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Cambrian-Early Ordovician Sequence Stratigraphy and Mount Simon Sandstone Petrology-Michigan Basin

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CAMBRIAN-EARLY ORDOVICIAN SEQUENCE STRATIGRAPHY AND MOUNT SIMON SANDSTONE PETROLOGY--MICHIGAN BASIN

by

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Michigan subsurface correlation is complicated in the Cambrian-Early Ordovician section due to limited availability of rock data. Core and cuttings examination demonstrate that similar stratigraphic sequences exist between the Michigan Basin and surrounding regions. Lithofacies in Wisconsin outcrop are similar to their basinal counterparts, and are correlated on the basis of sediment types, sedimentary structures, and the sequence stratigraphic concept.

The Mount Simon Sandstone in Michigan correlates with that observed in Illinois, Wisconsin, and Iowa. Isopach data throughout the Midwest indicate a single depocenter in Northeastern Illinois. Sedimentary structures and lithology indicate a subtidal environment that may be a progradational transition from a lower (shoreward) aeolian environment. Observed diagenetic patterns are influenced primarily by depth of burial. The deep pattern (below 14,250') exhibits extreme compaction. The shallow pattern (above 8900') exhibits pervasive carbonate and quartz cements, and authigenic clays. Secondary porosity developed from dissolution of carbonate, feldspar, and quartz.

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and John Fowler, who dropped by the Core Lab from time to time, and always provided input and insight.

Soli Deo Gloria.

Jeffrey T. Cottingham

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INTRODUCTION

The Michigan Basin has been an active site for petroleum exploration and production since the late 1920s. The basinal setting for thick deposits of Paleozoic sandstones and carbonates has created favorable burial conditions for both the maturation and entrapment of oil and natural gas. Cambro-Ordovician strata in the Michigan Basin have only recently come under scrutiny as potential new hydrocarbon producing horizons in Michigan. The existing St. Peter play is expanding (Harrison, 1987), and as newer and deeper wells are drilled, more information is becoming available about deeper formations.

Information on the Cambro-Ordovician is somewhat limited. Recent drilling has penetrated those horizons, but anything deeper than the St. Peter Sandstone has very little well control. The focus of this paper, however, lies within those formations below the St. Peter Sandstone: the Upper Cambrian Mount Simon, Eau Claire, Wonewoc, and Franconia formations, along with the Upper Cambrian Trempealeauan interval through the Lower Ordovician Prairie du Chien Group (Figure 1). Lithostratigraphic studies will rely on actual rock data to the extent allowed by the current database. Subsequent sections of this study will describe Michigan Basin stratigraphy and relate it to the upper Midwest regional picture of the Cambro-Ordovician paleogeography (Droste and Shaver, 1983; Dott, Byers, Fielder,

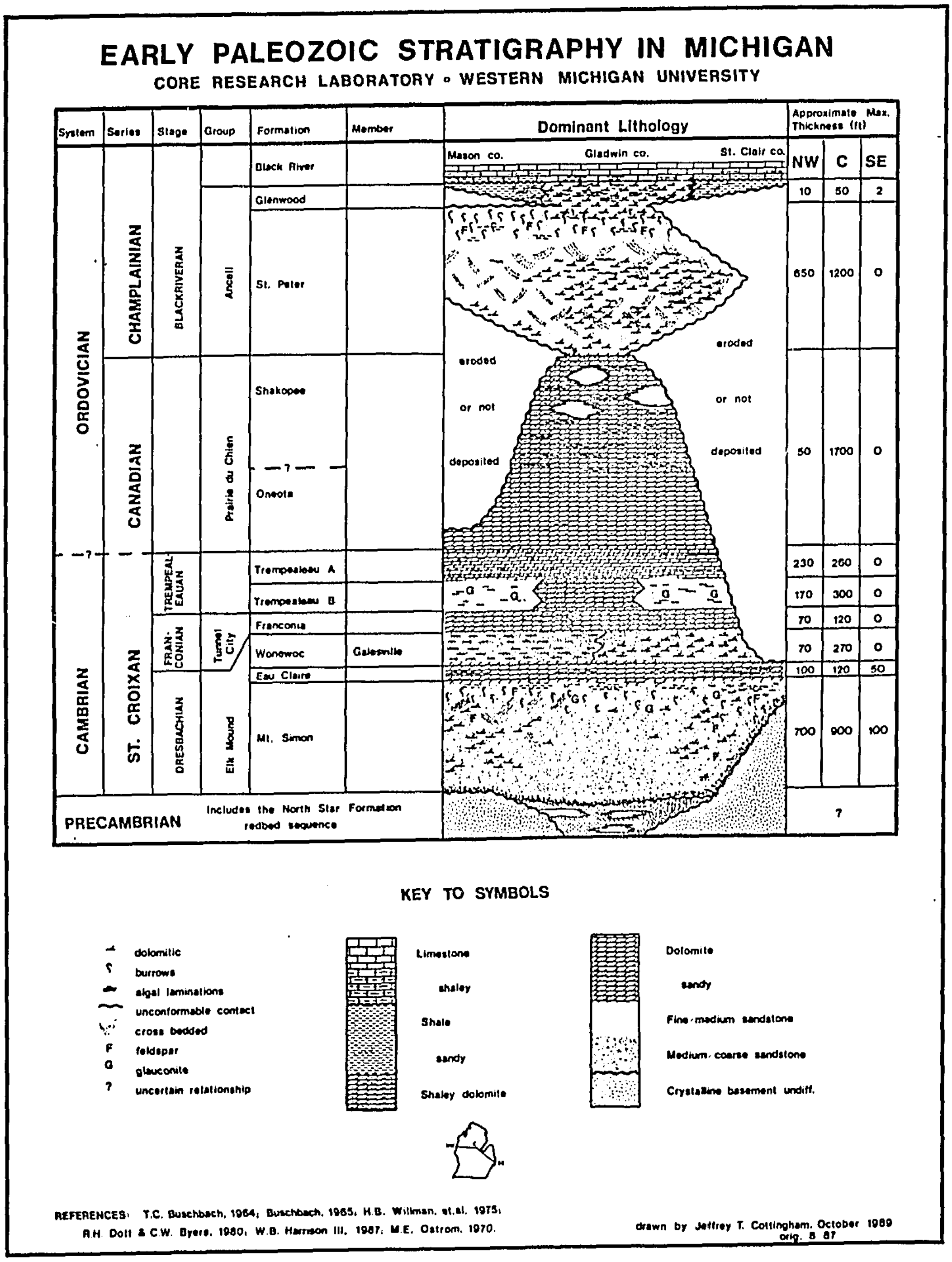

Figure 1. Stratigraphic Column for Lower Paleozoic Rocks in Michigan.

Stenzel, and Winfree, 1986). Droste and Shaver (1983) suggest similar histories for the Illinois and Michigan Basins. Thus, the Illinois basin geologic history could serve as a good model for analysis of the Michigan Basin. The Cambro-Ordovician stratigraphy in the Illinois subsurface and Wisconsin outcrop has been studied in great detail. Therefore, regional comparison and correlation between the Wisconsin/Illinois section and the Michigan Basin is presented here.

This study is primarily based on limited available core and cuttings control, although wireline logs are also extensively used. The strata of interest will be within the Late Cambrian and Early Ordovician systems, with special emphasis on the Cambrian Mount Simon Sandstone, because of the availability of cores and cuttings constituting the best geologic sample database. The Middle Ordovician St. Peter Sandstone (also known as the "Bruggers formation" or the "Massive Sand") is a better known unit above the section under scrutiny here.

The utilization of X-ray diffraction, scanning electron microscopy, standard petrographic analysis, and wireline logs will yield information that supports the regional lithologic correlations made here. Actual rock data will be tied into wireline logs to map basinwide facies distributions.

PREVIOUS STUDIES INVOLVING THE CAMBRO-ORDCVICIAN

Previous attempts at determining the geology of the Cambro-Ordovician in the Michigan Basin have offered conflicting analyses as to the stratigraphy and depositional history within the section. Numerous studies have been undertaken, but all are plagued by a lack of well control in the Michigan Basin and a sense of regional perspective beyond the basin. There were 68 wells that have cored intervals in the better known Middle Ordovician St. Peter Sandstone as of December 1987, (Harrison, personal communication), and 198 wells (as of September, 1988; Appendix A) that have drilled through the St. Peter in the Lower Peninsula, illustrated in Figure 2. Conversely, the Mount Simon Sandstone has 8 wells with cored intervals throughout the state, and only 72 wells that penetrate the Mount Simon, 44 of which have been drilled through and into the Precambrian. All but 20 of these wells are along the basin margins, and many of those are older and either were not logged or have poor quality logs that were made before modern logging techniques were developed. Hence, there is very little well control for an in-depth study of the magnitude completed for outcrop in Wisconsin and Illinois.

The earliest preliminary study was presented for a field trip into the Upper Peninsula, and a number of articles on Upper Peninsula strata were presented in guidebook format. Ells (1967) demonstrated similarities between well log signatures

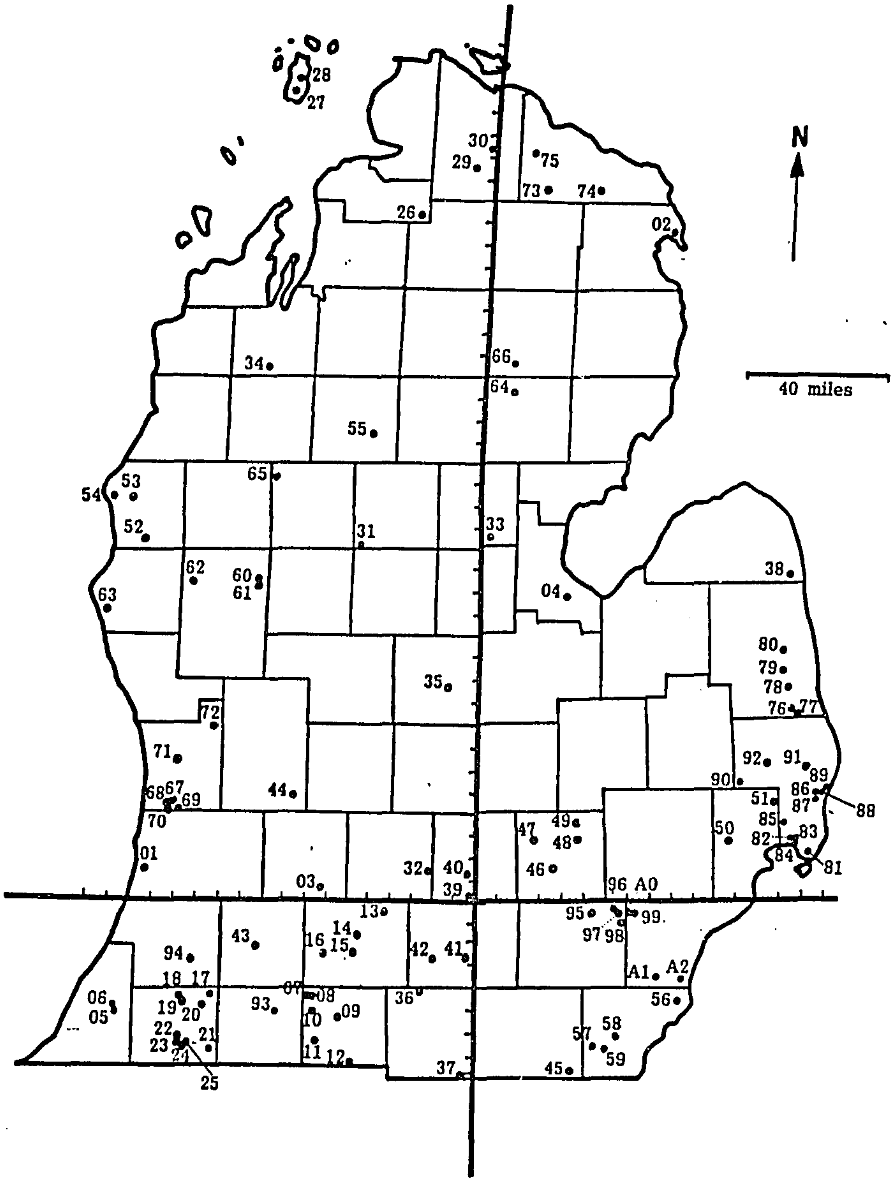

Figure 2. Distribution of Cambrian-Precambrian Wells. Appendix A Lists Well Data Corresponding to Well Numbers on Map.

of Illinois wells and early Michigan deep tests. A similar correlation is presented in Figure 3. However, Ells also correlated Michigan Basin strata with the outcrop region of the Upper Peninsula, which was also presented in more detail by Catacosinos (1973).

The earliest in-depth study was Catacosinos' (1973), which attempted an outcrop-to-basin center correlation. Unfortunately, both Ells and Catacosinos had a lack of geologic data control within the basin. Their correlation with outcrops in the Upper Peninsula of Michigan is also questionable, since the section there straddles an arch of Precambrian basement, and those rocks lie on the Superior basin side of the arch. Correlation problems between neighboring Wisconsin and the Upper Peninsula have also been attempted, without complete resolve (Ostrom and Slaughter, 1967). With the new well data available, a revised stratigraphy will be presented herein.

Bricker, Milstein, and Reszka (1983) present new information based entirely on well log correlation. The major shortcoming of this approach is the lack of rock data other than oil and gas well drillers' descriptions. Well logs are secondary and are used to correlate from wells with detailed rock data to areas without rock data. In addition, no attempt was made to correlate beyond the limits of the Michigan Basin. Work done in Illinois by Buschbach (1964), Willman, Atherton, Buschbach, Collinson, Frye, Hopkins, Lineback, and Simon (1975), in Indiana by Droste and Shaver (1983), in Wisconsin by Dott et al. (1986), and throughout the Midwest by

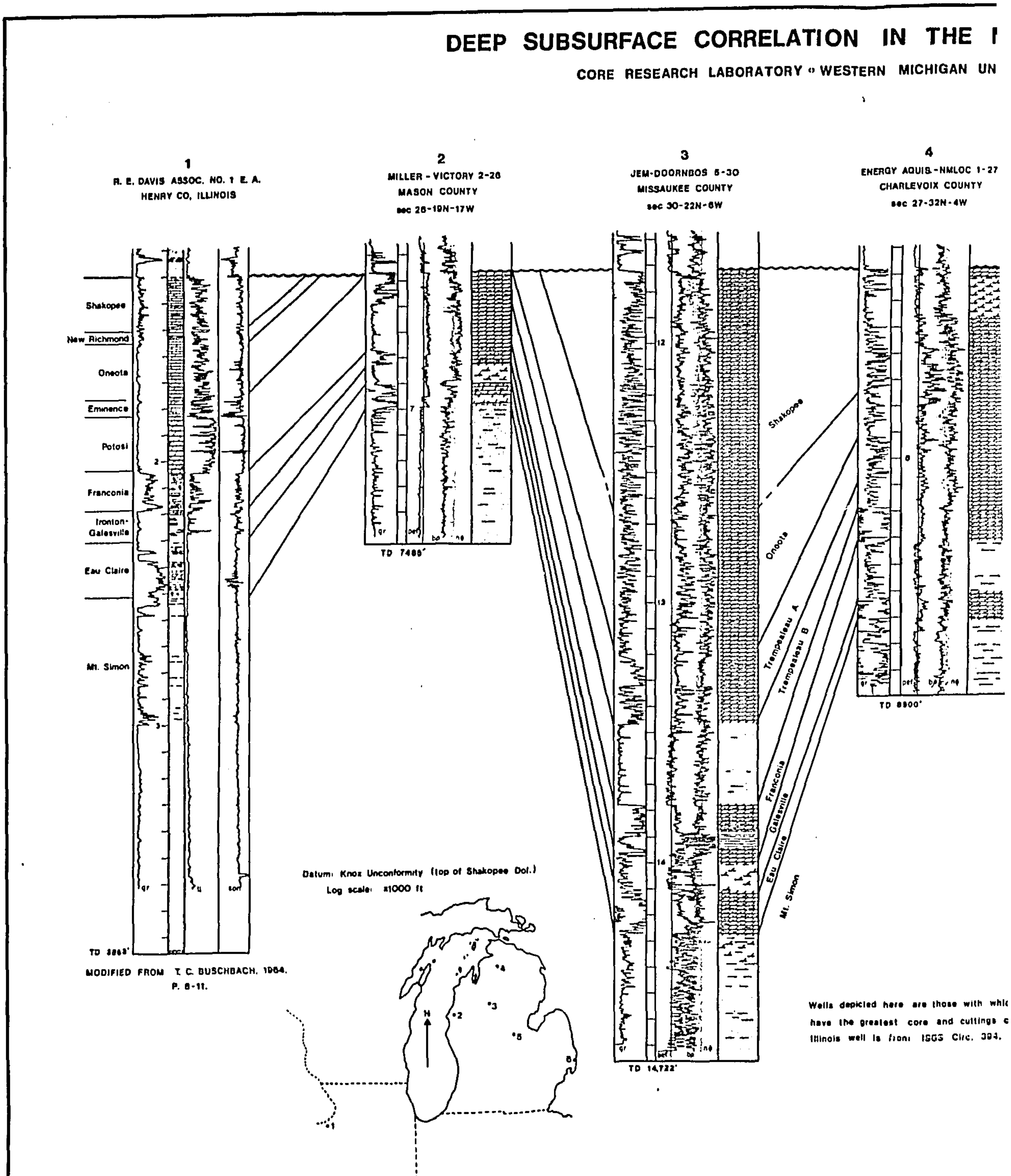

Figure 3. Correlation Chart for Selected Reference Wells in Michigan and Illinois.

SURFACE CORRELATION IN THE MICHIGAN BASIN

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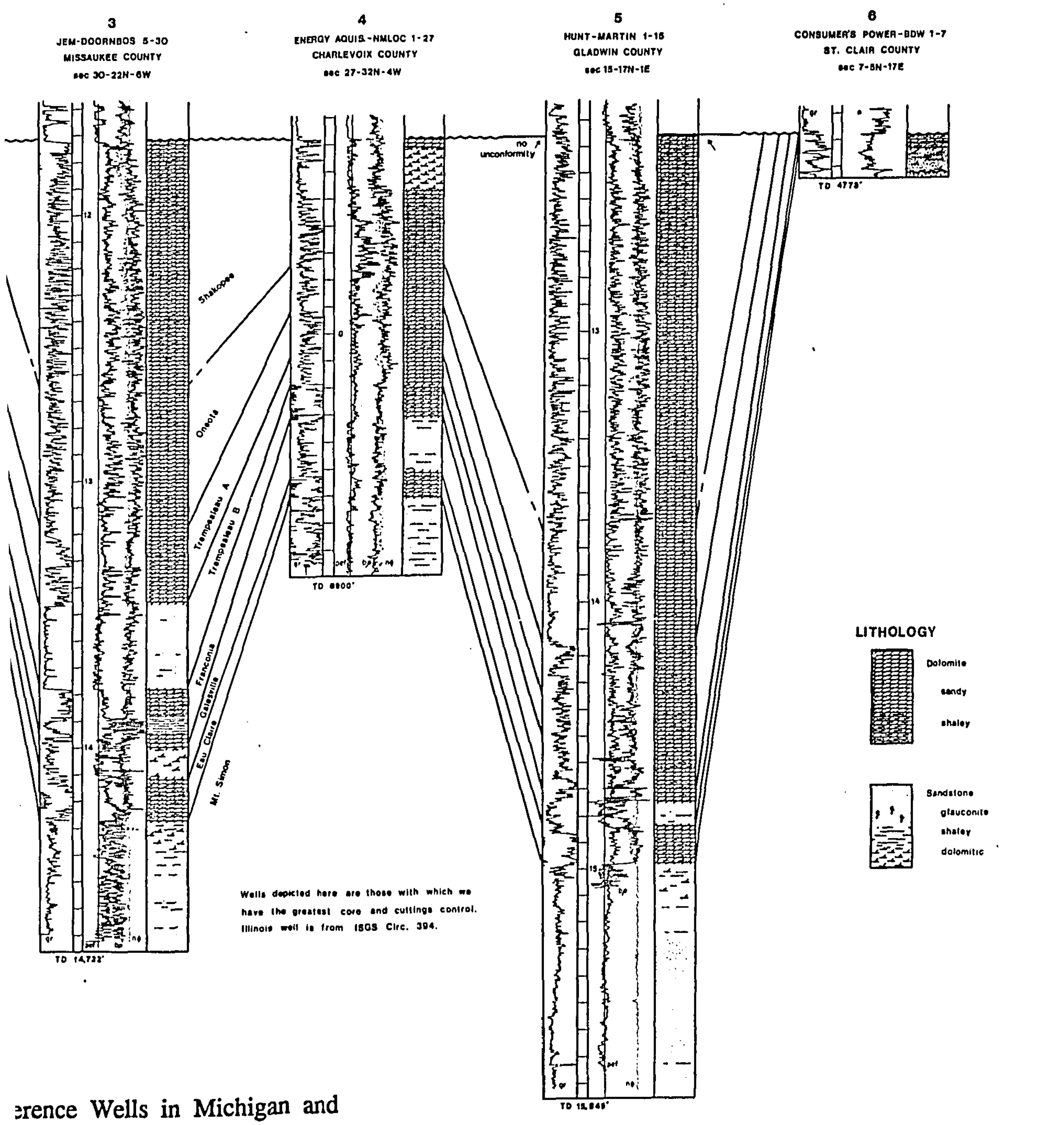


…erence Wells in Michigan and

Sloss (1963, 1984), all show that this is an undesirable and inaccurate approach to stratigraphic interpretation, since the entire Midwestern region has a relatively uniform sequence of strata.

Fisher and Barratt (1985), using well log and rock data, recognized distinct, mappable formations in the subsurface proposing the Bruggers and Foster formations, which are equivalent to the St. Peter Sandstone and Prairie Du Chien Group of Illinois and Wisconsin (Harrison, 1987). Here, also, no attempt at correlation outside of the Basin was made, and the formation names were taken from the name of the first well that they examined, rather than following the North American Stratigraphic Code, which states in article 22 part b, "the naming of new units in the subsurface is justified only where the subsurface section differs materially from the surface section, or where there is doubt as to the equivalence of a subsurface and a surface unit" (North American Commission on Stratigraphic Nomenclature, 1983, p. 856).

Their argument was objected to by Harrison (1987) who correlated the massive sandstone or the Bruggers formation (Fisher and Barratt, 1985) with the St. Peter Sandstone based on detailed analysis of over 30 cores at the Michigan Basin Core Analysis Laboratory, and extensive study of the Ordovician System in Wisconsin and Illinois. Utilizing Harrison's method in the deeper section, similarities between formations in Wisconsin outcrop and Michigan subsurface are also observed. These similarities would also be expected based on two observations: (1) The Mount Simon Sandstone has already been recognized to exist in both localities, and (2)

Wisconsin and Illinois studies show that sediments bounding the eastern edges of the Wisconsin and Kankakee Arches are dipping gently towards the center of the Michigan Basin (Buschbach, 1964; Ostrom, Dott, Byers, Morris, and Adams, 1978).

Brady and DeHaas (1988) present a detailed description of the Cambro-Ordovician section between the Precambrian and the Glenwood Formation. Their stratigraphy is based entirely on extensive well log correlation and mudlog description. No attempt is made to look at the rocks in a regional perspective. Rock data should be the single most important aspect in description and correlation of subsurface units.

In addition, such names as Franconia and Dresbach apply to both the Stage and the formation designations. With a greater rock database, these terms should eventually be abandoned in favor of lithostratigraphic terms as they have been in Wisconsin and Illinois (Willman et al., 1975). The same argument can be applied to the Trempealeau formation previously used in literature.

Additional studies presented by Wheeler (1988) also correlate based entirely on well logs and old oil and gas drillers' descriptions. No other rock data are used. Although the study presented here will also rely on log correlations, limited core and cuttings data, along with outcrop studies, are utilized to minimize the risk of error in correlating wireline logs.

METHODS OF STUDY

Lab and Sample Preparation

The most useful and reliable data in any analysis of basin history, stratigraphy, and hydrocarbon potential must come from the rock record when possible. The rocks are the primary source of information and should be relied on more than any other geologic data. Therefore, the fundamental factor in this study is the availability of core and cuttings samples. Unfortunately, abundant, quality samples for the Cambro-Ordovician in Michigan are quite limited. However, the Mount Simon Sandstone has more available rock data than the overlying Upper Cambrian-Early Ordovician formations and will, therefore, be the focal point of this study.

Detailed analysis of samples has been completed by such traditional methods as examination by thin section, X-ray diffraction, and scanning electron microscopy. Core and cuttings descriptions were taken from available samples, and have been utilized as the foundation to tie into wireline log correlations. Samples of the Mount Simon were derived from three sources: (1) from the outcrops in Western Wisconsin; (2) from 4 cores of wells in Michigan's Lower Peninsula, 2 cores from Iowa, and core descriptions from Illinois; and (3) from cuttings out of 3 additional wells in the Lower Peninsula of Michigan. A list of samples and analyses is found in Appendix B.

The cores are the more important of two primary sources of information for the remainder of the section. Core analysis from the Winterfield A-1 (Clare County), Doornbos 5-30 and Bruggers 3-7 (Missaukee County), Gingrich 1-31A and Eisenga 1-29 (Osceola County), and the State-Foster 1-28 (Ogemaw County) provided detailed information for Prairie du Chien correlation. Additional lithologic description taken directly from outcrops and published reports in Wisconsin, and from published material in Illinois and Wisconsin, is used for comparison and correlation with the Michigan section. This material can then be utilized to correlate well logs, which are secondary to the rock record, but can be used for basin-wide correlations. The author has tried to avoid the use of mudlogs and drilling logs, as many of them are biased by older outdated lithologic terms and descriptions, and older logs reflect a greater degree of inaccuracy without modern sampling techniques.

Additional wells with core control are as follows: JEM Petroleum Doornbos 5-30 in Missaukee County; Upjohn Brine Disposal Well #4 in Kalamazoo County; the Phillips 1-2 in Livingston County; and the Consumers Power Brine Disposal Wells #151 and #139 in St. Clair County. All cores are Mount Simon Cores, with additional core in the Prairie du Chien and the Trempealeau B intervals from the Doornbos well. Detailed footages from wells with sample control are outlined in Table 1. Representative cuttings sets come from the following wells: Northern Michigan Land and Oil Corporation 1-27 in Charlevoix County; Miller Brothers

Table 1

Wells With Rock Data Available

Well	County	Type	Footage	Formation
Reynolds 2-11	Cass	Cuttings	1750'-TD	Wonewoc
Smith 1-20	Cass	Cuttings	TD	Mount Simon
No. Mich. Land/Oil Corp. 1-27	Charlevoix	Cuttings	6550'-8900'TD	Mount Simon
Martin 1-15	Gladwin	Cuttings	12,180'-15,850' TD	Mount Simon
Victory 2-26	Mason	Cuttings	5810'-7485'TD	Mount Simon
Winterfield A-1	Clare	Core	11,605'-635'	Shakopee (PdC)
Upjohn BD#4	Kalamazoo	Core	4953'-5008'	Mount Simon
Phillips 1-2	Livingston	Core	??	Mount Simon
Doornbos 5-30	Missaukee	Core	12,712'-746'	Shakopee (PdC)
		Core	13,691'-696'	Trempealeau B
		Core	14,234'-359'	Mount Simon
Bruggers 3-7	Missaukee	Core	11,382'-568'	Shakopee (PdC)
State Foster #1	Ogemaw	Core	11,600' -12,996'	Prairie du Chien
Gingrich 1-31A	Osceola	Core	9994'-10,006'	Shakopee (PdC)
Eisenga 1-29	Osceola	Core	11,487'-510'	Shakopee (PdC)
BD 139	St.Clair	Core	4485'-4605'pC	Eau Cl/Mt Simon
BD 152	St.Clair	Core	4561'-4684'pC	Eau Cl/Mt Simon
BD 151	St.Clair	Core	4579'-4707'pC	Eau Cl/Mt Simon
Woodhaven BD #1	Wayne	Core	3233'-3710'pC	Eau Cl/Mt Simon

Note: Cuttings listed are only those stored at the Core Research Lab, Western Michigan University. Wells with cuttings begin with the Glenwood and list the deepest formation only.
TD=total depth, pC=Precambrian

Victory 2-26 in Mason County; and the Hunt Energy Martin 1-15 in Gladwin County. These cuttings have been washed and were sampled every 5 feet. Observation of major lithologic changes within the cuttings correspond closely with major changes interpreted from the well log response. Figure 3 illustrates a generalized cuttings/core lithology versus well log response for 5 Michigan wells and correlates them with one another and with a representative well, the R.E. Davis Associates no. 1EA (Buschbach, 1965), from Illinois.

