	10,236	
35099	State-Liberty 1-18	JEM Pet.	24N	9W	18	SWSWSW	1022	8,506	8,687	8,892	--	8,910	

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