Cuttings have limited applicability towards this project since a cutting sample is contaminated with debris from overlying formations, but in lieu of core control, they become a necessary second source of rock information. The cuttings were mounted and thin-sectioned for analysis and description. Vacuum impregnation of a representative cuttings sample in blue-dyed epoxy was used, creating a chip from which a thin section was then made.

Outcrop

Examination of the type sections for the Late Cambrian and Early Ordovician formations adjacent to the Wisconsin Arch, which flanks the Michigan Basin on the west, included sampling the type localities to compare lithotypes to Michigan Basin strata. In addition, observations by Ostrom (1964), Emrich (1966), Davis (1966, 1970), Stablein and Dapples (1977), Ostrom et al. (1978), Darby and Webers (1979), Dott and Byers (1980), and Dott et al. (1986), gave sufficient background and description for further comparison.

A similar comparison was made between the Illinois and Michigan sections, only more emphasis was placed on published literature and records at the Illinois State Geological Survey in Champaign, Illinois. Additional literature by Buschbach

(1964, 1965) and Willman et al. (1975), was of tremendous help and use.

Correlation and Sequence Stratigraphy

L.L. Sloss (1963, 1984) recognized distinct lithologic cycles in the cratonic interior that represented episodes of major sea level transgression and regression and associated sedimentation. These were termed "mega-sequences" and have been observed continent-wide in sedimentary successions. Additional observations in Wisconsin by Ostrom (1964, 1970) demonstrate that numerous stratigraphic cycles exist on a smaller scale within the larger transgressive sequences recognized by Sloss. Vail, Mitchum, and Thompson (1977), through the use of seismic analysis, also recognized these "second order cycles" within stratigraphic successions.

Harrison and Barnes (1988), in studies of the St. Peter Sandstone in Michigan, recognized these cyclic sediment patterns and use this "sequence stratigraphy" concept for correlation of midwestern sandstones with those observed in the Michigan basin.

Applying sequence stratigraphy to the underlying Cambrian-Early Ordovician section, one can expect to observe second, third, and fourth order cycles, bounded by sharp, erosional unconformities (Figure 4). Combining the observed cyclicity with corresponding lithologic characteristics then makes clear the correlation of Wisconsin outcrop lithotypes with those of the Michigan Basin. Observed cycles show basal sand units were deposited on older erosional surfaces, representing

Age	Sequence	Lithotopes	Lithostratigraphic Unit	
EARLY ORD.	V	Sequence unit continues upsection...		
		Quartzarenite	ST. PETER FORMATION	
	IV	Carbonate	SHAKOPEE FM.	Willow River Mbr.
		Argillaceous Sandstone and/ or Shale		
		Reworked Quartzarenite Quartzarenite		New Richmond Sandstone
	III	Carbonate	ONEOTA FM.	Hager City Mbr. *
		Argillaceous Sst. and/or Shale Reworked Qtzarenite		Stockton Hill Mbr.*
LATE CAMBRIAN		Quartzarenite	JORDAN FORMATION**	
	II	Carbonate	ST. LAWRENCE FM.* ** (Trempealeau A and B)	
		Argillaceous Sst. and/or Shale	Tunnel City Gp.	Lone Rock Fm. / Mazomanie Fm.
		Reworked Qtzarenite	WONEWOC FM.	Ironton Mbr.
		Quartzarenite		Galesville
	I	Carbonate	BONNETERRE FM. ***	
		Argillaceous Sst. and/or Shale	EAU CLAIRE FM.	
		Reworked Qtzarenite Quartzarenite	MOUNT SIMON SANDSTONE	

* further subdivided (Wisconsin)
** not currently recognized (Michigan)
*** present further south (Illinois/Missouri)

Figure 4. Wisconsin Outcrop Lithotopes and Sequence Stratigraphic Units (modified from Ostrom, 1970).

periods when relative sea level was at the lowest point. At such times, large areas of the craton were exposed, producing large volumes of clastic debris which collected in the nearby subsiding basins or areas with the greatest relative subsidence. As relative sea level rises, less craton is exposed, producing less clastic debris, and therefore allowing for the development of a mixture of finer clastic debris and carbonate, eventually grading into a predominantly carbonate sequence at the peak of the marine transgression. Relative sea level then drops, exposing more of the cratonic interior, and producing an erosional surface. At this time the cycle can then begin over, thus forming a sedimentary package which can contain numerous cycles. The most ideal conditions for the typical cycle would be in the basins where subsidence allows for the carbonate units to develop in deeper water and further from the source. Conversely, incomplete or modified cycles are expected and observed on the surrounding platforms and arches, where shallower water and/or close proximity to the source terranes exists.

REGIONAL TECTONICS, STRUCTURE, AND BASIN HISTORY

Tectonics

Recent Work by Hinze, Kellogg, and O'Hara (1975), Fowler and Kuenzi (1978), Sleep and Sloss (1978), Brown, Jenson, Oliver, Kaufman, and Steiner (1982), Klein and Hsui (1987), along with Catacosinos (1981), Cercone (1984), Nunn, Sleep,and Moore (1984), Dickas (1986), and Howell (1988), have all supported that the Michigan Basin first began as a failed intracratonic rift basin, and continued subsequent development as a sag basin. Gravity and magnetic surveys, along with deep COnsortium for COntinental Reflection Profiling (COCORP) seismic patterns have indicated the presence of a linear gravity/magnetic anomaly (Figure 5) associated with benched half grabens on either side of a deep subsurface trough in the Precambrian.

In the mid 1970s, an ambitious drilling project began as a joint venture between Shell, Amoco, and McClure Petroleum Companies to drill a deep borehole in Gratiot County along the central axis of the gravity anomaly. The Sparks, Eckelbarger, and Whightsil #1-8 well in Gratiot County reached a record depth of 17,466 feet, and several cores taken in the Precambrian show a sequence of redbeds and gabbroic intrusions dated approximately Middle Keeweenawan in age (Sleep and Sloss, 1978). This is the deepest well drilled in Michigan, and is the only well in the

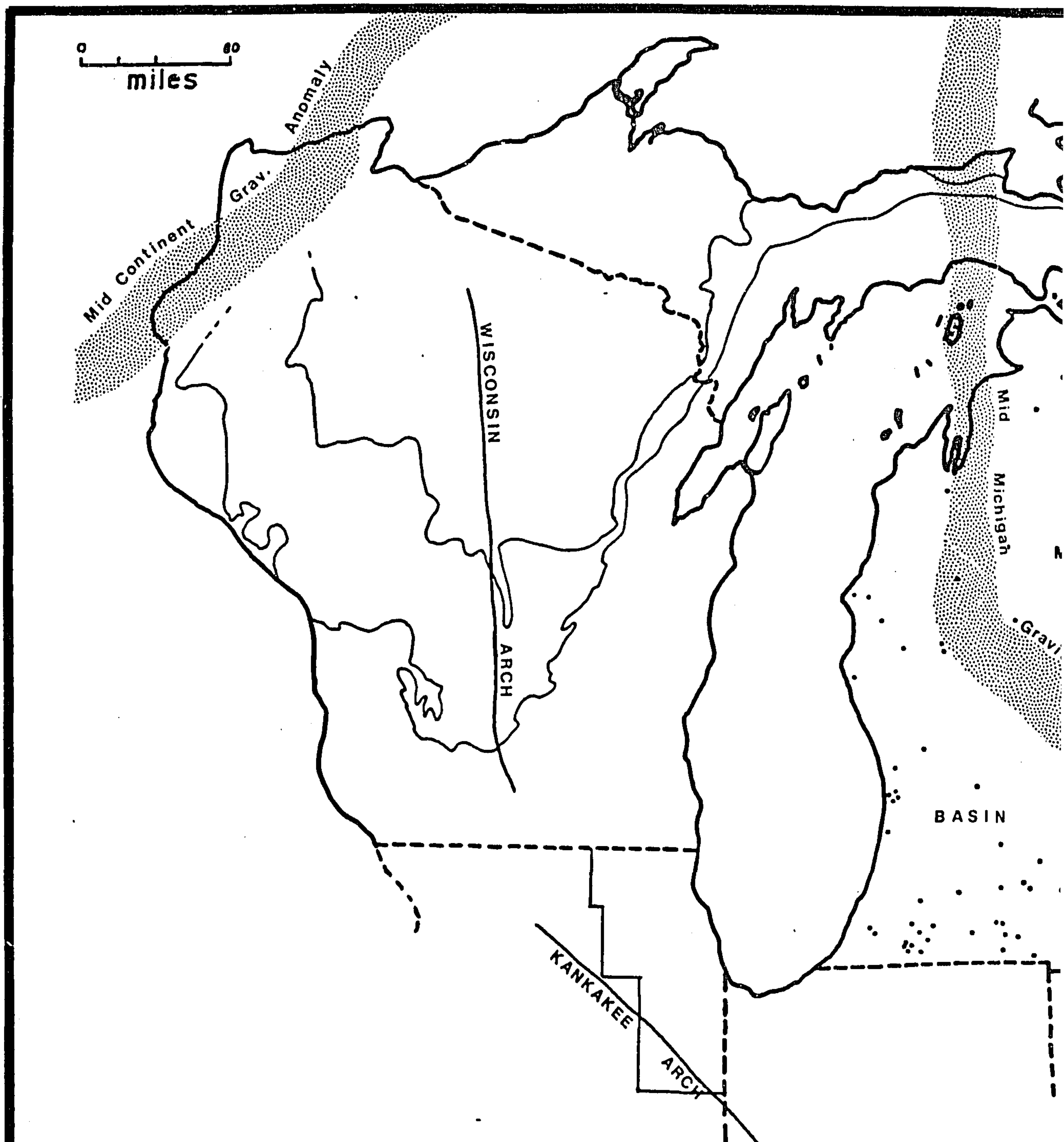
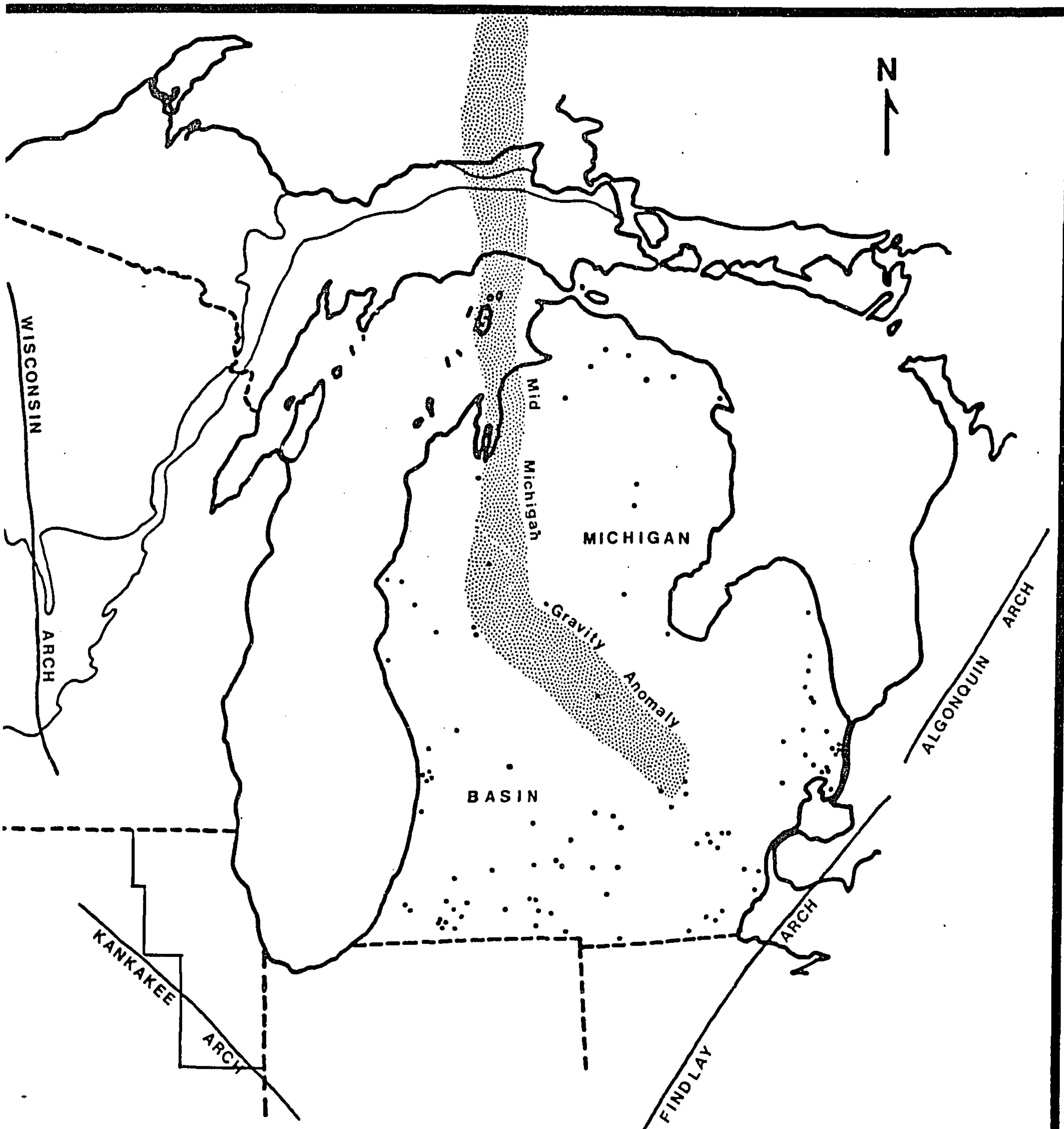


Figure 5. Midwestern Basement Structure. Dots in Michigan Correspond with Cambrian and Precambrian Well Locations (Figure 2).



ucture. Dots in Michigan Correspond with
n Well Locations (Figure 2).

central basin to penetrate Precambrian strata. There are 43 wells that penetrate the Precambrian in Michigan, and all but two of those lie in close proximity to the basin margins. All basin-margin wells encounter crystalline rock or a granite wash below the Mount Simon Sandstone with the exception of the McClure State-Beaver Island #1 well (Charlevoix County) which penetrated a similar sequence of redbeds to the Sparks et al. 1-8. The Beaver Island #1 also occurs along the axis of the Mid-Michigan Gravity anomaly (Fowler and Kuenzi, 1978).

In 1978, COCORP undertook a project to run 3 deep seismic profiles in the region of the Sparks et al. 1-8 well. The results are inconclusive, but an interpretation by Brown et al. (1982) shows deep reflecting horizons far below the strong reflection marking the Precambrian-Cambrian contact. The reflections show prominent half graben "benches" on either side of the gravity anomaly with a structural trough in the center, thus supporting the rift theory. The approximate center of the structural basin (Figure 6) is in the vicinity of the Hunt-Martin 1-15 in Gladwin County, interpreted from the greater thicknesses and depths found there. The Precambrian in the Sparks well, which lies just to the north and east of the seismic trough (Brown et al., 1982), is encountered at 11,413 feet below sea level. The Precambrian in the Hunt-Martin is estimated at 15,480 feet below sea level.

Structure

Several structural features, illustrated in Figure 5, are observed throughout the

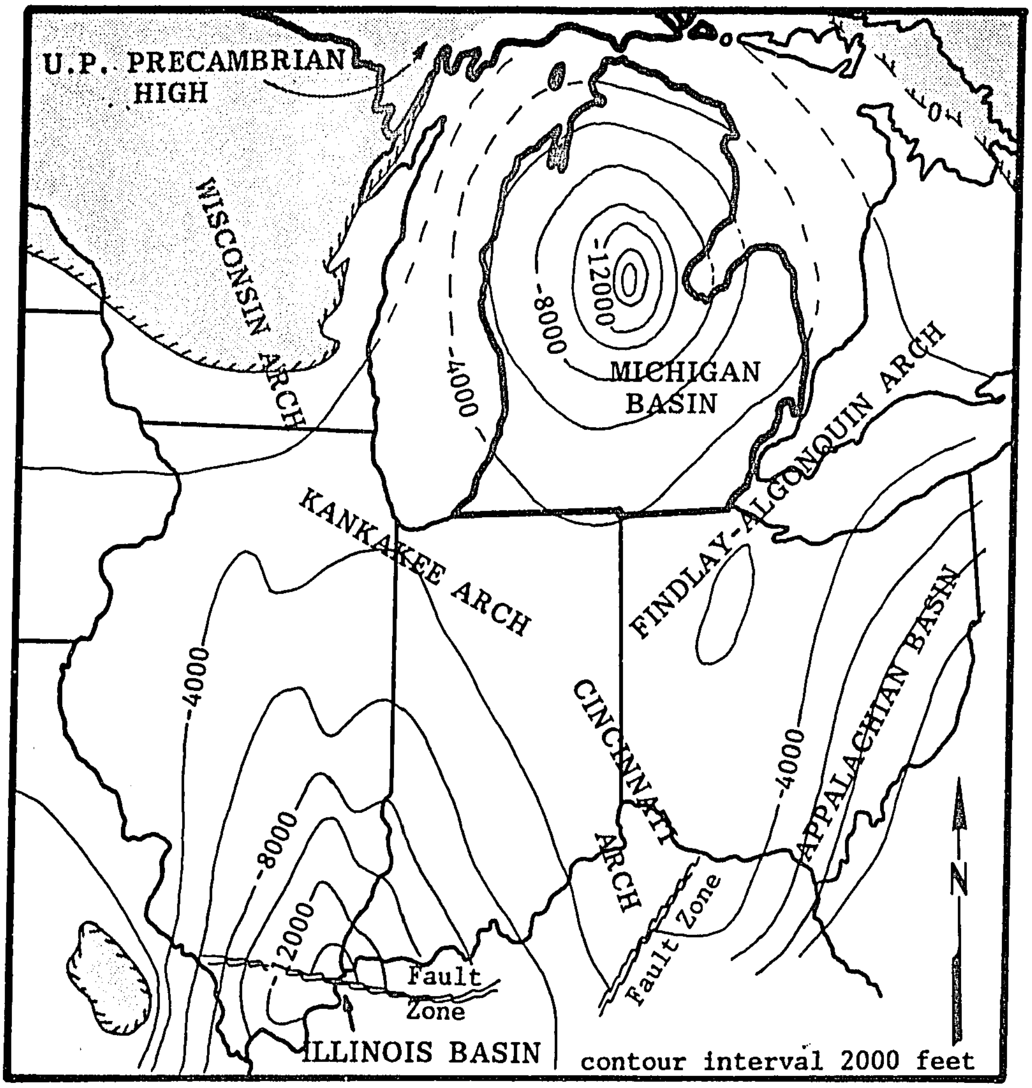


Figure 6. Midwestern Precambrian Contour Surface (modified from Droste and Shaver, 1983).

Midwest. Droste and Shaver (1983, p. 2) show that the Michigan basin is bounded on the southwest by the Kankakee arch in Illinois, and the Findlay-Algonquin arch on the southeast and east. To the west lies the Wisconsin arch, and beyond these features lie the Illinois basin to the southwest and the Appalachian basin to the southeast. The Canadian shield lies to the north and northeast, while to the northwest lies a Precambrian high in the Upper Peninsula (Dickas, 1986) and beyond the high lies the Superior basin.

The rifting event 1.1 billion years before present developed these structural features (Dickas, 1986), though the Kankakee Arch has a much more complex history to be discussed later. Subsequent mechanical and thermal subsidence initiated the development of several structural basins, notably the Illinois, Michigan, and Superior basins. These basins provided the "sink" for sediment accumulation, while surrounding highs provided the source of sediment. The sediment source for the Illinois and Michigan basins was the Canadian shield and associated metasediments, while the Wisconsin arch acted as a shoreline for the periodic lower Paleozoic deposition (Dott et al., 1986, p. 357).

Basin History

After the initial rifting event which began to pull apart the North American interior, subsidence in the Michigan Basin began 1.1 billion years before present (Dickas, 1986). Precambrian subsidence allowed for the accumulation of a thick sequence of redbeds and diabase sills (Fowler and Kuenzi, 1978). After this sequence was deposited, mechanical subsidence slowed greatly between .7 and .8 billion years before present (Klein and Hsui, 1987). Table 2 outlines the major

Table 2

Summary of Events of Basin Development

1. Early Keeweenawan (1.6 Ba) - Mantle upwelling creates initial rifting sequence associated with extension of the continental crust. Magmatic intrusions along faults and joints is common.

2. Middle Keeweenawan (1.3 Ba) - Extensional faulting continues, associated with the early stages of continental separation. This results in the development of a protoceanic basin. Magmatic intrusions still occurring as rhyolitic dikes and basalt flows.

3. Late Keeweenawan (1.1 Ba) - Extension begins to terminate, and the shallow asthenosphere now migrates downward. Subsiding basin begins to rapidly accumulate clastic sediment derived from nearby basin margins. Near the end of the Precambrian, the asthenosphere stabilizes and mechanical subsidence of the basin slows greatly and almost ceases. An erosion surface develops during latest Precambrian.

4. Late Cambrian (530 Ma) - The Sauk transgression renews sedimentation across the midwestern region.

5. Latest Cambrian/Early Ordovician (510 Ma) - Thermal subsidence begins and renews basin subsidence in both the Illinois and Michigan basins. Sedimentation continues during numerous fluctuations of relative sea level, causing facies tract migrations.

(Compiled from Fowler and Kuenzi, 1978; Dickas, 1986; Klein and Hsui, 1987; and Howell, 1988)

events in Michigan Basin history.

Observations in the Upper Cambrian Mount Simon sandstone show that the bowl shaped sedimentary package is much less pronounced, where a total thickness increase from 1246 feet in the Thalmann #1 (Berrien County) on the edge of the basin, to 1250 feet in the Sparks 1-8 (Gratiot County) is seen (Figures 7 and 8). Rather, the Mount Simon appears to be a trough-shaped package, where it thins to 700 feet (estimated) in the Victory 2-26 well (Mason County).

However, proceeding southwesterly from the Michigan Basin to the Kankakee arch, immediately a thickening trend occurs in each formation from the Cambrian Mount Simon sandstone to the Franconia formation (Figure 1). The Mount Simon sandstone seen in 4 cross sections of Figure 8, directly overlying the arch is 2550 feet (Buschbach, 1964) for an increase of 1300 feet, which is a much greater thickness than in the center of the Michigan Basin. This is the only observed thickening for the Mount Simon sandstone outside of the Michigan basin, and shows a major depocenter there during late Cambrian time, indicating the development of the Kankakee Arch at a later time.

Burial history analysis also indicates greater subsidence in the southwest region of the state. Figure 9 identifies two curves: a central basin curve and a basin margin curve. During Late Cambrian, the central basin was subsiding at a much slower rate than the southwest margin (nearest the Kankakee arch region). During the Ordovician, this trend reverses.

This pattern is seen in the overlying Eau Claire, Wonewoc, and Franconia formations as well (Figure 8), but changes abruptly in the Trempealeauan stage. At this point, renewed subsidence is suggested by Klein and Hsui (1987) at 520-550

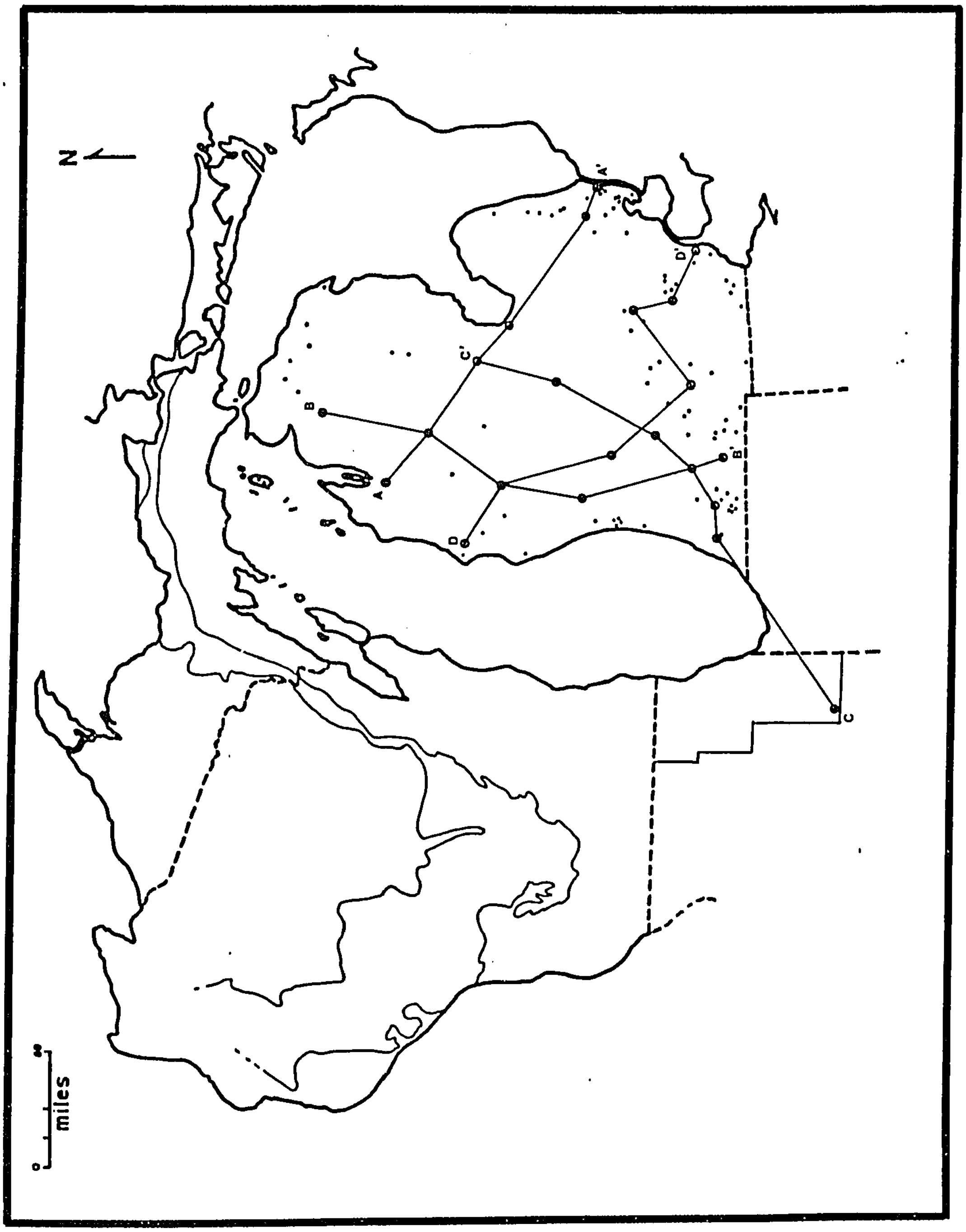


Figure 7. Index Map for Cross-Sections A-A' through D-D' in Figure 8a to 8d.

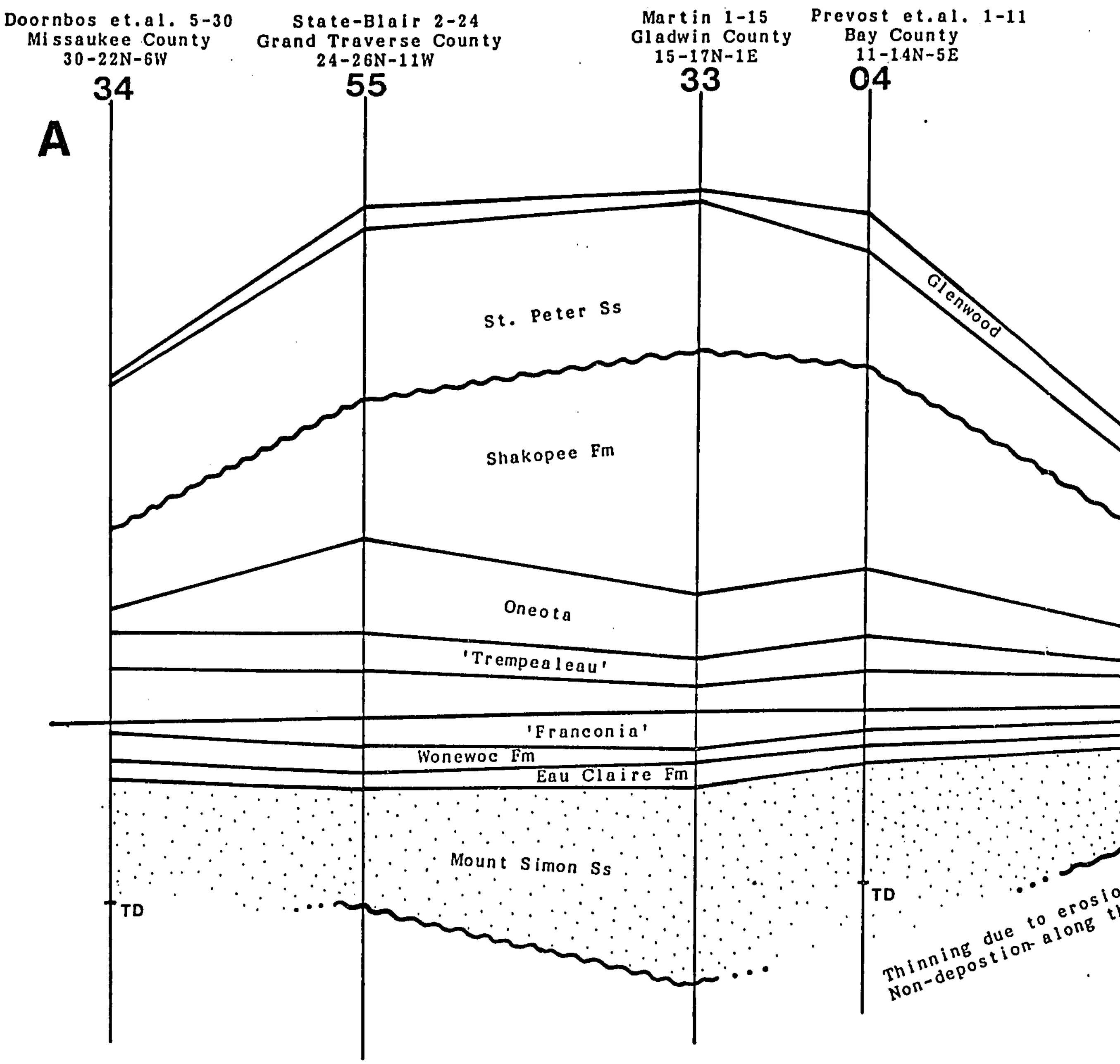
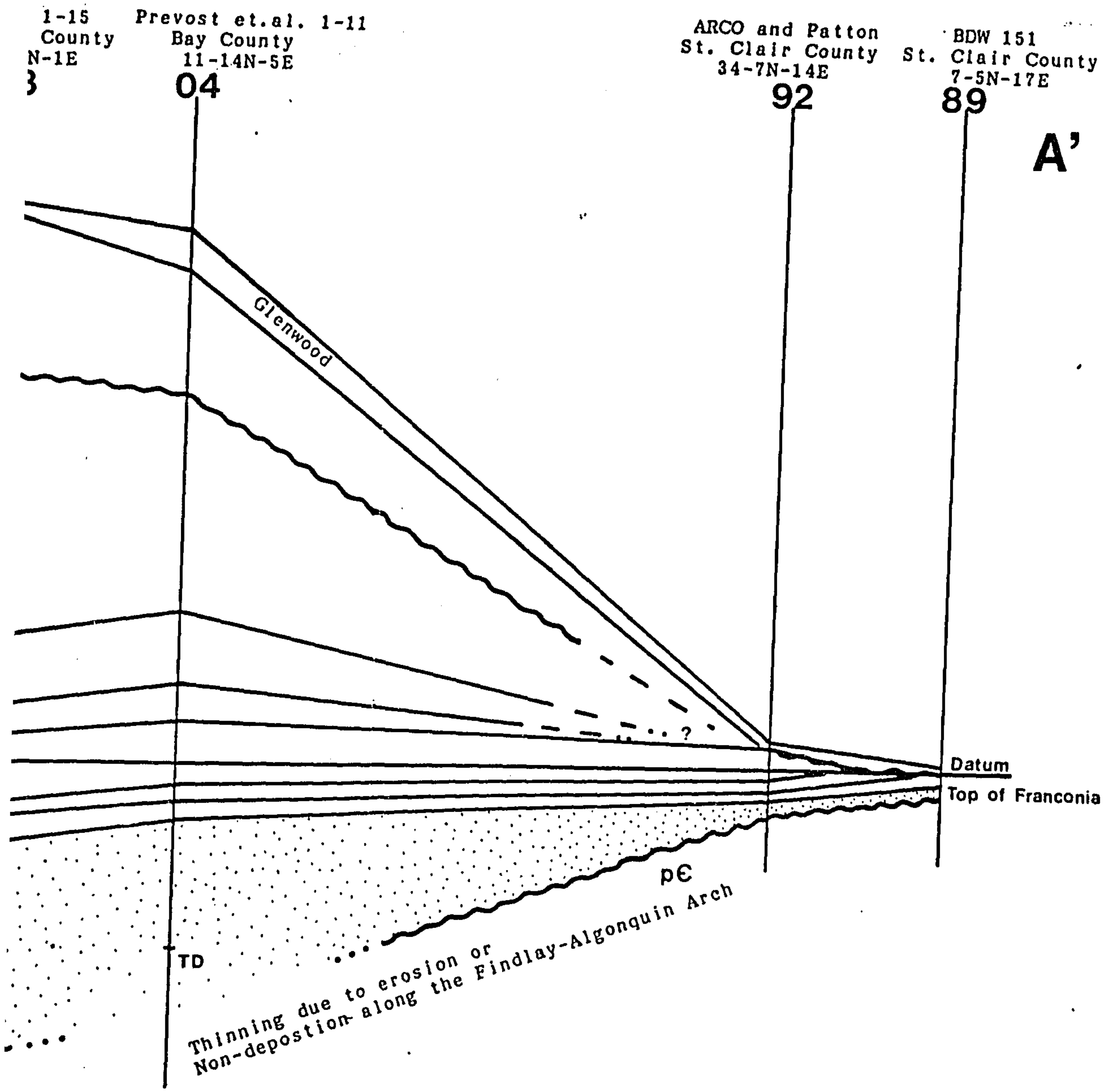
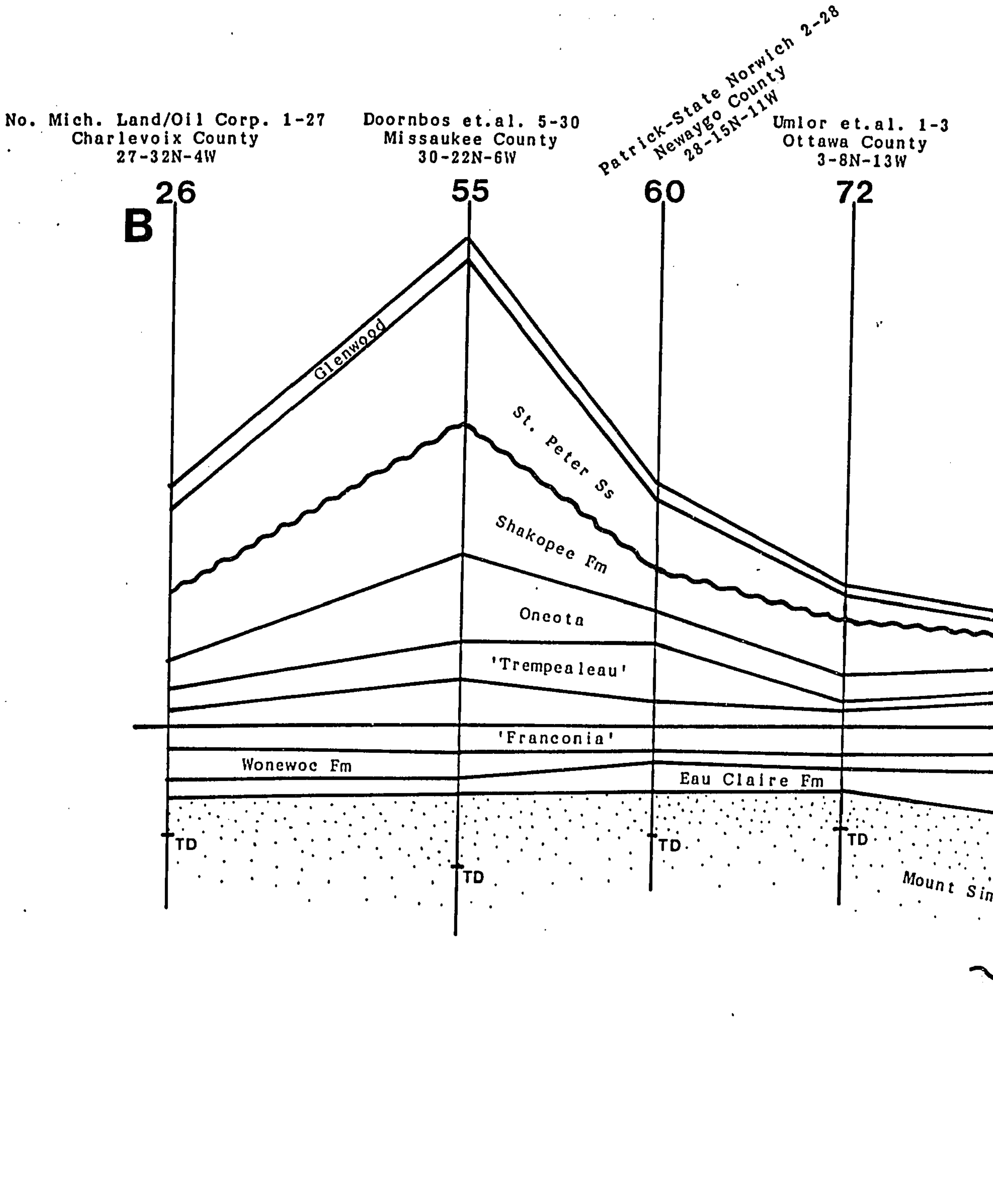
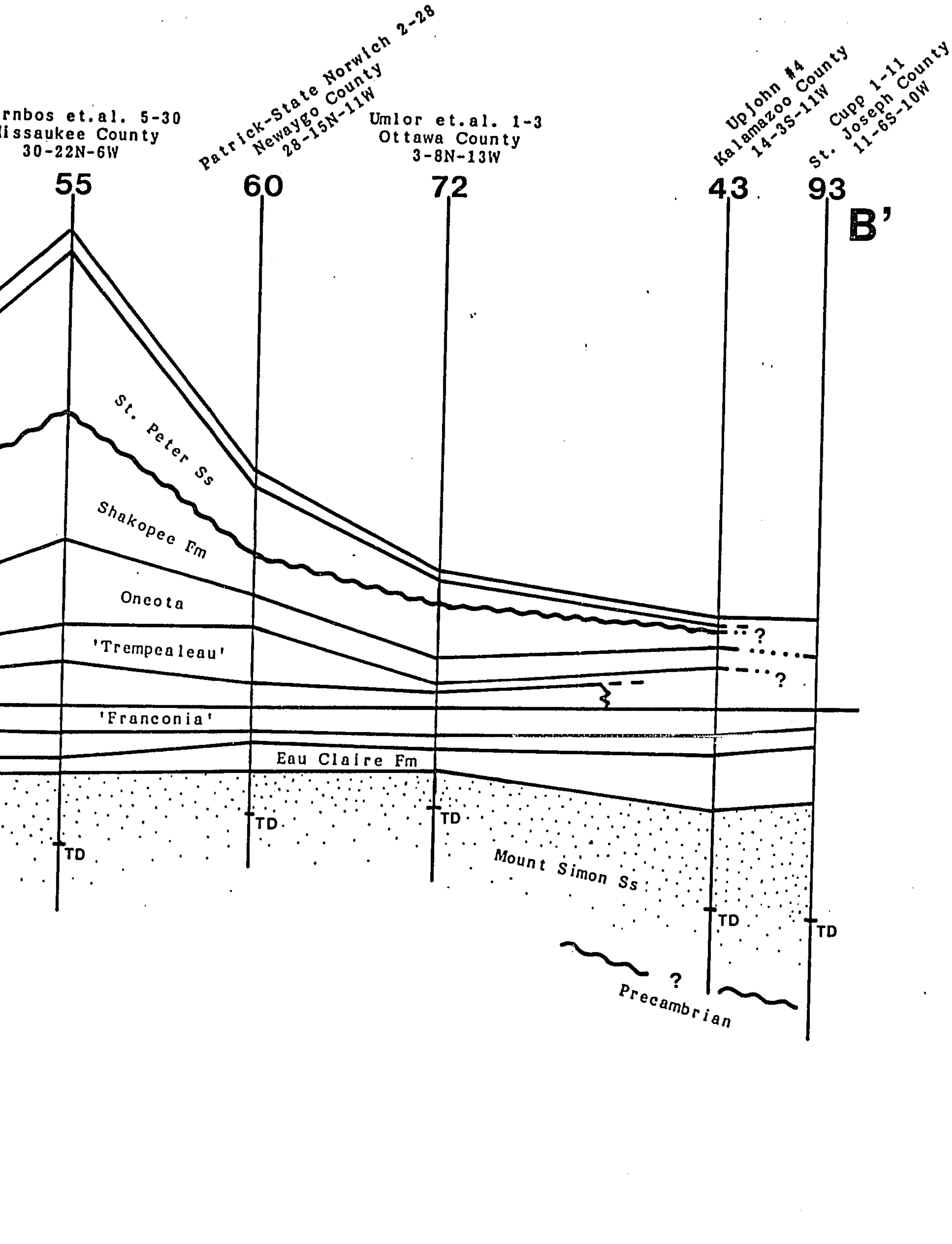


Figure 8. Cross Sections A-A', B-B', C-C', and D-D' (following pages).



' (following pages).


No. Mich. Land/Oil Corp. 1-27
Charlevoix County
27-32N-4W
Doornbos et.al. 5-30
Missaukee County
30-22N-6W
Patrick-State Norwich 2-28
Newaygo County
28-15N-11W
Umlor et.al. 1-3
Ottawa County
3-8N-13W
B
26
55
60
72
Glenwood
St. Peter Ss
Shakopee Fm
Oneota
'Trempealeau'
'Franconia'
Wonewoc Fm
Eau Claire Fm
TD
TD
TD
TD



rnbos et.al. 5-30
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30-22N-6W
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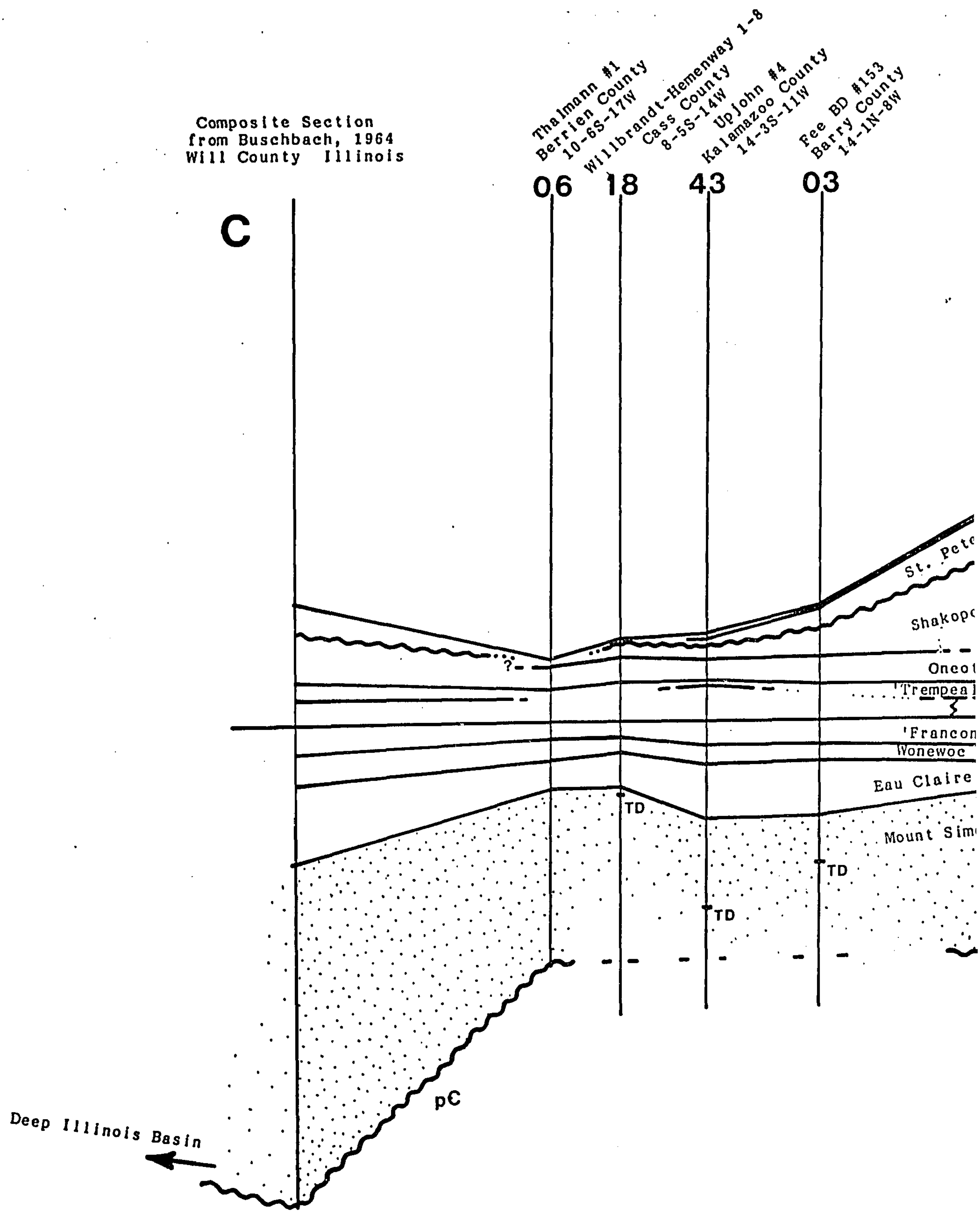
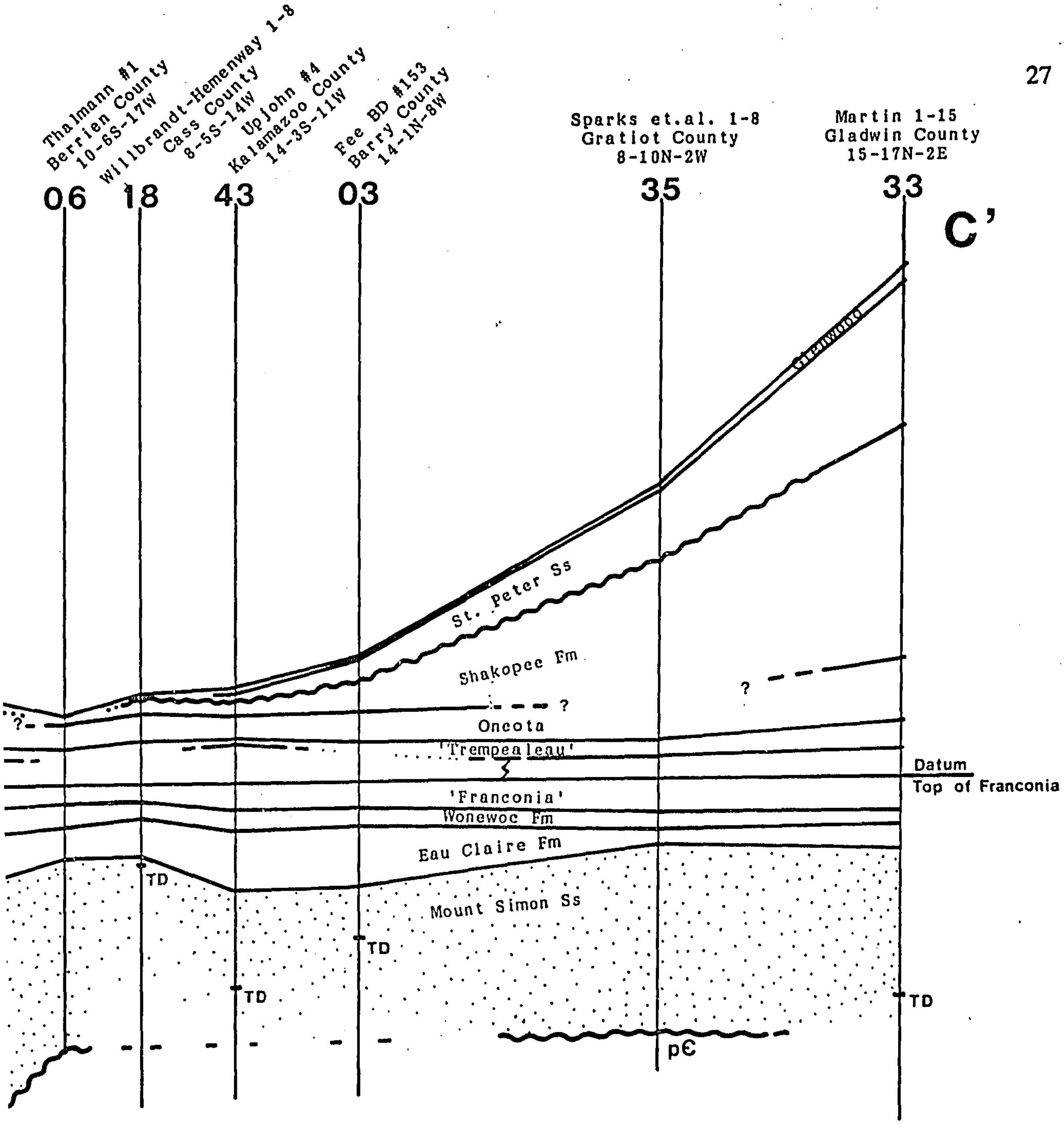
Patrick-State Norwich 2-28
Newaygo County
28-15N-11W
60
Umlor et.al. 1-3
Ottawa County
3-8N-13W
72
Upjohn #4
Kalamazoo County
14-3S-11W
43
Cupp 1-11
St. Joseph County
11-6S-10W
93
B'
St. Peter Ss
Shakopee Fm
Oneota
'Trempealeau'
'Franconia'
Eau Claire Fm
Mount Simon Ss
Precambrian
TD
?


Composite Section
from Buschbach, 1964
Will County Illinois
C
Thalmann #1
Berrien County
10-6S-17W
Willbrandt-Hemenway 1-8
Cass County
8-5S-14W
Upjohn #4
Kalamazoo County
14-3S-11W
Fee BD #153
Barry County
14-1N-8W
06
18
43
03
St. Pete
Shakopo
Oneot
Trempea
Francon
Wonewoc
Eau Claire
Mount Sim
TD
TD
TD
pC
Deep Illinois Basin


Thalmann #1
Berrien County
10-6S-17W
Willbrandt-Hemenway 1-8
Cass County
8-5S-14W
Upjohn #4
Kalamazoo County
14-3S-11W
Fee BD #153
Barry County
14-1N-8W
Sparks et.al. 1-8
Gratiot County
8-10N-2W
Martin 1-15
Gladwin County
15-17N-2E
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03
35
33
C'
Glenwood
St. Peter Ss
Shakopee Fm
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Oncota
'Trempealeau'
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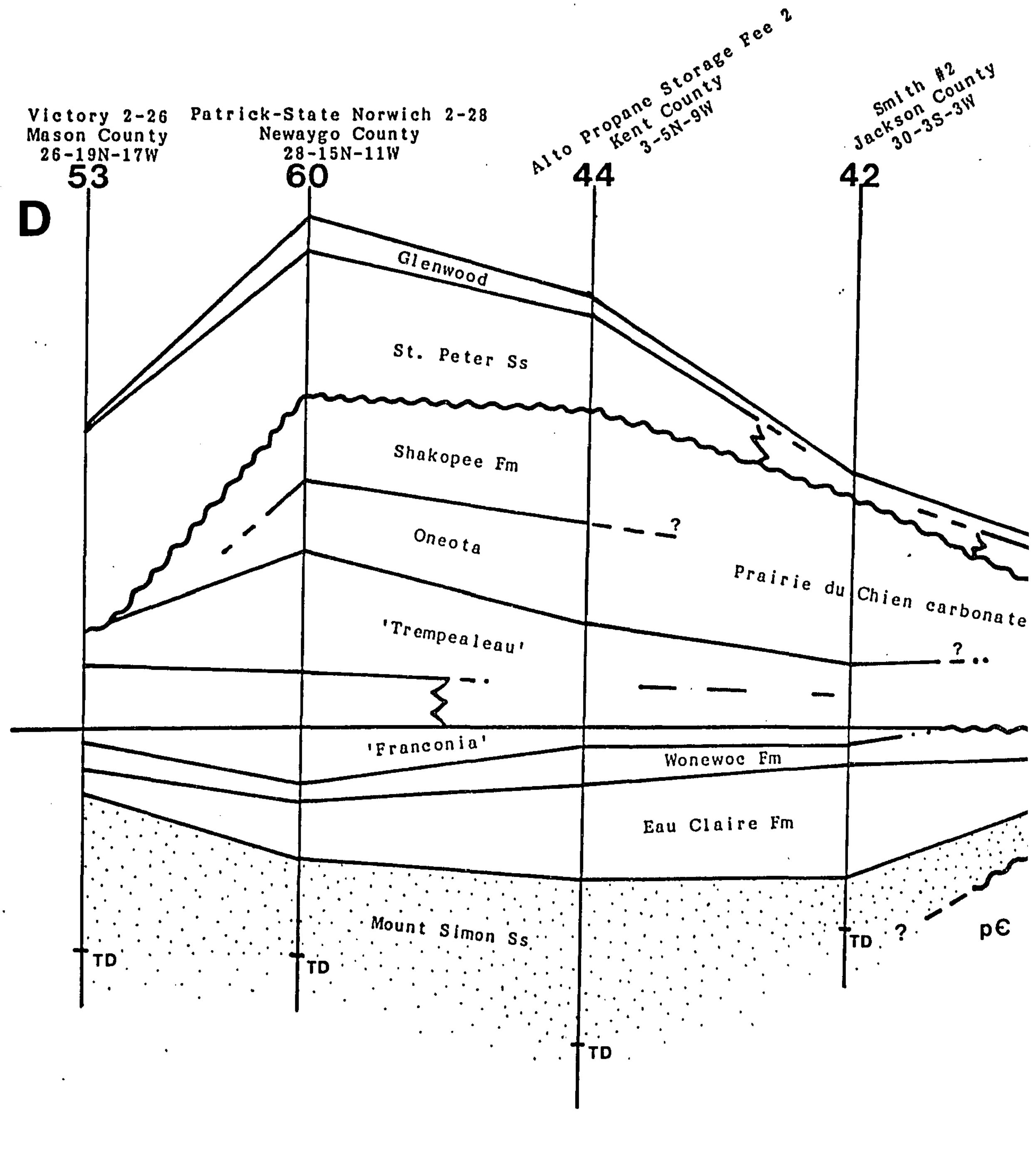
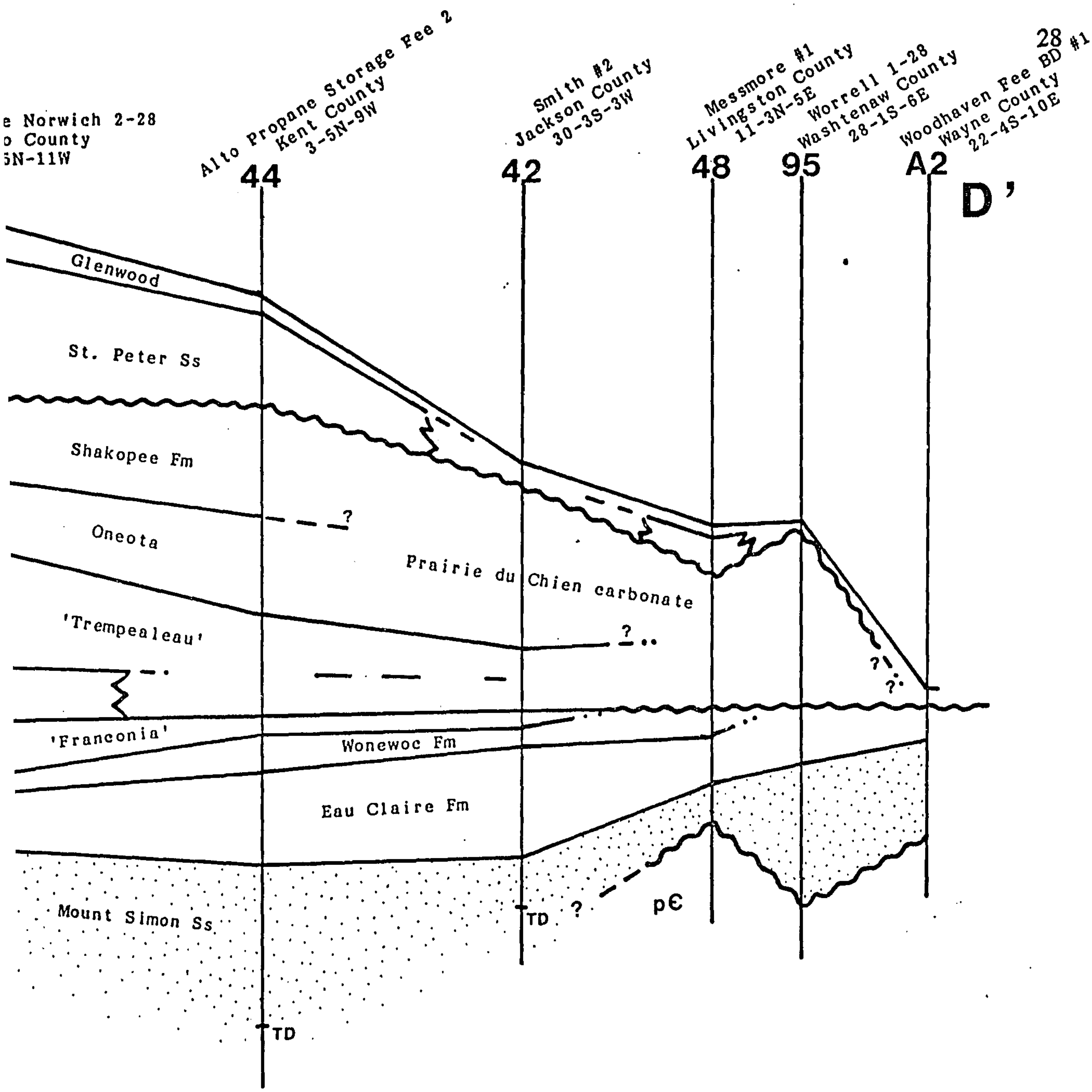
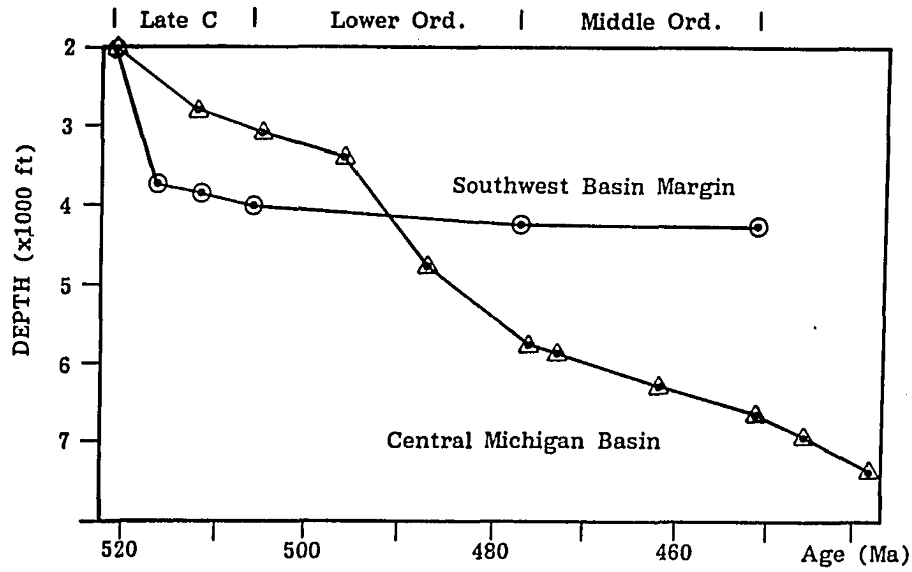
Top of Franconia
'Franconia'
Wonewoc Fm
Eau Claire Fm
Mount Simon Ss
TD
pЄ


Victory 2-26
Mason County
26-19N-17W
53
Patrick-State Norwich 2-28
Newaygo County
28-15N-11W
60
Alto Propane Storage Fee 2
Kent County
3-5N-9W
44
Smith #2
Jackson County
30-3S-3W
42
D
Glenwood
St. Peter Ss
Shakopee Fm
Oneota
Prairie du Chien carbonate
'Trempealeau'
'Franconia'
Wonewoc Fm
Eau Claire Fm
Mount Simon Ss
pЄ
TD


e Norwich 2-28
o County
5N-11W
Alto Propane Storage Fee 2
Kent County
3-5N-9W
44
Smith #2
Jackson County
30-3S-3W
42
Messmore #1
Livingston County
11-3N-5E
48
Worrell 1-28
Washtenaw County
28-1S-6E
95
Woodhaven Fee BD #1
Wayne County
22-4S-10E
28
A2
D'
Glenwood
St. Peter Ss
Shakopee Fm
Oneota
Prairie du Chien carbonate
'Trempealeau'
'Franconia'
Wonewoc Fm
Eau Claire Fm
Mount Simon Ss
pЄ
TD
TD



△ -Basement subsidence curve from Howell (1988).

⊙ -Basement subsidence curve, Thalmann #1, Berrien County.

Note that the margin was subsiding at a much faster rate in Late Cambrian time compared to the central basin.

Figure 9. Late Cambrian to Early Ordovician Burial History Curve for the Central Basin and the Southwest Basin Margin.

million years before present, only this time from a thermal imbalance. This thermal imbalance resulted from an uncompensated isostatic load from the heavier, mafic material of the rift (Klein and Hsui, 1987, p. 1097). This subsidence is observed in the increased sediment thickness evident in the Prairie du Chien carbonates and the St. Peter sandstone. Prairie du Chien carbonates increase from 50 feet in the Victory 2-26 well (Mason County) to 1850 feet in the Martin 1-15 well (Gladwin County) for an increase of 1800 feet in the center of the basin.

Droste and Shaver indicate a structural consequence of this model is that growth faulting should then be evident in those formations already in place at the time of renewed subsidence. They report that there is evidence for such features in the Illinois basin (1983), and if the Illinois and Michigan basins are developed along similar paths as Klein and Hsui suggest (1987), then these features should be evident in the deep Michigan basin as well. As study of the basin continues, such features may eventually be documented, but at present, there has been no evidence presented in literature.

CAMBRO-ORDOVICIAN SEQUENCE STRATIGRAPHY AND LITHOFACIES

Although the stratigraphy of the Cambrian and Lower Ordovician in Michigan has been previously described in published literature (Catacosinos, 1973; Bricker et al., 1983), a serious consideration of regionwide description and correlation has not been attempted in recent years. It should be noted, however, that Ells (1967) and Catacosinos correlated the Cambrian of the Upper Peninsula with that of the basin. However, the Upper Peninsula strata reflect more the Superior Basin than the Michigan basin, since most of the strata straddle a Precambrian high between the Michigan Basin and the Superior Basin (Dickas, 1986). Generally, sedimentary rocks of Precambrian age in the Upper Peninsula dip northwestward towards the Superior Basin (Ostrom and Slaughter, 1967; Dickas, 1986), while rocks of Cambrian age dip 35 to 45 degrees to the southeast, towards the Michigan Basin (Ostrom and Slaughter, 1967). Some of the Cambrian exposures dip southeast by virtue of numerous synclines in the Upper Peninsula, and the entire region has been tectonically altered by the Midcontinent and Mid-Michigan rifts (Dickas, 1986). Uncertainty between rock types in the Michigan Basin and the Upper Peninsula and the proximity of Upper Peninsula sediments to the Precambrian gravity anomaly of the rift make correlations between the two questionable.

Analysis of sedimentary rocks from the Cambro-Ordovician section in

Michigan, Illinois, Indiana, Wisconsin, Iowa, and Minnesota, shows remarkable similarity in overall gross lithofacies (Table 3) and overall stratigraphic units (Sloss, 1963; Ostrom, 1970). However, as isopach data from the Cambrian seen in Figure 10 indicates, there was little subsidence in the Michigan or Illinois Basins during Dresbachian time, and therefore a more uniform region-wide facies tract would result. This changes during Trempealeauan time (Figure 1) as the formations above show a tremendous thickening in the basin center, identified previously. Eventually by the end of Trempealeauan time, the basin is subsiding at a much greater rate than during Dresbachian and Franconian time, and several different facies are recognized in conventional wireline log and cuttings analysis. Trempealeauan sedimentation is the most complex because numerous lithofacies are observed, and also the most poorly understood in the Michigan stratigraphic sequence. Several formation names have been assigned in literature for observations made in this interval, such as the St. Lawrence formation and Jordan sandstone (Catacosinos, 1973), and most commonly, the Trempealeau formation (Bricker et al., 1983; Fisher and Barratt, 1985).

Cambrian System

No outcrops of the Cambrian exist anywhere in the lower Peninsula, but excellent exposures of the entire Cambro-Ordovician section can be seen along the flanks of the Wisconsin Arch in Western Wisconsin. These exposures represent the Cambrian and Ordovician systems along the Michigan Basin's western limit, and

Table 3

Comparison of Outcrop and Subsurface Lithology

Formation	Wisconsin/Illinois Lithology	Subsurface Lithology
Shakopee Dolomite	(Willow River Member) - Tan to cream sandy and intraclastic dolomite, that commonly exhibits algal stromatolites and oolitic dolomite. Minor amounts of grey-green shale and quartz sandstone are present. (New Richmond Member is a Sandstone lithology). Minor Amounts of Chert are included in Illinois, where color changes to light grey or brown.	The Shakopee in Michigan is a light to dark grey crystalline dolomite, exhibiting both sandy and argillaceous zones throughout. Algal stromatolites have been observed. Isolated bodies of dolomitic sandstone are also recognized.
Oneota Formation	In Wisconsin, the Oneota is a medium grained, tan to cream colored dolomite and sandy dolomite, with very minor amounts of chert, shale, and calcite. It is a purer dolomite than the overlying Shakopee. In Illinois subsurface, the medium-fine grained Oneota becomes light grey in color and contains slightly more chert and shale.	The Oneota in Michigan has little core control, and thus the lithology is less well known. In cuttings samples, the Oneota exhibits a light to medium grey crystalline dolomite with less sand and shale content than the overlying Shakopee.
Trempealeau A	In Wisconsin, the Trempealeau consists of the Jordan Sandstone, a fine grained cream colored quartzarenite. Illinois stratigraphy exhibits a lateral variation from the northern areas to the Eminence Dolomite seen elsewhere. The Eminence is a light grey to brown sandy dolomite that contains minor amounts of chert. A thin basal sandstone is reported.	The Trempealeau A in Michigan is a light to medium grey dolomite with no core control. It appears in cuttings to contain a higher shale percentage than the overlying Oneota. A hypothesis not pursued here is that this interval is part of the overlying Oneota and not assigned to the Trempealeauan Stage (figure 1).

Formation	Wisconsin/Illinois Lithology	Subsurface Lithology
Trempealeau B	The St. Lawrence Formation (Wisconsin) is a feldspathic siltstone and sandy dolomite. In Illinois this becomes the Potosi Dolomite, a light grey, fine grained, slightly glauconitic dolomite.	The Trempealeau B interval in Michigan is a medium quartzarenite in the northern and northeastern portions of the state, and undergoes a facies change in the southern and southwestern regions to a dolomite. This dolomite correlates with the Eminence/Potosi Dolomites of northeastern Illinois.
"Franconia"	The Franconia in Illinois is a light grey to pink fine grained dolomitic sandstone. This changes to a cream colored fine grained feldspathic and glauconitic sandstone and siltstone of the Lone Rock Formation, and a fine to medium grained quartzose and feldspathic sandstone of the Mazomanie Formation, both in Wisconsin.	In Michigan, the Franconia is generally a very sandy to silty/argillaceous light grey dolomite and having a sandier lithology nearer to the Wisconsin Arch and siltier away from the arch. The sand and silt content from cuttings is in excess of 40 percent.
Wonewoc Formation	The Wonewoc is a fine to medium grained dolomitic sandstone, with subround to round, well sorted grains. Generally a distinction is made in both Illinois and Wisconsin between the Galesville and Ironton members of the Wonewoc.	The Wonewoc in Michigan is generally a fine to medium grained quartzarenite with subround grains. The Wonewoc has a higher shale content closer to the Wisconsin Arch. Dolomite cement is common further from the arch (southeast)
Eau Claire Formation	The Eau Claire is generally a mixture of tan siltstones and shales, exhibiting fossil trilobites and brachiopods, glauconite, and abundant mica. Much of the Eau Claire is dolomitic, and in Illinois, a sandy dolomite member is also identified.	The Eau Claire in Michigan is an argillaceous and dolomitic siltstone, grading to a silty dolomite in many regions. It is generally light grey, tan, and pink, with minor algal markings present.

Formation	Wisconsin/Illinois Lithology	Subsurface Lithology
Mount Simon Sandstone	The Mount Simon is a medium to coarse grained quartzarenite that exhibits moderate sorting and subangular to subround grains. Vertical variations show a decrease in the feldspar content upwards in the section. Zones of pebbles are common. The Mount Simon becomes argillaceous in the upper section. Brachiopod fossils are found near the upper contact with the Eau Claire Formation.	The Mount Simon in Michigan is a medium to coarse, subround to subangular grained quartzarenite that is moderately to poorly sorted. Abundant feldspar is observed in the shallower cores, while deeper samples exhibit a more quartzose lithology. Minor amounts of glauconite are present, along with brachiopod fossils in the upper section. A basal conglomerate is present in many shallow wells.

therefore are a logical choice for comparison. The outcrops are actually along the western side of the arch in the "driftless area," but are the same formations seen in the subsurface in Wisconsin (Ostrom, 1978). The outcrop region is also where the type section for each formation is found.

The Cambrian System in Michigan begins with the Mount Simon Sandstone, a basin-wide cratonic sand that overlies Precambrian undifferentiated crystalline rock and metasediments along the margins of the basin and an unknown thickness of Precambrian sediment occupying part of the center of the basin along the axis of the gravity anomaly. The Mount Simon sandstone is overlain by the Eau Claire, Wonewoc, and Franconia Formations, which all exist basinwide and can be correlated outside of the basin. The Mount Simon, Eau Claire, Wonewoc, and Franconia

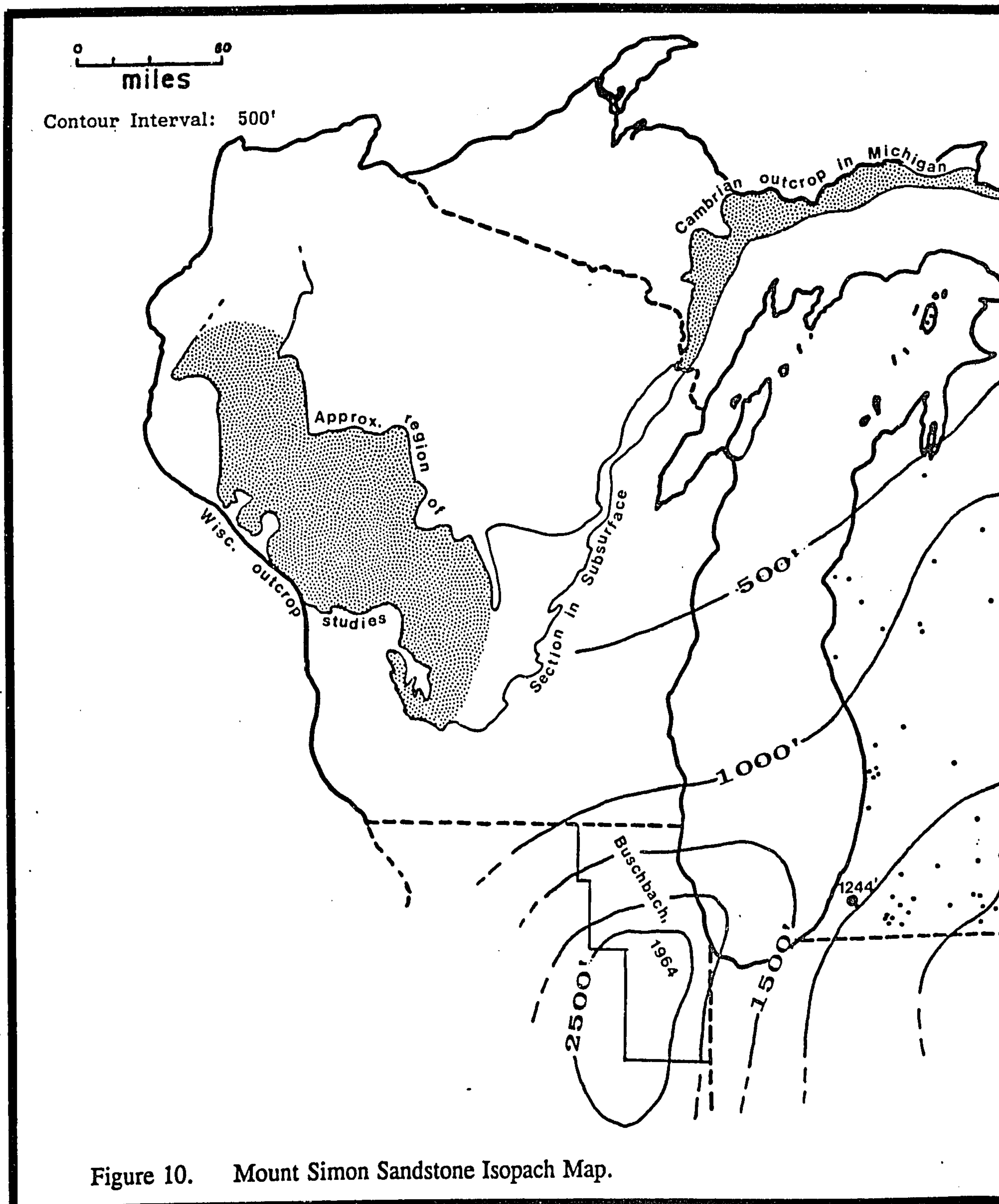
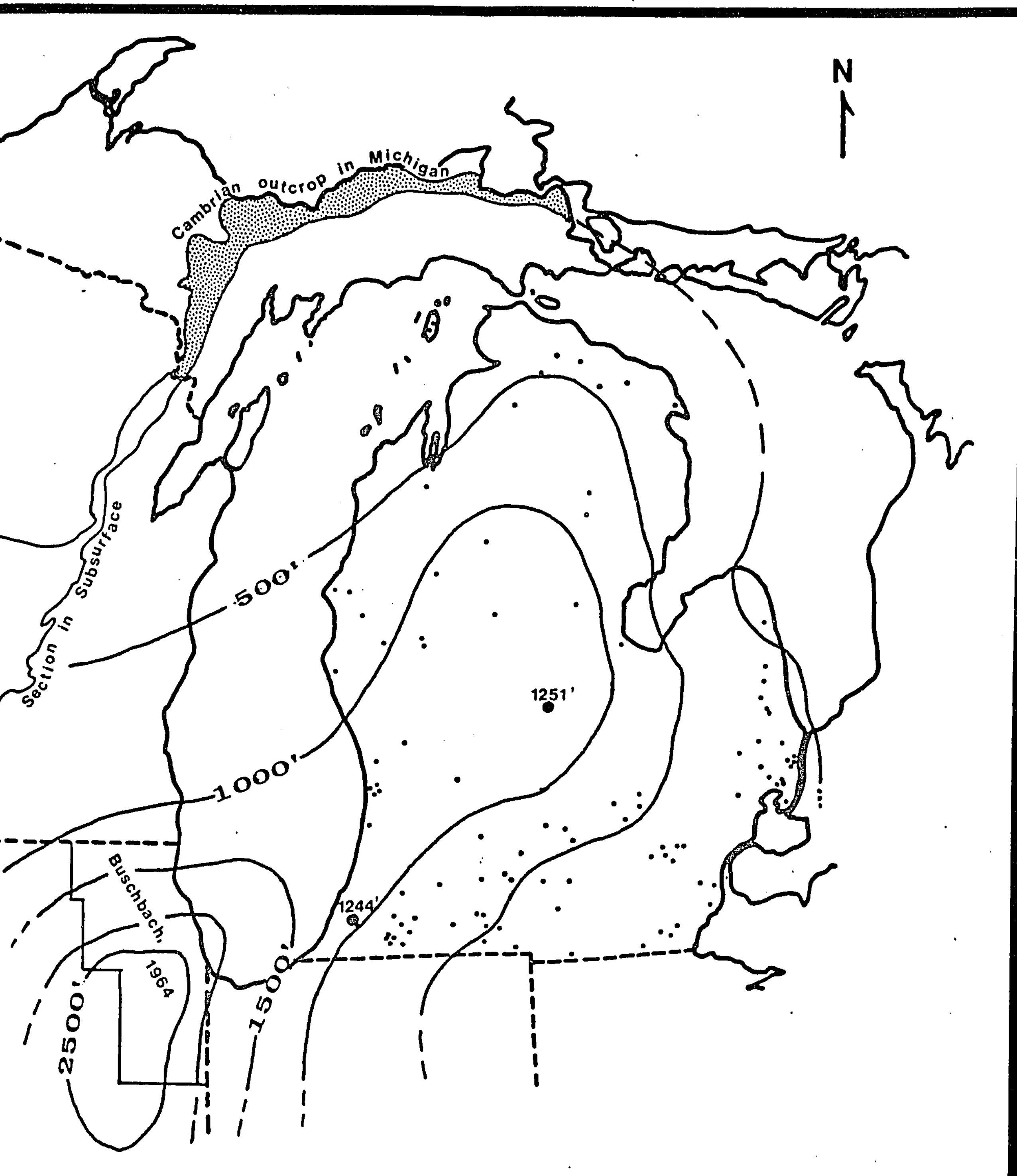


Figure 10. Mount Simon Sandstone Isopach Map.


N
Cambrian outcrop in Michigan
Section in Subsurface
500'
1000'
1500'
2500'
1251'
1244'
Buschbach, 1964

pach Map.

formations show a standard signature (Figure 3) on Gamma ray-Neutron logs, and the Mount Simon, Eau Claire, and Wonewoc are also uniform in thickness throughout much of the basin. Another exception is the southeast part of the state where all formations between Eau Claire and the Lower Ordovician Glenwood formation are absent, due to non-deposition or subsequent erosion, most likely due to the presence of the Findlay-Algonquin arch. In Huron County, even the Mount Simon and Eau Claire formations are absent, as observed in the Volmering #1.

The other rock units included in the Cambrian are those assigned to the Trempealeauan Stage, which include the Trempealeau A and B formations throughout much of the state, and the correlative carbonate facies of this interval in the center and southwest portions of the basin. There is no biostratigraphic control with any of these formations, so the actual Cambrian-Ordovician boundary has not been determined. However, physical correlation between the Michigan Basin and the Wisconsin and Illinois sections is possible because of the structural and sedimentary evidence which indicates the connection of both basins during the Dresbachian stage (Figure 1) (Droste and Shaver, 1983).

Cambro-Ordovician formations in Michigan are identified through conventional core and cuttings analysis. Lithology correlated with well log signature (Figure 3) then becomes the basis for correlation among the majority of deep wells in Michigan when actual rock data is unavailable. The distinction between formations in Illinois and Wisconsin also includes faunal assemblages in addition to lithologic data, that delineate biofacies (Ostrom, 1965; Willman et al., 1975). In Michigan, there aren't enough cores taken in any of the formations described here to include faunal assemblages in the description, although the presence of fossils will be noted.

Mount Simon Sandstone

The Mount Simon Sandstone is the oldest Cambrian formation in Michigan, and the lowermost of the Upper Cambrian Dresbachian Stage. The Mount Simon is originally named for excellent exposures of a medium-coarse, subround-rounded quartzarenitic sandstone at Mount Simon Hill in Eau Claire, Wisconsin (Walcott, 1914). In Michigan, the Mount Simon observed in cuttings and core samples ranges from the same white to cream colored lithology to subangular arkosic sandstone along the southeast margin of the basin. This change in lithology may be due to a direct influence of a source terrane different than that of most of the Mount Simon; possibly a local influence from the east-bounding Findlay-Algonquin arch which represents a Precambrian basement high. A localized basal granite wash or arkosic zone is observed in some wells along the basin margins that penetrate Precambrian (Bricker et al., 1983). Zones of brachiopod shells occur in the upper Mount Simon, just as they are found in outcrop. Vertical Skolithos and other burrows are also common.

Other differences between the Mount Simon of Wisconsin and the Mount Simon of Michigan are the amounts of diagenetic modification present and the change in grain size from outcrop to basin. Outcrop samples show little or no pore-occluding cements, but SEM analysis of samples of the Mount Simon show some minor quartz and dolomite cement that shows dissolution along crystal faces (Figure 11), indicating secondary dissolution processes. Subsurface samples however, show abundant amounts of authigenic and detrital clay, pervasive dolomite cements, quartz cement and compaction-dissolution of quartz grains. The Mount Simon in the basin shows a slightly finer (a difference of .5 to 1 phi) grain size range than that of the type section and outcrop areas, since the outcrop areas exist along the arch are and the probable source area for the sediment (Dott et al., 1986).

Eau Claire Formation

The Eau Claire Formation, also assigned to the Dresbachian Stage, exists basin-wide, and is gradational with the top of the Mount Simon. The Eau Claire represents interbedded shales and carbonates that are part of the first stratigraphic sequence (Figure 4) recognized by Ostrom (1970) and represents a more distal, lower energy environment, resulting from continued onlap. The Eau Claire is named for exposures of argillaceous, fossiliferous sandstone and siltstone seen in outcrop at Eau Claire Wisconsin (Willman et al., 1975, p. 42). In Michigan well logs, it is defined above the Mount Simon by a high gamma ray signature, and in sample shows a much higher dolomite content (Figure 12). The Eau Claire in Michigan is not the same as that of the type section: The basinal setting has allowed for development of a more

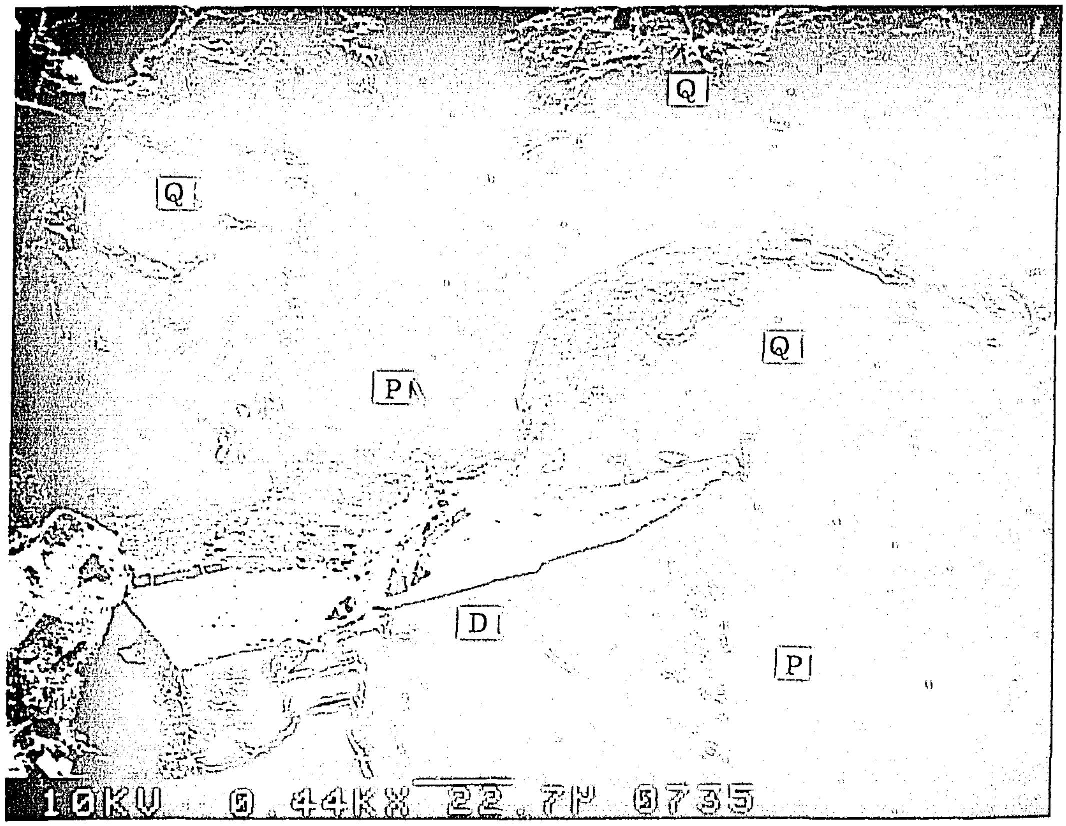


Figure 11. Scanning Electron Microscope (SEM) Photo of Mount Simon Sandstone Type Section in Wisconsin. P = Pore, Q = Quartz, D = Dolomite Cement.

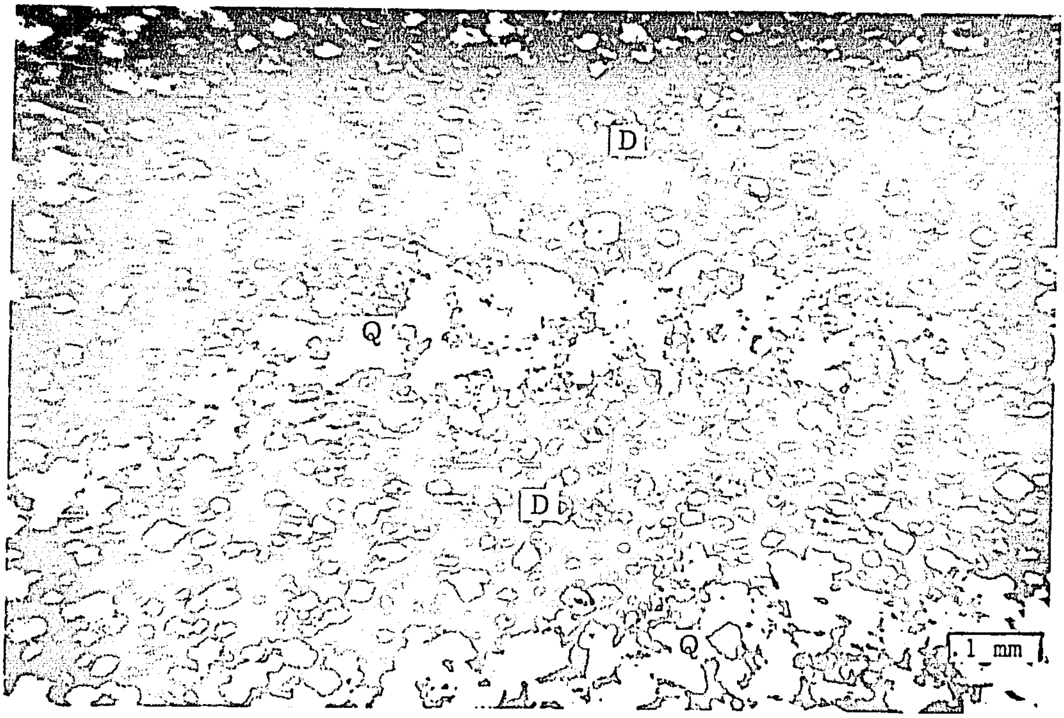


Figure 12. Typical Eau Claire Formation - Fine Grained Sandstone with Dolomite Cements. Q = Zone of Quartz Grains, D = Zone of Dolomitic Cementation.

dolomitic facies. Samples of Eau Claire from the Consumer's Power brine disposal Wells (#151, #139) in St. Clair County are excellent examples of this facies, but also show abundant amounts of fine sand present in intervals throughout. Little detrital clay is observed in core and cuttings samples. The high gamma ray signature in well logs therefore is attributed to the presence of both glauconite and feldspar, both identified in thin section analysis of Michigan samples.

There is some debate as to the actual contact between Mount Simon and Eau Claire (Mike Sargent, personal communication, Illinois State Geological Survey). In Wisconsin, the contact is distinguished by numerous criteria, including a finer grain size than the Mount Simon, abundant thinly bedded shale zones that contain trilobites and glauconite (Ostrom, 1970). In general, the boundary is considered at the point where a distinct lithologic change is recognizable, even though the contact is gradational. In Illinois, the initial presence of abundant detrital clay in the upper regions of the massive medium grained Mount Simon sandstone marks the contact between the two. Unfortunately, this debate cannot apply to Michigan, simply because not enough rock data is available (Table 1). For well log correlation, however, the top of the Mount Simon has been picked <u>above</u> the initial increase in the gamma ray curve, since correlation here is made with the Wisconsin outcrop belt. Because this upper arkosic and fossiliferous zone between Mount Simon and Eau Claire is predominantly a quartzarenite (from core lithology), its lithologic similarity also dictates usage of the Mount Simon top described above. The Eau Claire in

Michigan displays an arkosic dolomitic lithology, which is fundamentally different from the underlying sands of the Mount Simon. Brachiopod fossils observed in the Upjohn core (Kalamazoo County) and the upper Mount Simon of the BD 151 core (St. Clair County, Table 1), indicate correlation with the top unit of Mount Simon Hill in Eau Claire Wisconsin. This is the type section for the Mount Simon sandstone and is considered to be wholly Mount Simon (Ostrom, 1970). Identification of the brachiopod fossils has not been made at this time.

The Eau Claire is generally a pink, green, and grey argillaceous dolomite throughout the basin, including numerous sandy dolomite units. Porosity observed in samples is poor (Figure 12), making the Eau Claire a good seal for porous zones in the Mount Simon. The log signature is an easily distinguished high gamma ray curve, and is comparable to the log signature in Illinois wells penetrating the Eau Claire (Buschbach, 1964; 1965). The Eau Claire in outcrop is generally a cream colored mixture of shale and fine sand. Abundant Trilobites and Brachiopods are found along bedding planes. Unlike the type section, no fossils have been found in the 3 Michigan cores taken in the Eau Claire. Bedding is generally planar, and a relatively uniform formation thickness exists across the basin (Droste and Shaver, 1983). There is a thickening in the center of the basin of 20-30 feet that indicates minor subsidence. Brady and DeHaas (1988, part 8) report that the Eau Claire more than triples in thickness toward the Kankakee arch in Illinois as the upper Mount Simon thins, indicating a lateral facies relationship with the Mount Simon. Although cross sections indicate that the Eau Claire does indeed thicken toward the southwest (Figure 8), the underlying Mount Simon also thickens in a southwesterly direction, contrary to what Brady and DeHaas (1988, part 8) report. The observed thickness patterns clearly indicate that the depocenter during Dresbachian time which includes both the Mount Simon and Eau Claire formations, as well as the overlying Wonewoc formation, was in northeastern Illinois and not in the central Michigan Basin (Droste and Shaver, 1983) The Eau Claire thins dramatically along the southeastern margins of the basin (St.Clair, Macomb, Wayne Counties) due to erosion or nondeposition, where it is overlain by the Middle Ordovician Glenwood formation.

Wonewoc Formation

The Wonewoc Formation, divided into the Ironton and Galesville Sandstone members in Wisconsin (Emrich, 1966; Ostrom, 1970), appears throughout much of the Michigan Basin, but thins out due to erosion or non-deposition in the south central and southeast portions of the basin. The Wonewoc was named the Dresbach in early literature (Willman et al., 1975), but since the outcrops now have been defined and subdivided into formations and members, that nomenclature should also carry into the Michigan subsurface based on lithologic similarities to outcrop formations (North American Committee on Stratigraphic Nomenclature, 1983). Although the Michigan Geological Survey continues to apply the term "Dresbach" to this interval in Michigan (Bricker et al., 1983), its usage should be abandoned since it is a time stratigraphic term that covers the underlying Mount Simon and Eau Claire formations as well.

The Galesville member of the Wonewoc is named for exposures of the Galesville Sandstone in and near Galesville, Wisconsin (Trowbridge and Atwater, 1934). The Galesville in outcrop is a cream to rust-colored, well-sorted, well-rounded friable sandstone, containing zones of brachiopods (Ostrom, 1970). No fossils have been observed in the Michigan Wonewoc due to the lack of any core control. The only samples of Michigan Wonewoc are from cuttings sets (Table 1).

Within the Basin, the Wonewoc is generally an argillaceous to dolomitic sandstone, exhibiting an argillaceous facies closer to the Wisconsin arch and in shallower wells along the basin margins. The dolomitic facies is found in deeper wells and wells that are on the opposite side of the basin from the Wisconsin arch. The basin-wide log signature is a low gamma ray curve throughout the formation, distinguished from the high gamma ray spikes of the underlying Eau Claire formation and overlying Franconia interval (Figure 3).

No cores have been taken in the Wonewoc, but the Bulmer 1-33 well in Newaygo County had a show of gas in this interval. Cuttings from the Martin 1-15 in Gladwin County, where the Wonewoc is encountered below 14,748', show a white, fine grained sandstone that exhibits long contacts and occasionally sutured contacts between medium, subround grains. No visible porosity or other cement is noticed, and the cuttings are similar to those of the Mount Simon cuttings from this well in that they are small chips of heavily cemented and compacted sandstone. The Northern Michigan Land and Oil Corporation (NMLOC) 1-27 in Charlevoix county also shows a white to cream, medium grained sandstone with subangular grains.

The Wonewoc is equivalent to the Galesville in Wisconsin and Illinois, rather than the Ironton Member in that the Ironton is considered a much coarser grained sandstone than the underlying Galesville, and is also generally less than 100 feet thick in the Illinois Basin (Emrich, 1966; Willman et al., 1975). The Galesville is defined as a medium to coarse-grained, poorly sorted sandstone with minor amounts of clay (Emrich, 1966, p. 7; Dott et al., 1986). Michigan's Wonewoc is also generally a medium grained quartzarenite, and somewhat better sorted than the outcrop. Thickness remains uniform through much of the basin, except in the center (Gratiot and Gladwin Counties) where it increases abruptly by as much as 250%, and in the extreme southeast corner of the state where it is absent.

The Wonewoc is indicative of a shallow shelf environment, exhibiting trough cross beds and numerous fossils (Emrich, 1966). The sediment was derived from preexisting sediments from the Northern Michigan Highlands (p. 3). The Wonewoc represents the basal sandstone for another stratigraphic "sequence" (Ostrom, 1964; 1970). In well log signature, the Wonewoc shows a low gamma ray curve (Figure 3), comparable to wells in Illinois (Buschbach, 1964; 1965). The Wonewoc is distinguished from the underlying Eau Claire by a sharp contact with its characteristic high gamma ray curve. The overlying Franconia interval grades into a higher gamma ray response.

Franconia Formation

The Franconia is the oldest unit in the Franconian Stage (Figure 1), and the only unit assigned to this stage in Michigan. The Franconia was originally named for a glauconitic, argillaceous sandstone and dolomite at Franconia, Minnesota (Willman et al., 1975, p. 44). However, the outcrop region in Wisconsin does not display a "Franconia Formation" by that definition. Much work has been done in the Franconian interval in Wisconsin, and two distinct facies, the Lone Rock and Mazomanie formations, are recognized (Odom, 1978). In Illinois, this interval is recognized as the Franconia Formation, but thins to the north and east (Buschbach, 1964).

The Franconia exists throughout much of Michigan, but thins and disappears in the south central and southeast regions of the basin along the Findlay-Algonquin arch. The Findlay-Algonquin arch proves to be a barrier preventing deposition of this lithology to the southeast, as the correlative Kerbel and Knox formations in Ohio (Droste and Shaver, 1983) are of a differing lithology than their Michigan Basin counterparts (Dolly and Busch, 1972).

There are no cores in the Franconia interval in Michigan (Table 1). The lithology of the Franconia, therefore, is sketchy at best, but in cuttings samples and well log analysis appears as a sandy (feldspathic) dolomite throughout most of the basin, with stringers of interbedded shale further from the Wisconsin arch, and becoming sandy in zones closer to the arch. Cuttings from the Martin 1-15 (Gladwin County), NMLOC 1-27 (Charlevoix County), and Victory 2-26 (Mason County) show a much higher percentage of detrital feldspar and sand, indicating the lithology as a tan to light grey sandy and argillaceous dolomite, with abundant detrital feldspar throughout.

In well log analysis, the Franconia is identified rather easily as the high gamma ray signature above the low gamma ray curve of the Wonewoc. The sandy lithology of the Franconia along the western margins of the basin and the similarity of wireline log signatures between Illinois and Michigan wells (Figure 3) indicates a correlation between the Lone Rock/Mazomanie Formations and the Franconia of Michigan. The Lone Rock and Mazomanie Formations are time-equivalent facies of the Tunnel City Group (Figure 1) where deposition and lithology was affected primarily by the Wisconsin arch. The Mazomanie is a quartzose sandstone deposited directly over the axis of the arch, while the Lone Rock, which is subdivided into many members, is a more glauconitic, feldspathic sandstone and minor shale (Dott and Byers, 1980).

The more distal Tomah or Birkmose Members of the Lone Rock are not observed at present, however, and the increased presence of carbonate in a northwest Wisconsin to southeast Michigan lateral facies progression indicates the development of possibly a third facies apart from the Lone Rock and Mazomanie Formations. In

Wisconsin, low angle planar and trough cross beds, ripple marks and current lineations, occasional Trilobites, and also some mud cracks are common, indicating a shallow marine environment (Odom, 1978, p. 92). It is thought to be the continuation of a minor marine transgression that began with the Wonewoc Formation (a continuation of the second cycle, Figure 4), and represents an offshore shallow shelf environment. In Michigan, the lateral facies progression from the outcrop to the southeast would indicate a continuation of the offshore environment, evident by the increased presence of finer grained clastics and carbonate.

The exact correlation of the Franconia with the Lone Rock and Mazomanie Formations, however, remains obscure. The author agrees with Odom (1978, p. 91) that since the term Franconia was applied as a Stage name and is a generic term for virtually any litho- or biostratigraphic facies occupying this interval, its usage should be abandoned. Until such time as the Michigan lithology can be defined, its usage here is continued.

Trempealeauan Interval

This is the most poorly understood interval in Michigan. The rocks assigned here are those belonging to the Trempealeauan stage, named for outcrops in and around Trempealeau, Wisconsin (Willman et al., 1975). There are two recognizable stratigraphic horizons, herein called units, in the Michigan subsurface. The lower unit occupies the time interval of the St. Lawrence formation in Wisconsin, and the Potosi dolomite of northeastern Illinois. The upper unit occupies the time interval of the Jordan formation in Wisconsin and the Eminence formation in northeastern Illinois. Because the Trempealeau in Michigan has not previously been subdivided, for this report the upper unit in Michigan will be referred to as "Trempealeau A," and the lower unit will be referred to as "Trempealeau B." Recent studies of the overlying Prairie du Chien group and the St. Peter Sandstone (Fisher and Barratt, 1985; Harrison, 1987) have isolated the Trempealeau as a separate unit, but since this name has already been applied to the uppermost stage of the Cambrian, when enough rock data exist to further define the Trempealeau units in Michigan, unique formation names should be assigned and use of the term "Trempealeau" as a formation name should be abandoned.

In Michigan, lack of biostratigraphic data prevents exact dating of either the Trempealeau A or B units, so there is some question about whether both units belong in the Trempealeauan stage (Figure 1). The lower unit B could be the uppermost Franconia stage, or possibly the upper unit A could be a part of the overlying Prairie du Chien group. The upper unit A in previous literature has been commonly referred to the Trempealeau formation (Bricker et al., 1983; Brady and DeHaas, 1988), and the St. Lawrence formation (Catacosinos, 1973). The lower unit B has been correlated with the Jordan Sandstone of Wisconsin (Bricker et al., 1983), or assigned as part of the overlying "Trempealeau" or the underlying "Franconia," or simply unrecognized. In this report, the lower unit B is recognized as displaying a distinct facies change from northeast Michigan to the southwest state boundary, seen in the unnamed unit of Figure 8. The southern facies of unit B is lithologically similar to the Potosi Formation, which is the stratigraphic interval recognized in northeastern Illinois (Buschbach, 1964).

The entire Trempealeauan interval (units A and B) shows an increase in thickness toward the center of the basin, from 300 feet in Mason County to over 560 feet in Gladwin County. Along the southwestern margin near the Indiana border, the thickness is 231 feet in the Thalmann #1 in Berrien County. Like the underlying Franconia and Wonewoc intervals, the Trempealeau A and B units thin and disappear in the south central and southeast part of the basin, along the Findlay-Algonquin Arch (Figure 8, A-A'). The Trempealeau B in the north is described as a tightly compacted, cream colored quartzarenite that exhibits minor amounts of glauconite. There is a small 5 foot section of core that was taken in this interval at 13,691'-13,696' in the Doornbos 5-30 well in Newaygo County. This core exhibits no porosity, and the medium to fine grains are tightly compacted, with quartz overgrowths and minor sutured grain boundaries visible. Minor amounts of clay are present. The grains also show good undulatory extinction, which combined with the sutured and long grain contacts indicate a fair amount of compaction. In well logs, a low Gamma ray curve combined with a PEF curve in a range of 1.5 to 2.5 (reflecting sandstone) is characteristic, appearing above the high Gamma ray curve of the Franconia. The medium to fine-grained quartzarenite lithology of this unit correlates best with the Jordan Sandstone of Wisconsin as described by Odom and Ostrom (1978), but it occupies the St. Lawrence Formation stratigraphic interval of the Trempealeauan Stage.

To the south, this same interval undergoes a facies change (Figures 7B, 7C; and also wells #2 and #5 in Figure 3) to a sandy dolomite, very similar to the Potosi Dolomite of Illinois (Buschbach, 1964; Willman et al., 1975). No cores have been taken in this interval, and unfortunately, the only data available are derived from well log lithology. The PEF curve in well log signature is a higher value (2 to 4), indicating a definite change in lithology to a dolomitic rock as the unit approaches the Kankakee Arch in Illinois, the southwestern margin of the Michigan Basin.

The upper Trempealeau A unit appears basin-wide (again with the exception of the south-central and southeast portions due to non-deposition or erosion, and is generally a grey argillaceous dolomite that is marked by a characteristic double-humped gamma ray curve (Figure 3) below the gamma ray curve of the Oneota and above the Trempealeau A unit. The log signature is not easily recognized since the signature of the overlying Oneota Formation resembles the upper Trempealeau A unit.

The Upper Trempealeau A in Michigan is the time-stratigraphic equivalent of the Jordan Sandstone of Wisconsin and also possibly the lithic equivalent of the Uppermost member of the Jordan, the Coon Valley Dolomite (Odom and Ostrom, 1978). In Illinois, the stratigraphic equivalent is the Eminence Dolomite, a sandy dolomite that exists throughout much of northeastern Illinois (Buschbach, 1964). In Wisconsin, the Cambrian-Ordovician contact occurs within the Jordan Sandstone (Odom, 1978), but the contact in northeastern Illinois lies at the top of the Eminence Dolomite. The Eminence Dolomite is recognized as the time-stratigraphic unit immediately below the Jordan Sandstone (Willman et al., 1975).

Ordovician System

The Prairie du Chien Group is the only Ordovician rock assemblage that will be addressed in this paper, since others are currently working on the overlying St. Peter Sandstone at the Core Research Laboratory of Western Michigan University. The Prairie du Chien is the only group assigned to the Canadian Series which is lower Ordovician in age. The Canadian series is originally named for exposures of strata in Eastern Canada (Willman et al., 1975).

Prairie du Chien Group

The Prairie du Chien Group is absent in the south and eastern parts of the basin, along the Findlay-Algonquin arch. The next unit above the Cambrian Eau Claire formation in this region is the Middle Ordovician Glenwood Formation, which stratigraphically overlies the St. Peter Sandstone elsewhere throughout the basin. The group thickens dramatically toward the center of the basin, from 640 feet in Grand Traverse County and just 54 feet in Berrien County, to over 1700 feet in Gladwin

County.

The Prairie du Chien is named for exposures of dolomite and sandstone in and around Prairie du Chien, Wisconsin (Bain, 1906). It is generally subdivided into the lower Oneota and upper Shakopee Formations. The Oneota is a tan sandy dolomite and pure dolomite in outcrop (Davis, 1970, p. 34-35), and in Michigan also exhibits sandy and pure dolomitic characteristics, but with a more moderate to dark grey color. The Oneota is recognized in well log tracings by a dolomite signature ranging from 3 to 5 in PEF log, and a relatively low gamma ray curve compared to the overlying Shakopee formation. Distinction between the Oneota and the upper Trempealeau A interval is more obscure because the gamma ray signature is similar. The Oneota also has a high bulk density (2.7-2.8)/low neutron porosity (0%-5%) curve. Because the overall lithologic features between the Oneota in Michigan and the Oneota in Wisconsin are similar with the exception of color, the application of the formation name in Michigan is also warranted.

The upper Shakopee formation in Wisconsin is subdivided into the lower New Richmond Sandstone and the Upper Willow River Dolomite. The contact between the Shakopee and Oneota is believed to be erosional (Charlie Byers, personal communication). The New Richmond Sandstone is a pure cream-colored quartz sandstone to interbedded sandstones and dolomites. The Willow River member is a sandy, intraclastic dolomite with abundant algal stromatolites (Davis, 1970, p. 40-41). The Shakopee in Michigan has a much higher gamma ray curve than the overlying

St. Peter Sandstone and the underlying Oneota. The Shakopee as seen in the Doornbos 5-30 and the Bruggers 3-7 (Missaukee County), the Gingrich 1-31A and Eisenga 1-29 (Osceola County), and the Winterfield A-1 (Clare County) is a dark grey dolomite with argillaceous stringers and small amounts of sand locally present. Figure 13 illustrates the petrography from outcrop for the Shakopee. The Basinal Shakopee is similar in lithology and appearance, but has a grey color. The presence of isolated bodies of sand also mark the contact between the two. These isolated bodies may be roughly equivalent to the New Richmond member of the Shakopee, since they occupy the same stratigraphic horizon, but lack of sample control prevents a lithologic comparison. The Sun Huber 1-26 in Arenac County is producing out of one such sand body. This well is the only documented well producing below the St. Peter formation (Michigan's Oil and Gas News, 1988-1989), though it is possible that other producing wells such as in the Snowplow field of Alpena County may actually produce out of such sand bodies (Bill Harrison, personal communication).

Rock data are limited in the Prairie du Chien, but eight wells have cored intervals in the strata (Table 1). In addition to those cores previously listed, two other cores have reported cored intervals in this part of the Cambro-Ordovician section. The whereabouts of the cores from the Dow-Taggart Ludington #32 and the Superior Oil Sippy #17, both in Mason County are unknown. The longest cored interval is from the State Foster 1-28 in Ogemaw County, which has 1396 feet of Prairie du Chien Core preserved. Conodont data by Repetski and Harris (1981)

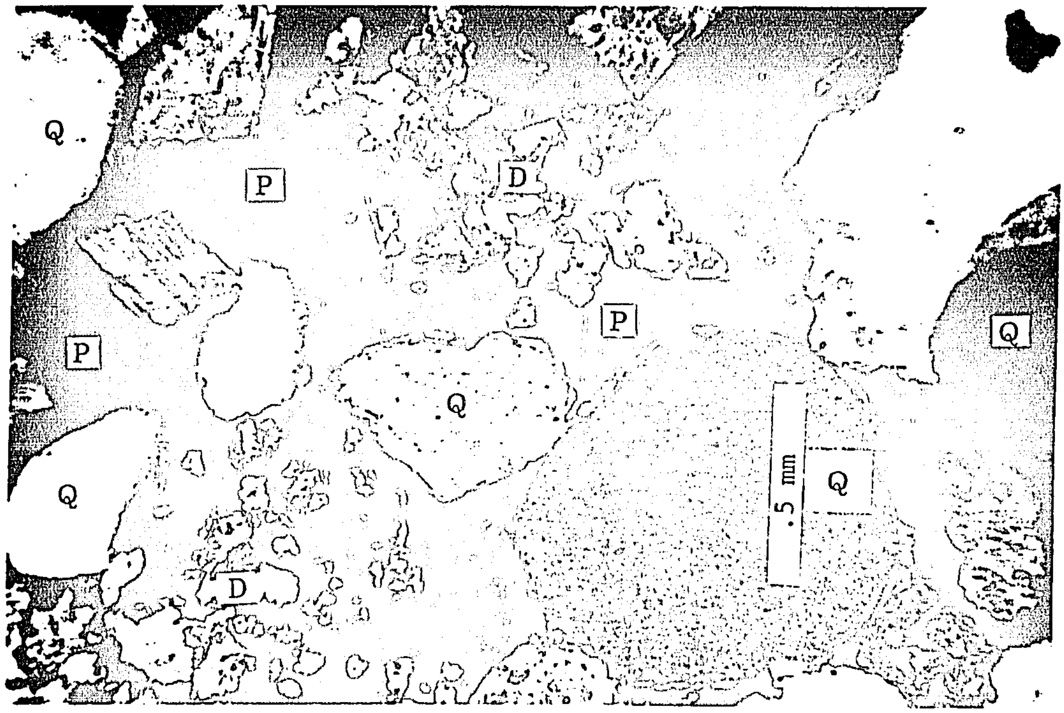


Figure 13. Shakopee Formation Outcrop Thin Section. Q = Quartz Grain, D = Dolomite Matrix, P = Pore. Basinal Shakopee is Similar in Appearance, but with Lower Porosity and Grey Color.

reported in Fisher and Barratt (1985) indicate that the cores belong to the uppermost Canadian and lowest Champlainian Series (Figure 1), which would correlate them with the Shakopee of Wisconsin. The cored interval is immediately below the contact with the St. Peter Sandstone. Some of the core extends above the Canadian/Champlainian Boundary, so it is hypothesized that there was little or no post-Sauk erosion between the Shakopee and the St. Peter in the center of the Michigan Basin. Additionally, conodont data from the Core Lab at Western Michigan University (Figure 14) shows that the St. Peter is of an older age than the St. Peter

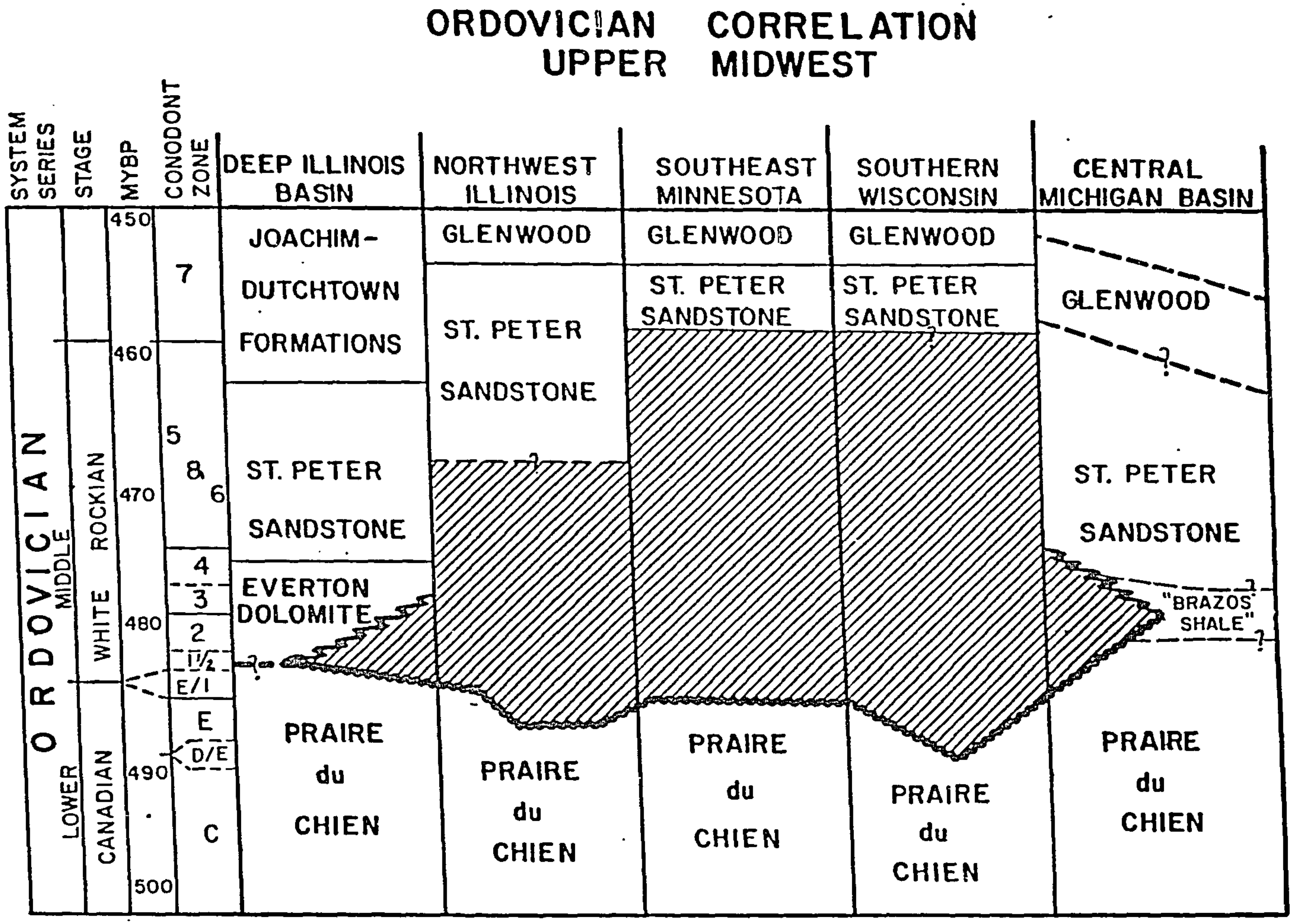


Figure 14. Ordovician Correlation in the Upper Midwest. Reprinted from Harrison and Barnes (1988). Used with Permission.

of the outcrop belt. Fisher and Barratt (1985, p. 2068) also mention that wavy bands within upper portions of the core could be algal markings, further tying the "upper Prairie du Chien" in Michigan with the Shakopee of Wisconsin. Examination of Michigan cores and thin sections reveals a petrography very similar to that of Wisconsin outcrop (Figure 12). Therefore, the term "Foster" (Fisher and Barratt, 1985) should be abandoned in favor of the pre-existing Wisconsin outcrop nomenclature (Shakopee formation) for this stratigraphic horizon.

The Shakopee formation is capped by the Sauk unconformity, a major unconformity marking the offlap of the Cambro-Ordovician Sauk Sequence (Sloss, 1963). This unconformity is seen throughout Michigan, especially in the southeast counties of Saint Clair, Macomb, Wayne, and Monroe, where the entire stratigraphic sequence from the Eau Claire formation to the St. Peter formation is missing. Preliminary data from central Michigan basin wells show that the unconformity in the central basin is significantly reduced and may not exist. Nonexistence of the unconformity then indicates a continuous depositional tract throughout the depositional hiatus. The "Brazos Shale" interval reported in many central basin wells such as the Hunt-Martin 1-15 in Gladwin County is a transitional unit across the unconformity, and diminishes in all directions away from the center of the basin, where the unconformity then becomes more prominent (Barnes, Harrison, and Shaw, 1989)

In summary, the Prairie du Chien Group represents the offshore carbonate sequence at the period of greatest marine onlap and the uppermost unit in a minisequence recognized in outcrop also (Ostrom, 1970). The upper contact of the Prairie du Chien represents the Sauk unconformity, which appears in core and wireline logs as a sharp lithologic contact throughout the basin except in the center (Figure 3). There, conodont data indicate an extension of sedimentary layers through the hiatus of the Sauk Unconformity.

MOUNT SIMON SANDSTONE PETROLOGY

Despite that the Huber 1-26 in Arenac County produces out of a small sand body in the Prairie du Chien, and the Bulmer 1-33 in Newaygo County had shows of gas in the Wonewoc, the best reservoir possibilities below the existing St. Peter play are in the Mount Simon Sandstone. The Mount Simon is the most widespread sandstone below the St. Peter, and samples of the Mount Simon show a complex diagenetic history. Porosity is reported as high as 19% in St. Clair County, where the Consumer's Power Company of Michigan has drilled several brine disposal wells into the Mount Simon for waste fluid injection. Most of southeast Michigan is dotted with such disposal wells, but they exist elsewhere too (Environmental Protection Agency, 1988). The Upjohn Company has drilled 4 disposal wells in Kalamazoo County, and the core from Upjohn #4 is currently at the Core Laboratory at Western Michigan University.

The Environmental Protection Agency, in the summer of 1986, funded Western Michigan University to undertake a study of the Mount Simon and Eau Claire formations for waste injection potential. In Michigan, the Mount Simon has already been the target of such injection in St. Clair and Kalamazoo County Disposal wells. It has been recognized that the potential reservoir quality of Mount Simon is better than average in Michigan (Ells et al., 1964; Environmental Protection Agency, 1988), but only along the flanks of the basin where porosity is greatest. The Mount Simon shows a uniform framework lithology across the basin, but the greatest variation in overall lithology is found in the diagenetic modifications that have occurred basinwide. These modifications are associated with current depth of burial.

Diagenetic cements within the Mount Simon can be interpreted based on existing core and cuttings samples. Samples show 2 recognizable diagenetic patterns (compare Hoholick, Metarko, and Potter, 1984) that exist within the basin. The deepest pattern 1 is predominantly a sedimentary quartzite; that is, a quartzarenite that has been heavily cemented with quartz overgrowths. Authigenic clay exists in slightly shallower depths. The shallower pattern 2 is dominated by authigenic clays, dolomite cements, and the development of secondary porosity.

Pattern 1 is greater than 90% to 100% quartz exhibiting undulatory extinction in both detrital grains and overgrowths, with long and often sutured grain contacts (Figure 15). Visible porosity is less than 1%. This pattern, observed in the Hunt Martin 1-15 (Gladwin County) and the Jem Doornbos 5-30 (Missaukee County), is seen at and below approximately 14,250 feet depth in the central basin. Samples from the Doornbos 5-30 below 14,250 feet exhibit all of these features. In the deepest part of the basin, the Martin 1-15 was not cored in the Mount Simon, but cuttings are large, well-cemented chips of rock, and the amount of cementation and compaction has converted the sandstone into an orthoquartzite. All contacts are long and often sutured, and SEM examination shows minute (<1%) amounts of dolomite and porosity. Limited core control does not permit an exact depth at which this facies begins, but the presence of stylolites in both the Martin 1-15 and the Doornbos 5-30 (Figure 15) indicates pressure solution, which in turn provides a source for the abundance of quartz cementation (Sibley and Blatt, 1976). The abundance of quartz cement in these deep wells suggests primary cement that has not been removed by dissolution, and indicates an association with greater depth of burial. The Doornbos 5-30 well also exhibits authigenic chlorite rims surrounding rounded quartz grains seen in SEM photomicrographs (Figure 16) and X-ray diffraction patterns (Figure 17), with a pervasive hematite and quartz overgrowth cement occluding the remaining pore space at 14,234 feet. This is the shallowest that pattern 1 is observed.

A simplified paragenetic sequence at this depth indicates the initial coating of sand grains with authigenic chlorite, perhaps after the dissolution of early cements (Pettijohn, Potter, and Siever, 1987, p. 426). The initiation of pressure solution then provides a source for silica, which occludes remaining pore space.

The shallower pattern 2 is seen at depths of 4,000-5,000 feet along the margins of the basin, again suggesting a relationship between porosity and cementation with depth of burial (Hoholick et al., 1984). Brine disposal well cores in St. Clair County exhibit authigenic chlorite and illite (Figures 18, 19) within a pervasive dolomite cement surrounding subrounded-subangular quartz and feldspar grains. Zones of secondary porosity exist within the sandstone, where ferroan dolomite (stained blue in thin section) has undergone partial dissolution, as seen in

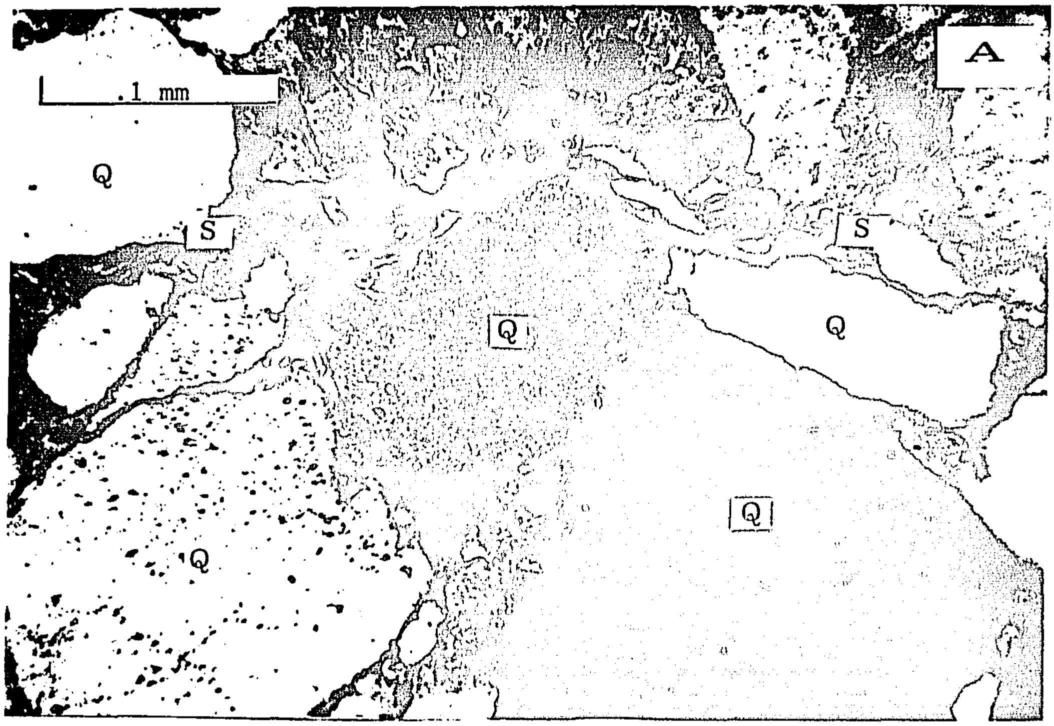
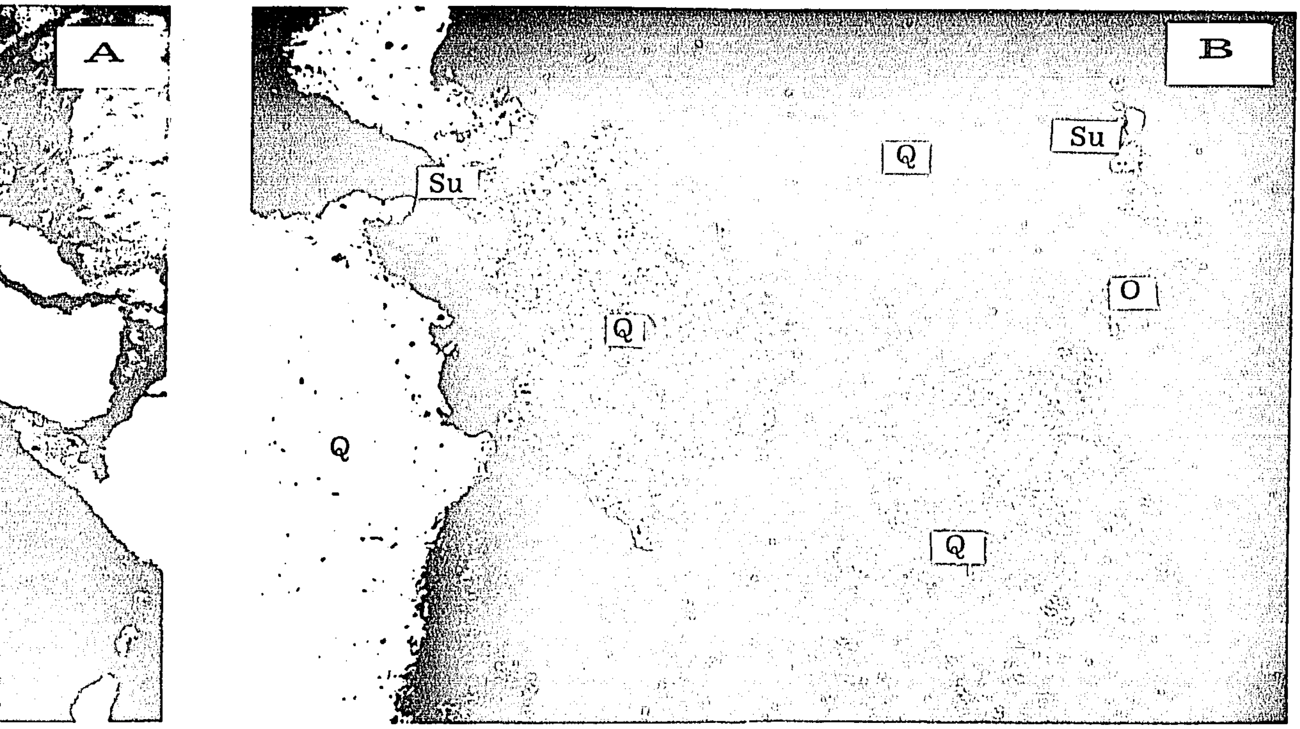


Figure 15. Mount Simon Sandstone Deep Diageneti
15 Well, B = Doornbos 5-30 Well, (
Stylolite, Su = Sutured Contact, O = Qu



ıon Sandstone Deep Diagenetic Pattern. A = Martin 1-
B = Doornbos 5-30 Well, Q = Quartz Grain, S =
ˈu = Sutured Contact, O = Quartz Overgrowth.

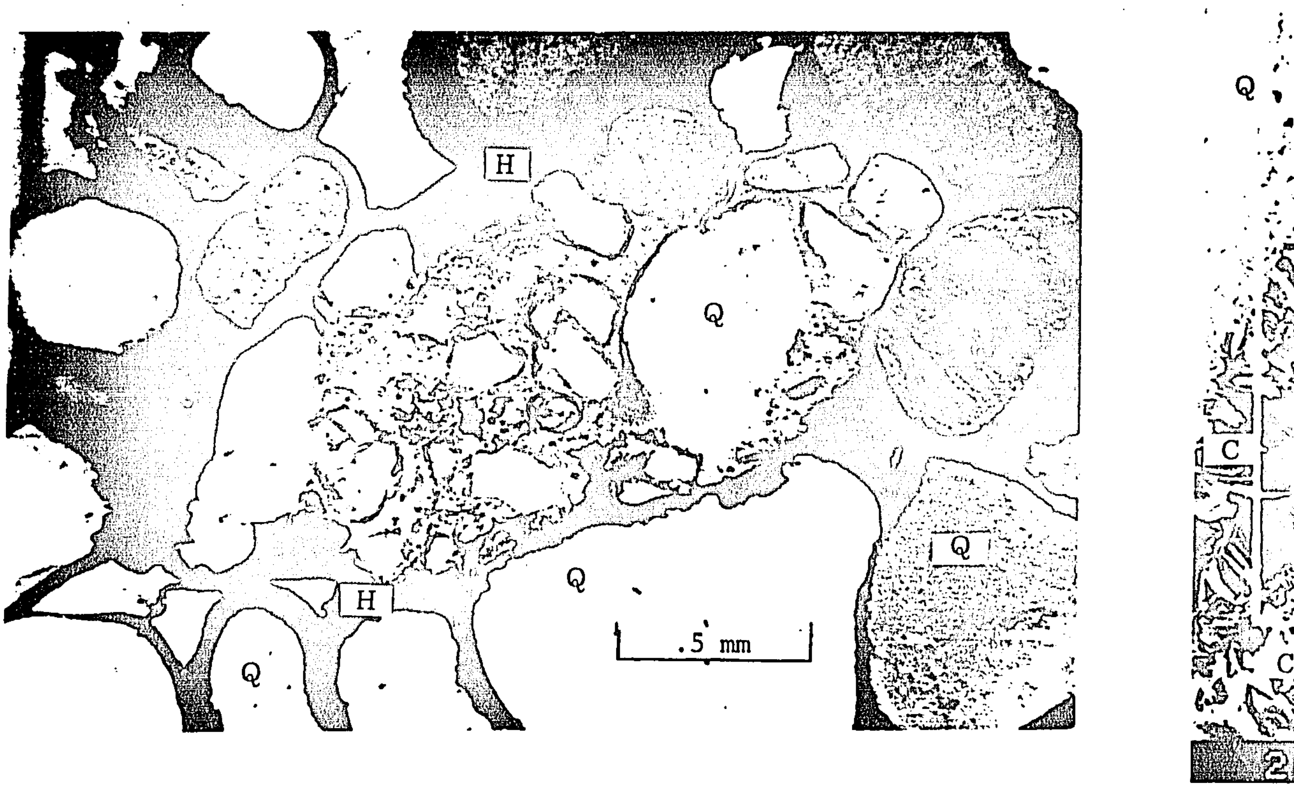
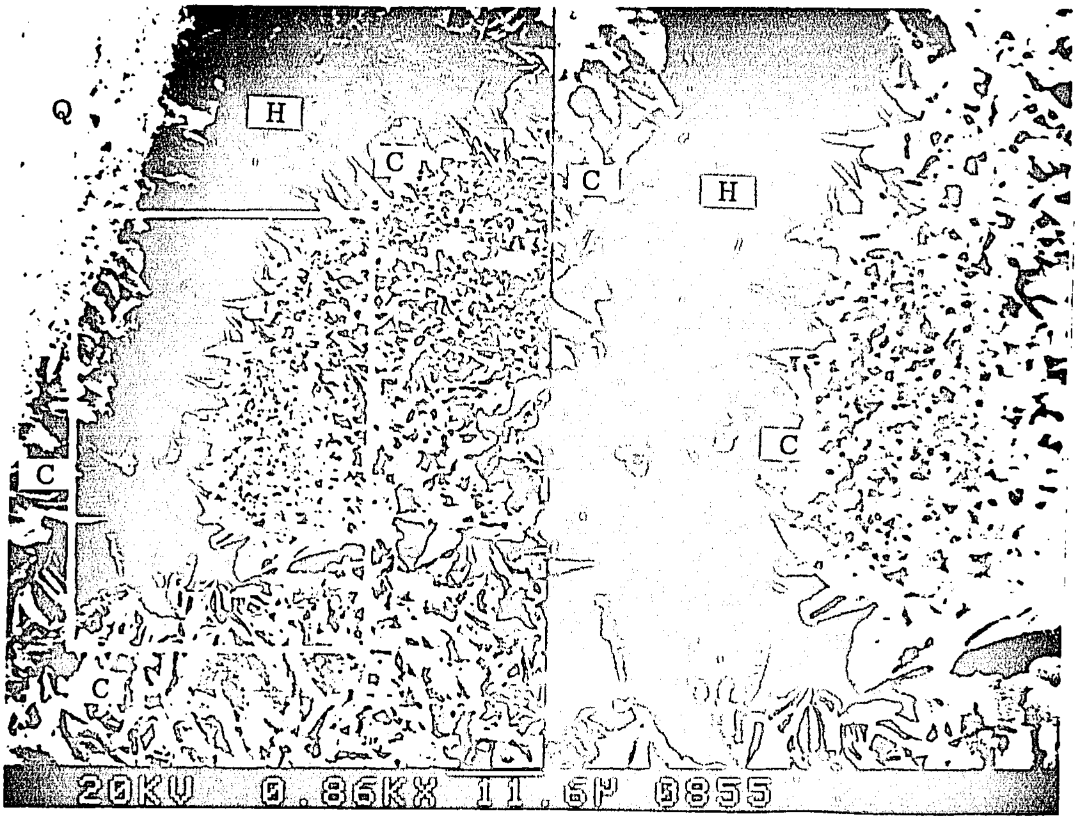


Figure 16. Thin Section and SEM Photomicrographs of the Mount Simon Sandstone from the Doornbos 5-30 at 14,234' Depth. Q = Quartz Grain, C = Chlorite Grain Coating, H = Hematite Cements and Quartz Overgrowths.



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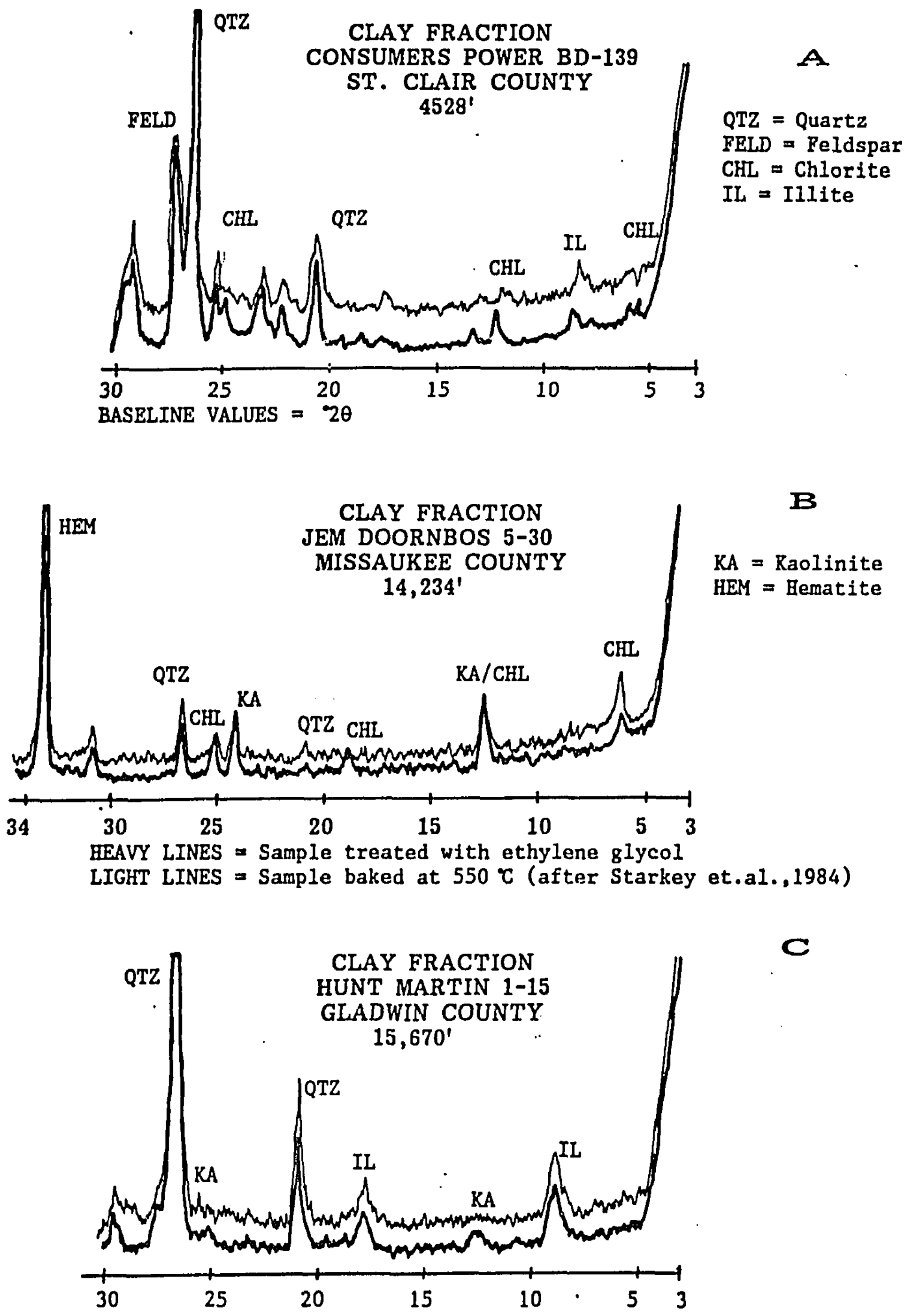


Figure 17. Selected X-Ray Diffraction Patterns for Clay Fractions of Whole Rock Samples. A = Consumers Power BD-139 Well, B = Doornbos 5-30 Well, C = Martin 1-15 Well.

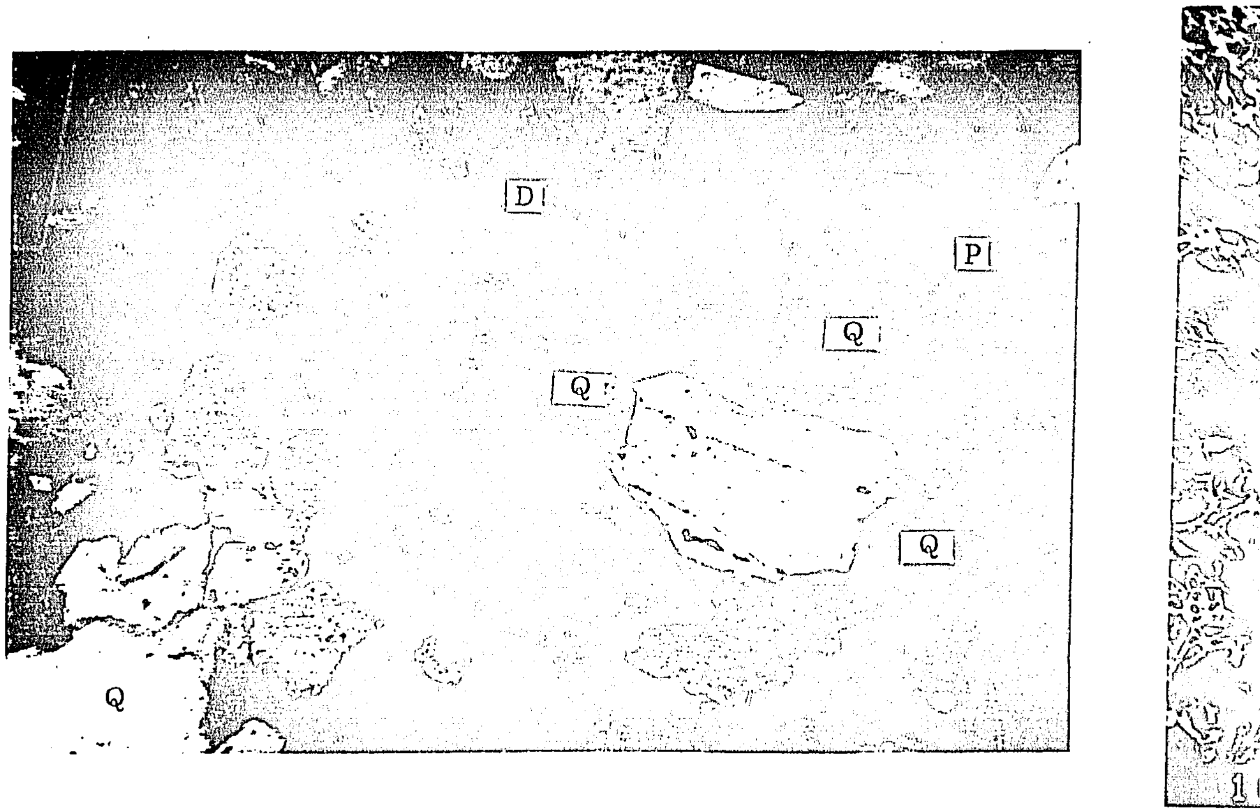
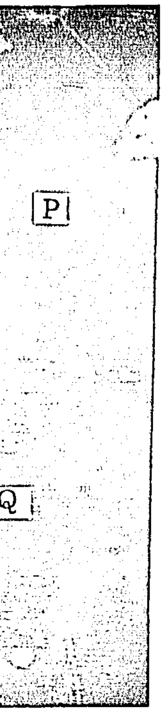
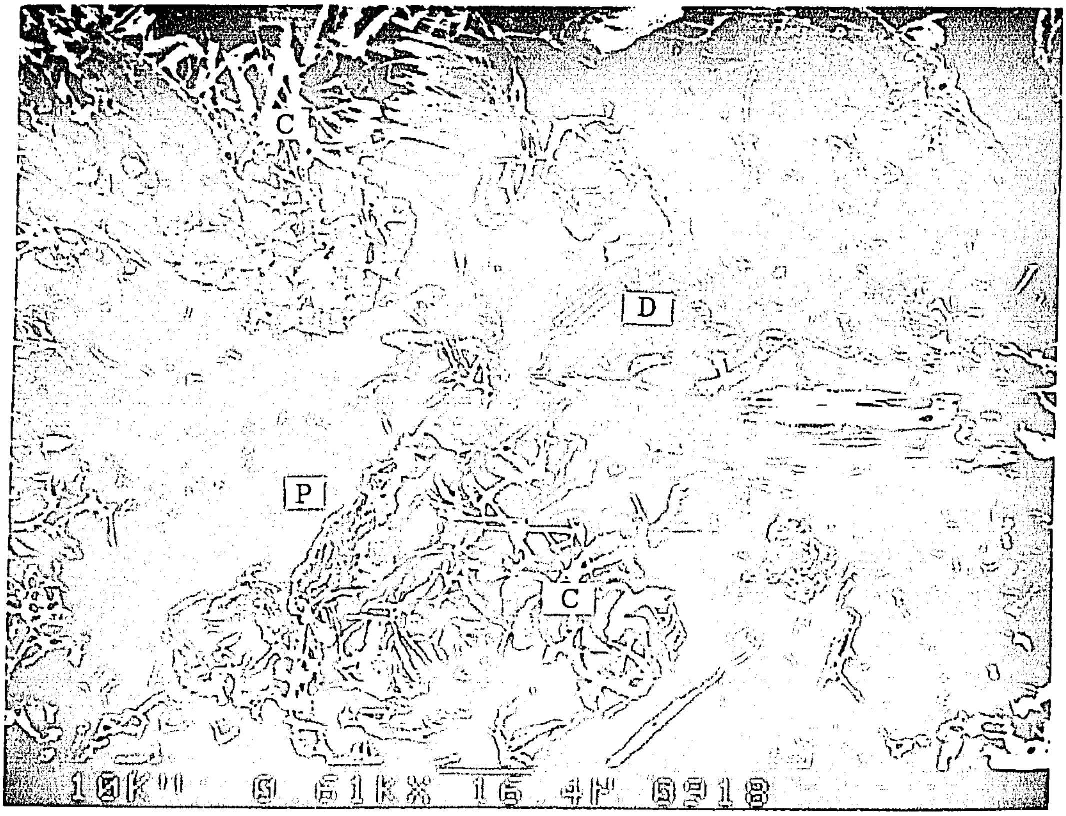


Figure 18. Thin Section and SEM Photomicrographs of Typical Mount Simon Sandstone Shallow Diagenetic Pattern. Both Photos From Consumers Power BD-139 Well. Q = Quartz Grain, D = Ferroan Dolomite Cement, P = Pore, C = Authigenic Illite and Chlorite.





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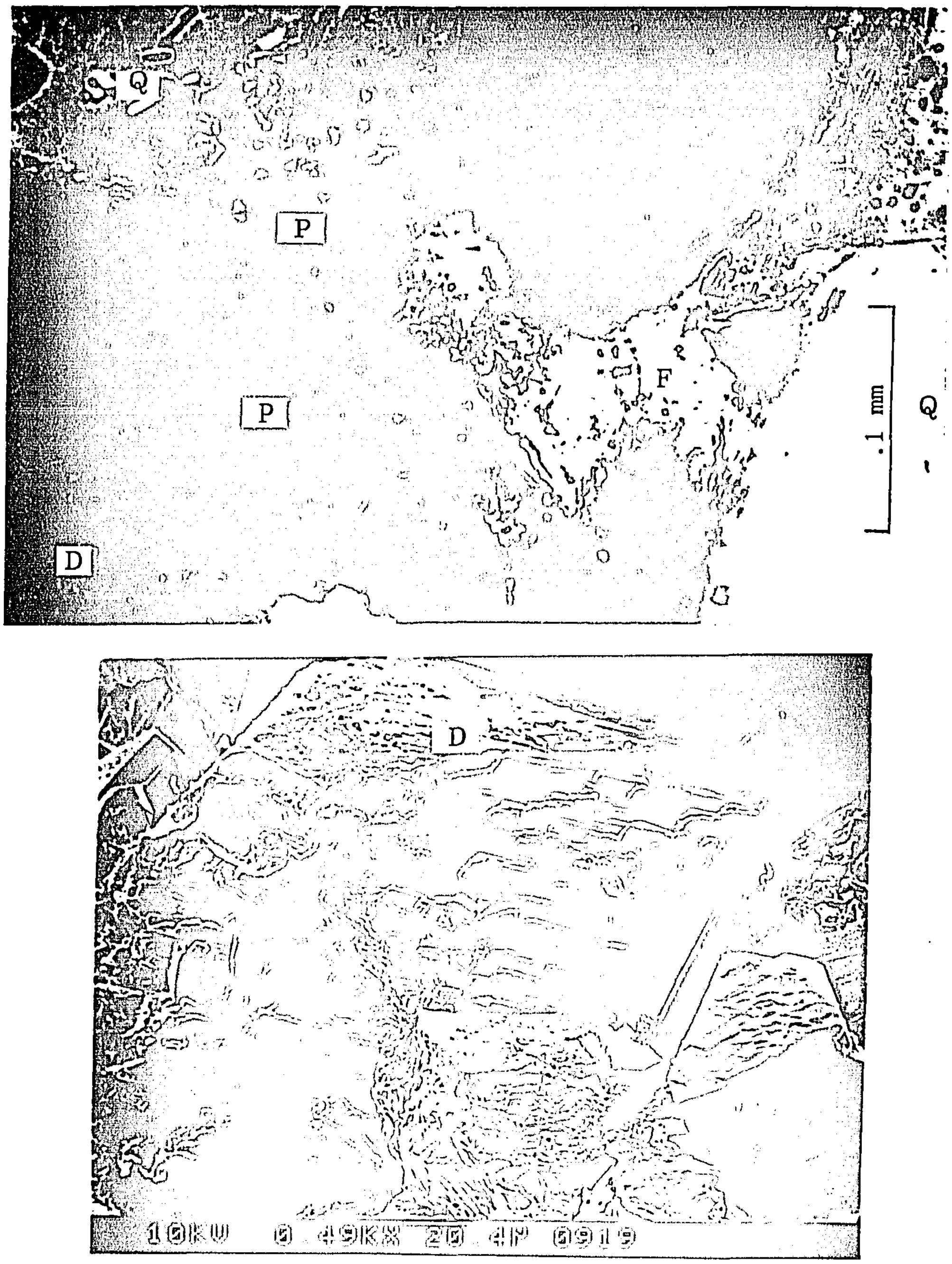


Figure 19. Thin Section and SEM Photomicrographs of Feldspar, Quartz, and Dolomite Dissolution in the 'Shallow' Diagenetic Pattern. Both Photos from Consumers Power BD-139 Well. Q = Quartz Grain, D = Dolomite Grain with Dissolution Front, F = Feldspar Grain with Dissolution Front, P = Pore Developed from Dissolution of Quartz.

thin section and SEM photos of Figure 19. Similar occurrences of this pattern can be seen in the upper Mount Simon of the Upjohn #4 Brine Disposal well (Kalamazoo County). The Mount Simon is encountered at 4940 feet in the Upjohn #4 (Kalamazoo County), and at 4650 feet in the Consumer's BD 1-7 (St. Clair County). Table 4 summarizes the various diagenetic modifications to the Mount Simon Sandstone associated with both the deep pattern and the shallow pattern.

Lithofacies Characteristics

Work done by Droste and Shaver (1983) shows a tremendous thickening of the Mount Simon in northeastern Illinois, where a single depocenter existed. The Mount Simon is very similar to the overlying Wonewoc and St Peter Sandstones in that it is a continuous sheet sandstone over much of the Midwestern United States. Taking this into consideration, along with the structural features presented by Droste and Shaver (1983), a marine shelf/shoreline model can be hypothesized for the Mount Simon depositional system (Figure 20).

The major feature during this time is the developing Wisconsin Arch (Figure 5) and the southward margin represents the approximate position of the shoreline during much of the Paleozoic (Dott et al., 1986). The Mount Simon depositional package then represents the basal sandstone in the Sauk Transgressive cycle (Sloss, 1963, 1984), and the first minicycle within the Sauk (Ostrom, 1970). Bioturbation and the presence of minor amounts of glauconite in the upper Mount Simon in St.

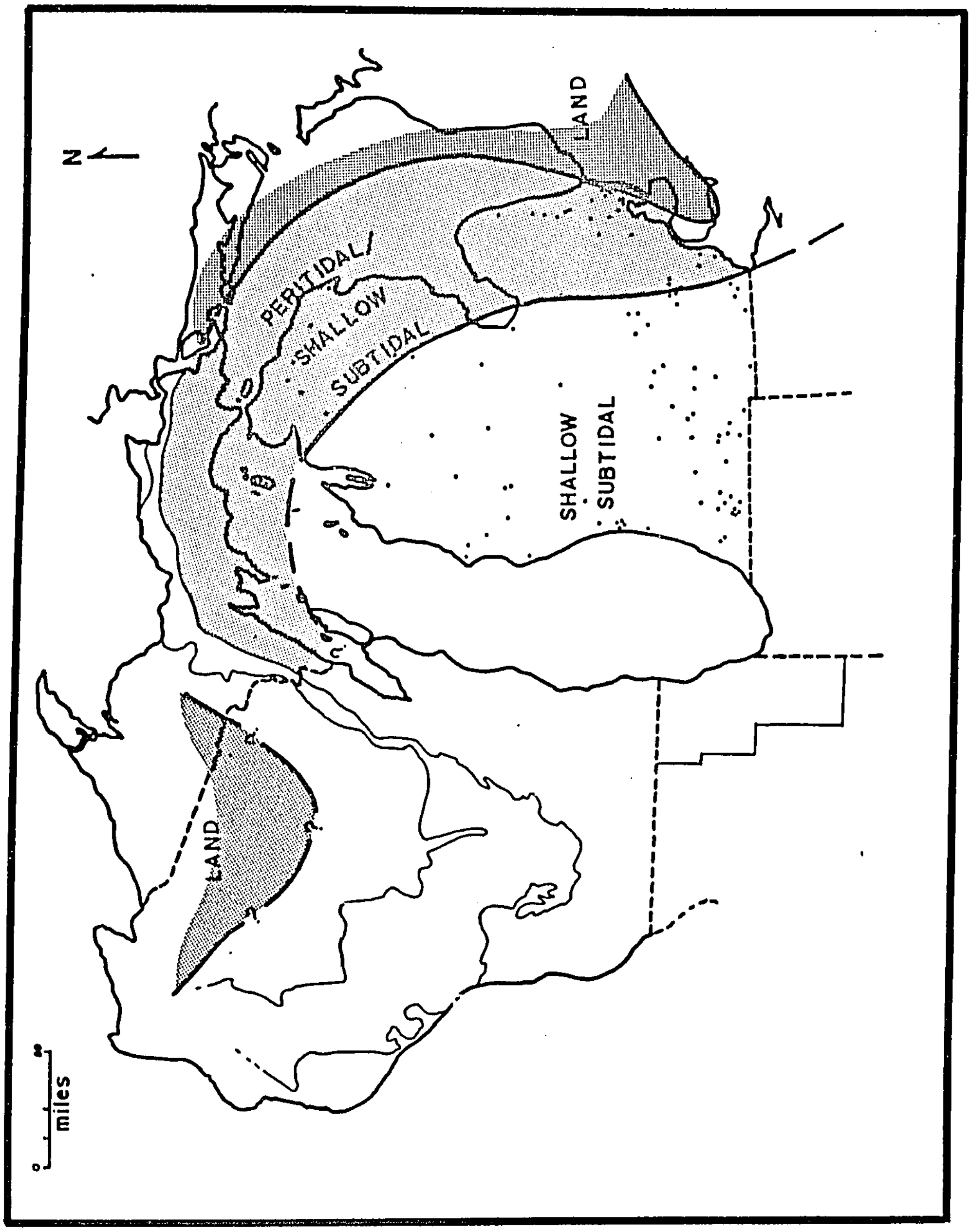


Figure 20. Paleogeography of the Mount Simon Sandstone. Modified from Droste and Shaver (1983).

Table 4

Observed Diagenetic Modifications and Paragenesis of the Mount Simon Sandstone

Deep Pattern			
	A:		B:
1.	Emplacement of chlorite rims locally on loosely packed quartz grains (an early burial stage).	1.	Initiation of quartz overgrowths.
2.	Dolomite (locally hematite and ferroan dolomite cementation) occluding porosity.	2.	Extreme compaction, creating long and sometimes sutured grain contacts. Stylitization develops.
Shallow Pattern			
	A:		
1.	Early emplacement of chlorite and illite, with minor kaolinite. Pervasive ferroan dolomite cementation follows.		
2.	Subsequent dissolution of dolomite, creating secondary porosity in zones, reaching 19% measured porosity.		

Clair county wells indicate a more offshore environment which is further from the theorized shoreline. The Upjohn well (Kalamazoo County) shows repeated storm/fair weather cycles (from Reading, 1985, p. 266-268) (Figure 21), which is in the uppermost Mount Simon, and indicates an offshore environment below fair weather wave base.

The observations in cores of the Mount Simon show a distinct marine facies

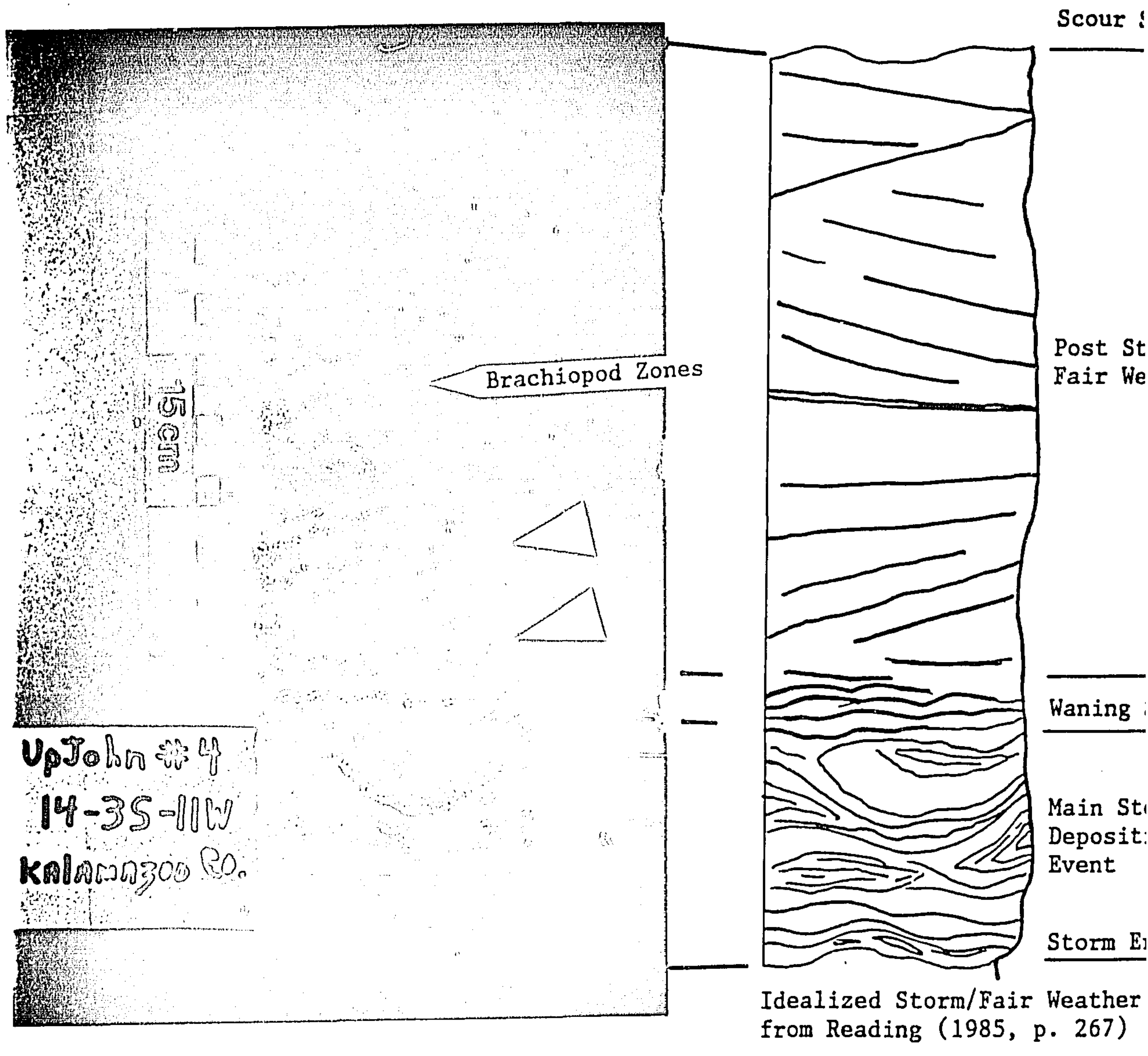
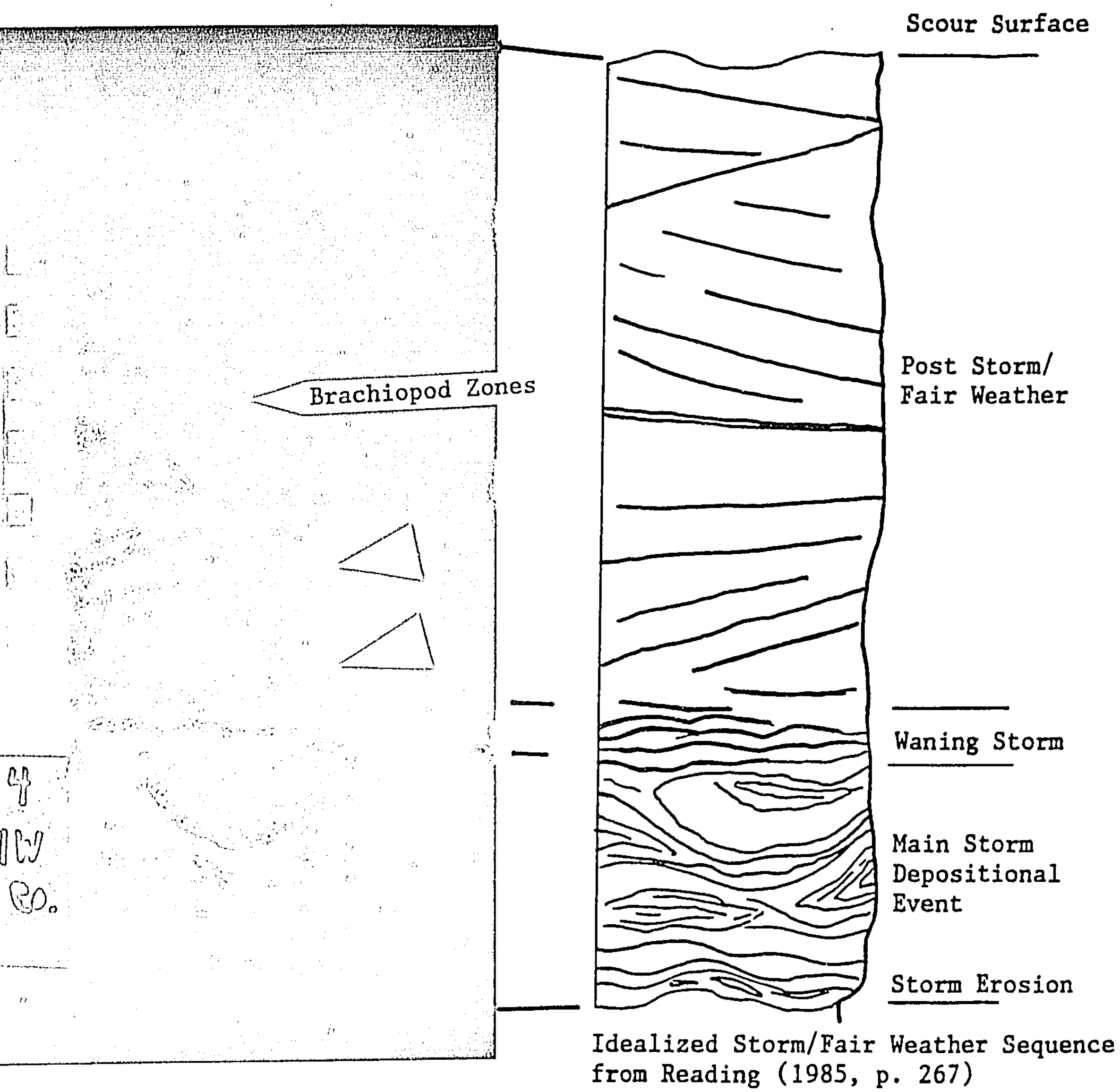


Figure 21. Interpreted Storm/Fair Weather Sequence for The Upjohn #4 Well.



21. Interpreted Storm/Fair Weather Sequence for The Upjohn #4 Well.

associated with the upper units of the formation. Observations primarily in the St. Clair County disposal well cores show a more massive sand, with no bioturbation. However, few cross beds that are generally smaller and of a low angle are observed within the cores.

MOUNT SIMON SANDSTONE RESERVOIR CHARACTERISTICS

Porosity Predictions

Predictions of which facies would be encountered for a given depth can be modelled based on existing petrologic data. Figure 22 illustrates a depth versus porosity plot for the Mount Simon sandstone in the Michigan basin. The dissolution of quartz and feldspar (Figure 19) in shallow wells (Brine Disposal wells, St. Clair County; Upjohn #4, Kalamazoo County) has enhanced porosity at depths above 5000 feet (Pettijohn et al., 1987). However, porosity then declines with depth, and measurements of less than 1% porosity are common below 14,000 feet (Doornbos 5-30, Missaukee County; Martin 1-15, Gladwin County).

The shallow diagenetic pattern has the greatest potential for hydrocarbon exploration, based on the excellent zones of porosity reaching 19% measured in the BD 139, St. Clair County (Ells et al., 1964). The Environmental Protection Agency (1988) states that the Mount Simon in Southern Michigan has a good confining layer in the overlying Eau Claire Formation. Despite this, these zones of secondary porosity have good reservoir potential within the Mount Simon because of the surrounding zones of pervasive dolomite cement that form both traps and seals for emplacement. Thin section examination of the shallow diagenetic pattern reveals that zones of high porosity (15-19%) are generally surrounded by regions of poor porosity

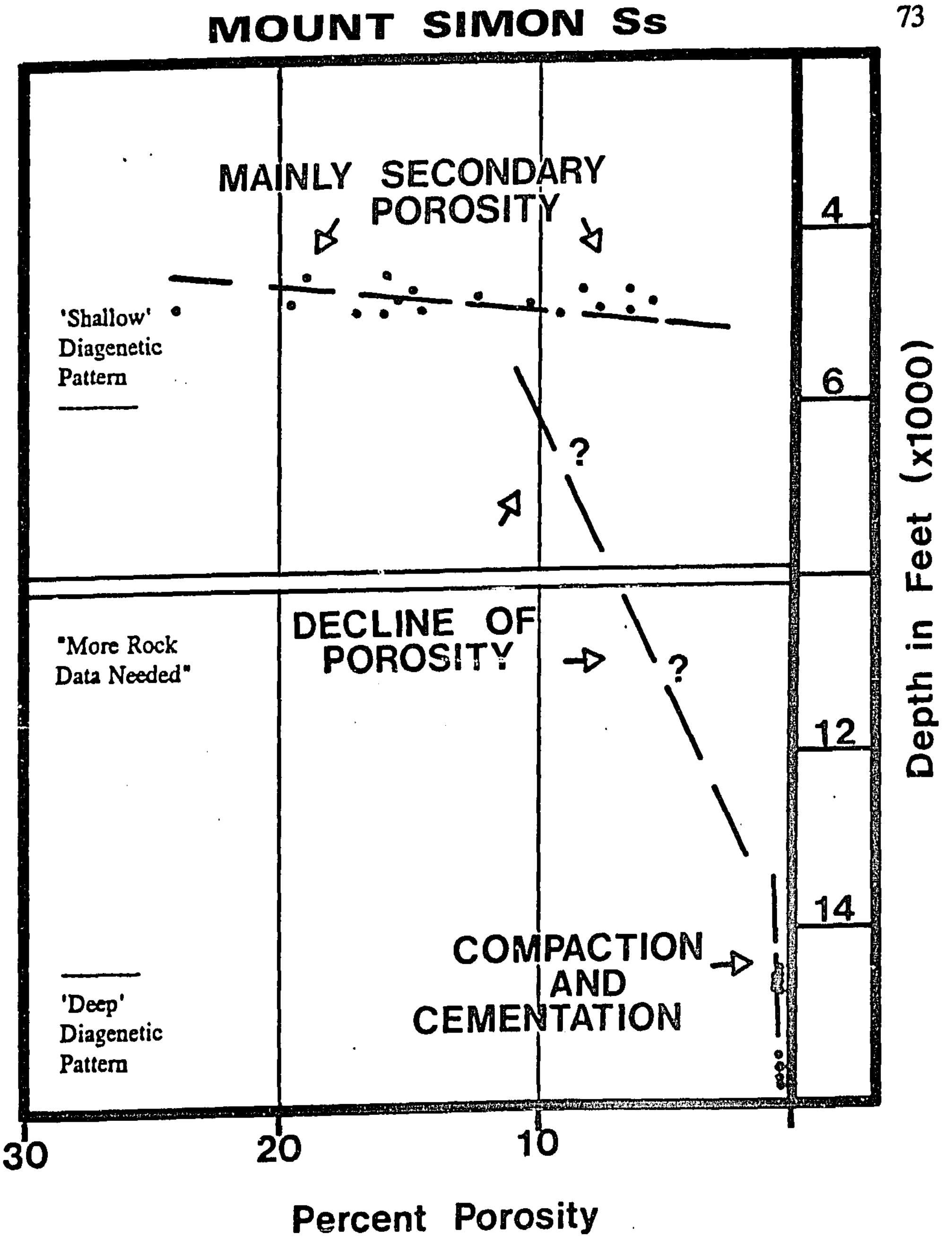


Figure 22. Comparison of Depth Versus Porosity in Mount Simon Sandstone Samples from Michigan Wells. Dots Represent Sample Control.

(1-5%). Published porosity measurements for Consumers Power BD-139 in St. Clair County (Ells et al., 1964) show several zones of high porosity separated by regions of low porosity in a vertical succession. Each zone of high porosity is generally less than 3 feet long.

Observed diagenetic patterns that have been discussed previously can be predicted on a statewide level based on current depth of burial (Figure 21). Figure 21 illustrates observed porosity data versus depth, all of which is contingent on the previously discussed diagenetic patterns. If the Mount Simon sandstone is to be the target for future oil exploration, the shallow pattern holds the greatest potential because of the development of secondary porosity. However, there is a large "hole" between 5500' and 14,000' depth. Until core data is available in this interval, the diagenetic pattern there remains obscure.

Source Rocks and Thermal Maturation

The Mount Simon is generally too organic-poor to be considered a source rock for hydrocarbons, but some of the carbonate units in the Cambro-Ordovician are organic-rich and may play a key role in the potential for hydrocarbon migration into the Mount Simon. Burial and thermal history calculations by Cercone (1984) show that all Cambro-Ordovician strata have been buried deeply enough throughout the basin to undergo thermal maturation of organic components. Present day exploration below Cercone's "window" of 8,200 feet maximum depth (1984, p. 130) in the St.

Peter Sandstone yields natural gas, as predicted in her model. Therefore, it is possible that hydrocarbon reserves may exist in the deeper Mount Simon Sandstone.

However, the Mount Simon shows little or no porosity in the center of the basin, and has no known source terrane below it to allow for hydrocarbon generation and accumulation. The Mount Simon along the margins of the basin is at an ideal depth (4,000-5,000 feet), but again has no source terrane underlying it to allow for generation of hydrocarbons. Here also, the Mount Simon is too organic-poor to generate its own. Precambrian sediments encountered in the McClure-Sparks 1-8 well (Gratiot County) have not been considered a source for hydrocarbon generation previously. The Precambrian Nonesuch shale in the Upper Peninsula of Michigan has demonstrated source rock capabilities (Dickas, 1986), but it is unknown if the Nonesuch or a similar formation exists in the central Michigan basin. The Sparks 1-8 is the only well to have penetrated central basin Precambrian sediments, and the redbeds encountered there do not demonstrate a high organic content (John Fowler, personal communication).

Although chemical source rock evaluation has not been attempted for the Mount Simon, it is possible that oil could be emplaced within these zones of porous sand after migrating "down section" from stratigraphically higher source units that are actually deeper in the center of the basin. Migration could occur along faults and other conduits within the basin. A stratigraphically higher unit such as the massive Prairie du Chien Group or the Utica Shale (a known petroleum source) has undergone thermal maturation in the center of the basin, where it lies structurally lower than the peripheral Mount Simon. Faults and other conduits of greater flow such as bedding planes would then allow mature hydrocarbons to migrate out toward the basin margins, while at the same time migrating "down section," eventually to become emplaced within a diagenetic or formational trap associated with the Mount Simon.

Toth (1988) presents a model by which migration in the manner presented above could occur. The hydraulic theory of petroleum migration (Toth, 1988, p. 495) essentially forces petroleum outward and upward away from the deep central basin through compaction, diffusion, and gravity flow.

Although no reserves are currently producing in the Mount Simon, evidence provides potential source rocks, a process for migration, and methods for entrapment in the Mount Simon Sandstone. The lack of existing reserves may be due wholly to a sparsity of deep tests.

DISCUSSION AND CONCLUSIONS

The stratigraphic evidence presented here illustrates the clear correlation between the Late Cambrian-Early Ordovician section in Michigan with that of surrounding regions. Application of the sequence stratigraphic concept and the minicycles of Ostrom (1970) to this section demonstrate that the subsidence of the Michigan basin was not uniform during Cambro-Ordovician time, and that during periods of low subsidence, a more uniform stratigraphic package was deposited throughout the midwest. During periods of higher subsidence, stratigraphic units in Michigan began to take on a slightly differing character from their Wisconsin outcrop counterparts.

The Michigan basin is poorly understood in terms of basement tectonics, due in part to the extreme depth to Precambrian in the center of the basin, and along the axis of the Midcontinent gravity anomaly (depths below 16,000 feet to Precambrian), which generally is not targeted for oil exploration. Hence, only 4 wells have ever penetrated the Mount Simon or the Precambrian in the center of the basin. However, recent work by Fowler and Kuenzi (1978), Hinze et al., (1975), and Dickas (1986) indicate that the basin is the product of a failed intracratonic rift.

The Mount Simon Sandstone offers good reservoir potential when encountered at depths above 5500 feet, due to development of secondary porosity from dissolution of both carbonate and quartz cements. Limited core and cuttings control enables diagenetic facies patterns to be observed, and based on these facies, predictions of where the best locations for good reservoir rocks can be made. Generally, this location lies in a doughnut-shaped ring around the central basin, from approximately the 6000 foot contour (Figure 6), to the state boundaries.

Oil exploration in the Mount Simon sandstone is limited. To date, no known reserves exist. There is a possibility of oil reserves in the Mount Simon sandstone, based on the reservoir potential at shallow depths of 4,000-5,000 feet, and the possibility of hydrocarbon migration along faults and bedding planes from stratigraphically higher source rocks in the center of the basin, utilizing the hydraulic theory of petroleum migration (Toth, 1988). With only 44 wells that have completely penetrated the Mount Simon sandstone (Appendix A), any attempt at ruling out the possibility of petroleum reserves in that interval would be premature. Further studies of the Mount Simon should be aimed at obtaining better core and cuttings control throughout the basin. This, of course, can only occur with renewed drilling into the Mount Simon sandstone. Emphasis should be placed on the Mount Simon between 5500 feet and 14,000 feet, since there is no core at these depths, and, therefore, the reservoir potential is undocumented.

Additional drilling will also provide a better database for stratigraphic interpretations in the remaining Late Cambrian-Early Ordovician strata. The greatest limitation in identifying potential reservoir rocks there is that there is no sample control outside of a five foot section of core in the Wonewoc sandstone from the Doornbos 5-30 well in Missaukee County. Additional coring in the interval between Prairie du Chien strata and Mount Simon strata will yield a better understanding of these rocks and will identify additional potential reservoirs. When renewed exploration yields a greater rock database, the nomenclature problems that have plagued exploration in the Michigan basin will be resolved once and for all.

Appendix A

A List of Late Cambrian/Precambrian Wells in the Michigan Basin

Data Column: L=log; T=ticket D=Drlg rpt; X=cuttings; C=core

NO.	COUNTY S-T-R	PERMIT DATA	OPERATOR, WELL, T.D., AND COMMENTS
01	Allegan 9-2N-16W	35186 X,	Martin Properties Inc., Howard Hunt unit 1, 6000' (pC 5582')
02	Alpena 5-31N-9E	25690 L,T	Panhandle East Pipeline Co., Ford Motor 1-5, 6380' (Eau Claire)
03	Barry 14-1N-8W	BD 153 L,	Battle Creek Gas Co., Fee #BD 153, 6618', (Mt. Simon)
04	Bay 11-14N-5E	37779 L,T,	Shell Western E&P, Prevost et.al. 1-11, 14,549' (Mt Simon)
05	Berrien 14-6S-17W	23545 T,D,	R. O. Leighton, Anstiss 1-A, 2970' (Eau Claire)
06	Berrien 10-6S-17W	26112 L,T,	Security O&G, Thalmann #1, 5632' (pC 4604')
07	Branch 7-5S-8W	29774 L,T,	Consumers Power Co. and Quintana Prod. Co., Lindsey-Hostetler et.al. #1, 5432' (pC 5375')
08	Branch 8-5S-8W	29969 L,T,	Consumers Power Co. and Quintana Prod. Co., Harvey Clark #1, 5475' (pC 5418')
09	Branch 13-6S-7W	38045 L,T,	Atlantic Richfield Co., ARCO and Gaglio 1-13, 5378' (pC 5206')
10	Branch 3-6S-8W	37569 L,T,	ARCO, ARCO and Johnson 1-3, 5253' (pC 5210')
11	Branch 15-7S-8W	20685 L,T,	Ambassador Oil Corp., Harry E. Schlautmann #1, 3990' (Eau Claire)
12	Branch 13-8S-6W	33019 L,T,	J.O. Mutch and Shell, Richard A. Rensel/ Alva Allan 1-13, 4633' (Mt. Simon)
13	Calhoun 13-1S-5W	30468 L,T,	Earl R. Midlam, Midlam (Fee) #1, 6000' (Franconia)
14	Calhoun 32-2S-6W	38822 L,T,	Farmers Oil and Gas, Eyde Brothers 1-32, 5600' (Eau Claire)
15	Calhoun 15-3S-6W	23389 T,	Petrosonic, Maynard #1, 4646' (Eau Claire)
16	Calhoun 13-3S-8W	22352 T,	Trenton Petr. Co. and McClure Oil, Bernloehr Bole and McClure #1, 4739' (Eau Claire)
17	Cass 11-5S-13W	37536 L,T,X,	Federated Nat. Res. (Raffaele Expl.), Reynolds 2-11, 3900' (Wonewoc) (WMU file) (Cuttings from 1750'-3900')
18	Cass 8-5S-14W	34763 L,T,D,	Hallwell Inc., Willbrandt-Hemenway 1-8, 4000' (Eau Claire)
19	Cass 26-5S-14W	34367 T,D,	Hallwell, Inc., McKenzie #1, 4000' (Eau Claire)
20	Cass 8-6S-13W	34773 L,T,D,	Hallwell Inc., McKenzie 1-8, 4000' (Eau Claire)
21	Cass 31-7S-13W	35459 L,	Hallwell Inc., Holdeman 1-31, 3800' (Eau Claire?)
22	Cass 8-7S-14W	23289 L,	C.A. Perry and Son, Warren Wooden #1, 3947' (Mt. Simon)
23	Cass 20-7S-14W	36985 L,T,X,	Mannes Oil Co., Smith 1-20, 4007' (Mt. Simon) (unwashed cuttings)
24	Cass 28-7S-14W	35967 T,	Hallwell Inc., Hawks and Adames 1-28, 2998' (Mt. Simon) (WMU core lab file)
25	Cass 28-7S-14W	34304 L,T,	Hallwell Inc., Lawson #1, 3875' (Mt. Simon)
26	Charlevoix 27-32N-4W	34824 L,T,X,	En. Aquis. Corp., No. Mich. Land and Oil Corp.1-27, 8900' (Mt Simon) (WMU core lab file)
27	Charlevoix 6-37N-10W	23478 L,T,	McClure Oil Co., State Beaver Island #2, 4,800' (pC 4718')
28	Charlevoix 27-38N-10W	23435 L,	McClure Oil Co., State-Beaver Island #1, 5,383' (pC 4566')
29	Cheboygan 11-34N-2W	35060 L,T,	Sun Oil Co., Salling Hanson Co. Trust 1-11, 5940' (Franconia)
30	Cheboygan 24-35N-1W	30682 L,T,	No. Mich. Expl. Co., State Waverly 1-24, 5753' (Mount Simon 5617')
31	Clare 34-17N-6W	34790 L,T,	Dome Petroleum Corp., Brandt #1-34, 13022' (Eau Claire) (Log tracing)
32	Eaton 24-2N-3W	29117 L,T,	Mobil Oil Corp., Gladys Kelley unit 1, 7200' (Mt. Simon)
33	Gladwin 15-17N-1E	35090 L,T,X,	Hunt Energy Corp., Martin 1-15, 15845' (Mt. Simon) (WMU core lab file)

34	Gr Traverse 24-26N-11W	34292 L,T,	Shell Oil, State Blair #2-24, 11,020' (pC 10,910')
35	Gratiot 8-10N-2W	29739 L,T,	Mclure Oil, Sparks et.al. 1-8, 17,466' (pC 12,176', deepest test in Michigan)
36	Hillsdale 3-5S-3W	40414 T,	Marathon Oil, Rowe W A-8, 5917' (pC 5804')
37	Hillsdale 3-9S-1W	27024 L,T,	Liberty Pet. Corp., Joseph Horwath #1, 3976' (Eau Claire)
38	Huron 26-15N-15E	29191 L,T,	Mobil Oil Co., C.J. Volmering #1, 9086' (pC 8872')
39	Ingham 36-1N-1W	29672 L,T,	Mobil Oil Corp., Reeve #1, 6300' (Franconia)
40	Ingham 29-2N-1W	28607 L,T,	Mobil Oil Corp., Walter Kranz jr. #1, 7866' (pC 7690', hit basement) (log ends at 5800')
41	Jackson 29-3S-1W	22275	C.W. Collin and J. Oliver Black, Harold Dancer #1, 6088' (Mt Simon)
42	Jackson 30-3S-3W	27137 L,T,	Nanco Inc., Alfred Smith #2, 5936' (Mt. Simon)
43	Kalamazoo 14-3S-11W	BD 21 L,C,	Upjohn Co., Upjohn #4, 5600' (Mt Simon) (Mt Simon Core at WMU core lab)
44	Kent 3-5N-9W	BD 156 L,T,	Ohio NW Dev. Inc., Alto Propane Storage Fee 2-156, 7820' (Mt Simon)
45	Lenawee 32-8S-5E	10448 D,	Walter H. Eckert, Harry Taylor #1, 3902' (pC 3865')
46	Livingston 14-2N-4E	25868 L,T,	Brazos O&G Co. div. Dow Chem., T.J. and F.B. Kizer #1, 7210' (Mt. Simon)
47	Livingston 2-3N-3E	40438 L,T,C,	Terra Energy and Smith Petr., Phillips 1-2, 7450' (pC 7400') (Mt. Simon Core)
48	Livingston 11-3N-5E	27986 L,T,C,	Mobil Oil Corp., Howard J. Messmore #1, 7589' (pC 7150') (1 PdC carbonate core?)
49	Livingston 23-4N-5E	37893 L,T,D,	Don Yohe Enterprises, Inc., Laier 1-23, 7548' (Franconia? or Mt. Simon?)
50	Macomb 23-3N-12E	39859 L,T,	Mich. Petr. Expl. Inc., Gaultieri et.al. 1-23, 5027' (Mt Simon)
51	Macomb 24-5N-14E	33737 L,	Energy Aquisition Corp., Grierson 1-24, 5389' (pC 5340')
52	Mason 25-17N-16W	18905 C,D,	Superior Oil, Sippy #17, 7249' (Franconia) (6 PdC cores - lost?)
53	Mason 26-19N-17W	39984 L,T,	Miller Bros., Victory 2-26, 7485' (Mt. Simon) (WMU core lab file - St. Peter Core)
54	Mason 27-19N-18W	17789 L,C,D,	Dow Chemical Co. (Brazos O&G), Ludington #32, 6622' (Mt Simon) (20 cores in PdC/lower, lost?)
55	Missaukee 30-22N-6W	34376 L,T,C,	JEM Petroleum, Doornbos et.al. 5-30, 14,722' (Mt. Simon) (Core at U of M, Eau Claire + Mt. Simon)
56	Monroe 29-5S-10E	11221 D,	Joseph W. Sturman, D.L. and R.L. Chapman #1, 3377' (pC 3342') (Granite Wash)
57	Monroe 16-7S-6E	25494 T,	Ferguson and Garrison, Merlin Shimp #1, 3671' (pC 3637') (3670' gr.)
58	Monroe 1-7S-7E	35948 L,T,	Reef Petr. Corp., Cousino 1-1, 3512' (3470' pC)
59	Monroe 19-7S-7E	7702 D,	Jacob Beck, Mrs. James Sancrant #1, 5495' (pC 3595')
60	Newaygo 28-15N-11W	39856 L,T,	Wolverine O&G, Patrick-State Norwich #2-28, 10,180' (Mt Simon) (Log is Xerox)
61	Newaygo 33-15N-11W	39916 L,T,	Wolverine Oil and Gas, Bulmer 1-33, 9375' (Eau Claire) (show of Gas in Wonewoc)
62	Newaygo 20-15N-14W	26662 L,T,	Thunder Hollow O&G Co., Walter and Rosilea Thompson #1, 8215' (Mt Simon) (Log is at 6585' TD)
63	Oceana 10-13N-18W	33134 T,	Amoco Prod. Co., Schiller 1-10, 7240' (pC 6427')
64	Ogemaw 28-24N-2E	25099 L,T,C,	Brazos O&G, Sun, and Superior Oil, State Foster #1, 12989' (Eau Claire) (1300' of PdC core at MSU)
65	Osceola 19-20N-10W	39854 L,T,	Petrostar Energy, Boyce 2-19, 12,810' (Mt. Simon) (Log is tracing)
66	Oscoda 14-25N-2E	34070 L,T,	Hunt Energy Corp., USA Big Creek Unit 1, 11,691' (Eau Claire)
67	Ottawa 20-5N-15W	BD	Parke Davis & Co, Brine Disposal #3, 5945' (Mt. Simon)
68	Ottawa 30-5N-15W	BD	H. J. Heinz, Heinz WDW #1, 5915' (Mt. Simon)
69	Ottawa 30-5N-15W	IDIS	H. J. Heinz, Heinz WDW #2, 6221' (pC)

70	Ottawa 30-5N-15W	 L,	Holland Suco Color Co., Waste Disposal Well #1 (Mt Simon)
71	Ottawa 30-7N-15W	wdw 3 L,	Heinz, H.J., Heinz WDW #3, 5905' (Mt. Simon)
72	Ottawa 3-8N-13W	34885 L,T,	Gulf Oil, Robert Umlor et.al. 1-3, 7250' (Mt. Simon)
73	Prsque Isl 14-33N-3E	35085 L,T,	Jennings Petr., Moll 1-14, 6667' (Franconia)
74	Prsque Isl 13-33N-5E	29372 L,T,	Shell Oil, Taratuta 1-13, 6738' (pC 6500'-granite wash at 6545? See Milstein Mt. Simon Map)
75	Prsque Isl 29-35N-2E	27199 L,T,	Cook Bros. (Pan Am. Petr. Corp.), Donald E. Draysey BDW 1, 5940' (pC 5877')
76	Sanilac 16-9N-15E	25357 L,T,	Humble Oil, Hoppinthal #1, 6787' (log TD) (Eau Claire)
77	Sanilac 27-9N-15E	26480 L,T,	Hallwell Oil and Gas, Spencer #1, 6292' (Eau Claire)
78	Sanilac 19-10N-15E	33999 L,T,	Mid American O&G Corp., Woodruff 1-19, 8511' (pC 8298')
79	Sanilac 30-11N-15E	35779 L,T,	Traverse Oil Co., Frostic 1-30, 7824' (Eau Claire)
80	Sanilac 20-12N-15E	30974 L,T,	McClure O&G @ Mich. Nat. Res. Co., Richard Hewett et.al. and Albert Shadd 1-20, 8975' (pC 8859')
81	St.Clair 17-2N-16E	25780 L,T,	Bernhardt O&G, Puzzuoli #1, 4188' (pC 4152')
82	St.Clair 10-3N-15E	23796 T,	C. W. Collin, Bidal-Faucher-Levrau #1, 4494' (Franconia)
83	St.Clair 10-3N-15E	39755 L,T,	No. Mich. Expl. Co., Salisbury and Paganes 1-10, 4571' (pC 4520')
84	St.Clair 14-3N-15E	30376 L,T,	Mich. Consolid. Gas Co., Alvin & Florence Osterland et.al. 1-14, 4627' (pC 4449')
85	St.Clair 31-4N-15E	BD 139 L,T,C,	Consumers Power Co., Consumers Power Co. BD 139, 4634' (pC 4605') (Mt Simon Core at U of M)
86	St.Clair 11-5N-16E	22002 L,T,	Panhandle Energy Expl., Roney #1, 4798' (Eau Claire)
87	St.Clair 26-5N-16E	196	St. Clair O&G Corp., Hurst #1, 4770' (pC 4730')
88	St.Clair 7-5N-17E	BD 152 L,T,C,	Consumers Power Co., Consumers Power 2-7 BDW 152, 4702' (pC 4684') Eau Cl + Mt. Simon Core at U of M)
89	St.Clair 7-5N-17E	BD 151 L,T,C,	Consumers Power Co., Consumers Power 1-7 BDW 151, 4773' (pC 4707') Mt. Simon Core at U of M)
90	St.Clair 30-6N-13E	38964 L,T,	Miller Bros. Inc., ARCO and Senyk 1-30, 6676' (pC 6545')
91	St.Clair 6-6N-16E	24722 T,	Goll, Graves, and Mechling, Sumrack #1, 5391' (Eau Cl?)
92	St.Clair 34-7N-14E	38965 L,T,	Atlantic Richfield Co. Inc. and Miller Bros., ARCO and Patton 1-34, 6310' (pC 6270')
93	St.Joseph 11-6S-10W	31335 L,T,C,	Marathon Oil Co., Lloyd Cupp 1-11, 5283' (pC 5074') (Mt Simon Core)
94	Van Buren 35-3S-14W	25706 T,	Tri County Development, Reed #1, 3678' (Franconia)
95	Washtenaw 28-1S-6E	34223 L,T,	Hunt Energy Corp., Robert H. Worrell 1-28, 6330' (pC 6294')
96	Washtenaw 16-1S-7E	10141	Calvin and Assoc. @ Elect., Wm. F. Voss Comm. #1, 6410' (pC 6374')
97	Washtenaw 27-1S-7E	10792	I.C. Chamnes, Troy and Roddenberry Comm. #1, 6094' (pC 6075')
98	Washtenaw 12-2S-7E	11341	Calvin and Assoc. @ Rot. St., Viola Meinzinger #1, 5692' (pC 5670')
99	Wayne 17-1S-8E	19496	Woodson Oil Co. and Consumer's Power Co., Detroit House of Correction #3, 5483'
A0	Wayne 18-1S-8E	19329 T,	Taggart (O&G?), George #1, 5130' (Wonewoc)
A1	Wayne 16-4S-9E	10430	Colvin and Assoc. @ Elect., Theison Estate #1, 4046' (pC 3985')
A2	Wayne 22-4S-10E	BD 146 L,T,C,	Miller Bros. Inc. (Marathon Oil), Woodhaven (Fee) BD #1, 3752' (pC 3710') (Eau Claire + Mt. Simon cores)

(102 Listings current thru September, 1988. Updated 6-30-89)

(list compiled from Milstein- DNR, Lundgren- WMU, DNR RI#26, WMU scout ticket files, Drilling Progress reports-DNR, Permit Files-DNR)
List compiled by Jeff Cottingham, WMU Core Lab.

Appendix B

Thin Section, X-Ray Diffraction, and Scanning Electron Microscope Samples Used

Well or Outcrop Name	County	Footages	Sample Type	Lith. Interval	T-S	XRD	SEM
Victory 2-26 (MI)	Mason	6495'-6500'	Cuttings	'Trempealeau'	X		
Victory 2-26		6615'-6620'	Cuttings	'St. Lawrence'	X		
Victory 2-26		6685'-6690'	Cuttings	'St. Lawrence'	X		
Victory 2-26		6725'-6730'	Cuttings	Franconia	X		
Victory 2-26		6805'-6810'	Cuttings	Franconia	X		
Victory 2-26		6855'-6860'	Cuttings	Wonewoc	X		
Victory 2-26		6945'-6950'	Cuttings	Eau Claire	X		
Victory 2-26		7125'-7130'	Cuttings	Mount Simon	X		
Victory 2-26		7255'-7260'	Cuttings	Mount Simon	X		
N.M.Land/Oil 1-27 (MI)	Charl.	7395'-7400'	Cuttings	PdC	X		
N.M.L.O.C. 1-27		7535'-7540'	Cuttings	PdC	X		
N.M.L.O.C. 1-27		7715'-7720'	Cuttings	PdC	X		
N.M.L.O.C. 1-27		7895'-7900'	Cuttings	Trempealeau A	X		
N.M.L.O.C. 1-27		8125'-8130'	Cuttings	Trempealeau B	X		
N.M.L.O.C. 1-27		8255'-8260'	Cuttings	Franconia	X		
N.M.L.O.C. 1-27		8455'-8460'	Cuttings	Wonewoc	X		
N.M.L.O.C. 1-27		8575'-8580'	Cuttings	Eau Claire	X		
N.M.L.O.C. 1-27		8695'-8700'	Cuttings	Mount Simon	X		
N.M.L.O.C. 1-27		8805'-8810'	Cuttings	Mount Simon	X		
Doornbos 5-30 (MI)	Misauk.	12,173'	Core	PdC	X		
Doornbos 5-30		12,719'	Core	PdC	X		
Doornbos 5-30		13,691'	Core	Trempealeau B	X		
Doornbos 5-30		14,234'	Core	Mount Simon	X	X	X
Doornbos 5-30		14,240'	Core	Mount Simon	X		
Doornbos 5-30		14,265'	Core	Mount Simon	X	X	X
Doornbos 5-30		14,288'	Core	Mount Simon	X		
Doornbos 5-30		14,299'	Core	Mount Simon	X	X	X
Doornbos 5-30		14,320'	Core	Mount Simon	X		
Doornbos 5-30		14,347'	Core	Mount Simon	X		
Brine Disp. 151 (MI)	St.Clr	4612'	Core	Eau Claire	X		
Brine Disp. 151		4631'	Core	Eau Claire	X		
Brine Disp. 151		4659'	Core	Mount Simon	X		
Brine Disp. 151		4686'	Core	Mount Simon	X	X	X
Brine Disp. 151		4689'	Core	Mount Simon	X		
Brine Disp. 139 (MI)	St.Clr	4528'	Core	Mount Simon	X	X	X
Brine Disp. 139		4529'	Core	Mount Simon	X	X	X
Martin 1-15 (MI)	Gladwin	12,270'-75'	Cuttings	PdC	X		
Martin 1-15		13,140'-45'	Cuttings	PdC	X		
Martin 1-15		13,550'-55'	Cuttings	PdC	X		
Martin 1-15		14,100'-105'	Cuttings	PdC	X		
Martin 1-15		14,210'-15'	Cuttings	Trempealeau A	X		
Martin 1-15		14,600'-605'	Cuttings	Wonewoc	X		
Martin 1-15		14,780'-85'	Cuttings	Wonewoc	X		
Martin 1-15		14,870'-75'	Cuttings	Eau Claire	X		
Martin 1-15		15,270'-75'	Cuttings	Mount Simon	X	X	
Martin 1-15		15,310'-15'	Cuttings	Mount Simon	X	X	X
Martin 1-15		15,350'-55'	Cuttings	Mount Simon	X	X	
Martin 1-15		15,670'-75'	Cuttings	Mount Simon	X	X	
Upjohn #4 (MI)	Kalmzoo	4954'	Core	Mount Simon	X		
Upjohn #4		4955'	Core	Mount Simon	X		
Upjohn #4		4958'	Core	Mount Simon	X		
Upjohn #4		4959'	Core	Mount Simon	X		
Upjohn #4		4960'	Core	Mount Simon	X		
Upjohn #4		4964'	Core	Mount Simon	X		
Upjohn #4		4966'	Core	Mount Simon	X		
Upjohn #4		4968'	Core	Mount Simon	X		
Upjohn #4		4971'	Core	Mount Simon	X		
Upjohn #4		4986'	Core	Mount Simon	X		
Upjohn #4		4998'	Core	Mount Simon	X		
Winterfield A-1 (MI)	Clare	11,605'	Core	PdC	X		
Winterfield A-1		11,605'	Core	PdC	X		
Winterfield A-1		11,605.2'	Core	PdC	X		
Winterfield A-1		11,605.6'	Core	PdC	X		
Winterfield A-1		11,606'	Core	PdC	X		

Well or Outcrop Name	County	Footages	Sample Type	Lith. Interval	T-S	XRD	SEM
Winterfield A-1		11,610.5'	Core	PdC	X		
Winterfield A-1		11,615'	Core	PdC	X		
Winterfield A-1		11,620'	Core	PdC	X		
Winterfield A-1		11,624'	Core	PdC	X		
Winterfield A-1		11,629'	Core	PdC	X		
Bruggers 3-7 (MI)	Misauk.	11,402'	Core	PdC	X		
Bruggers 3-7		11,403'	Core	PdC	X		
Bruggers 3-7		11,404'	Core	PdC	X		
Bruggers 3-7		11,421'	Core	PdC	X		
Bruggers 3-7		11,425'	Core	PdC	X		
Bruggers 3-7		11,427'	Core	PdC	X		
Bruggers 3-7		11,427.4'	Core	PdC	X		
Bruggers 3-7		11,434'	Core	PdC	X		
Bruggers 3-7		11,447'	Core	PdC	X		
Bruggers 3-7		11,449'	Core	PdC	X		
Bruggers 3-7		11,450'	Core	PdC	X		
Bruggers 3-7		11,454'	Core	PdC	X		
Bruggers 3-7		11,464.5'	Core	PdC	X		
Bruggers 3-7		11,468'	Core	PdC	X		
Bruggers 3-7		11,478'	Core	PdC	X		
Bruggers 3-7		11,486'	Core	PdC	X		
Bruggers 3-7		11,494'	Core	PdC	X		
Bruggers 3-7		11,494'	Core	PdC	X		
Bruggers 3-7		11,498.6'	Core	PdC	X		
Bruggers 3-7		11,501'	Core	PdC	X		
Bruggers 3-7		11,504.8'	Core	PdC	X		
Bruggers 3-7		11,505'	Core	PdC	X		
Bruggers 3-7		11,507'	Core	PdC	X		
Bruggers 3-7		11,510'	Core	PdC	X		
Bruggers 3-7		11,523'	Core	PdC	X		
Bruggers 3-7		11,527'	Core	PdC	X		
Bruggers 3-7		11,535'	Core	PdC	X		
Bruggers 3-7		11,537.4'	Core	PdC	X		
Bruggers 3-7		11,537.9'	Core	PdC	X		
Bruggers 3-7		11,544'	Core	PdC	X		
Bruggers 3-7		11,554'	Core	PdC	X		
Bruggers 3-7		11,565.8'	Core	PdC	X		
Bruggers 3-7		11,568.5'	Core	PdC	X		
Bruggers 3-7		11,568.8'	Core	PdC	X		
Lehmann #1 (Iowa)	Dallas	2924'	Core	Mount Simon	X	X	X
McCallum #A1 (Iowa)	Dallas	3008'	Core	Mount Simon	X		
C1 #2 (Indiana)	Lake		Core	Mount Simon	X		
D1 #3 (Indiana)	Lake		Core	Mount Simon	X		
BC #1 (Indiana)	Lake		Core	Mount Simon	X		
E2 #4 (Indiana)	Lake		Core	Mount Simon	X		
E2D #5 (Indiana)	Lake		Core	Mount Simon	X		
Cuppy #1 (Illinois)	6-6S-7E		Drilling record only - No samples				
Mary Streich #1 (IL)	2-11S-6E		Drilling record only - No samples				
Goodwin #1 (IL)	30-29N-2E		Drilling record only - No samples				
Irvine Park (Wisconsin)	31-29N-8W		Outcrop	Mount Simon	X	X	
Irvine Park (WI)			Outcrop	Mount Simon	X	X	
Mount Simon Hill (WI)	8-27N-9W		Outcrop	Mount Simon	X	X	X
Mount Simon Hill			Outcrop	Mount Simon	X	X	
Town Road Exposure (WI)	2-26N-8W		Outcrop	Eau Claire			
Bruce Valley Quarry (WI)	9-23N-8W		Outcrop	Eau Claire	X		
Bruce Valley Quarry			Outcrop	Eau Claire	X		
Bruce Valley Quarry			Outcrop	Wonewoc	X		
Bruce Valley Quarry			Outcrop	Wonewoc	X		
Bruce Valley Quarry			Outcrop	Wonewoc	X	X	
Whitehall Roadcut (WI)	12-22N-8W		Outcrop	Lone Rock	X	X	
Whitehall Roadcut			Outcrop	Lone Rock	X		
Whitehall Roadcut			Outcrop	Lone Rock	X		
Mazomanie Hill (WI)	16-8N-6E		Outcrop	Mazomanie	X	X	
Mazomanie Hill			Outcrop	Jordon (Tremp)	X		
Mazomanie Hill			Outcrop	Jordon (Tremp)	X	X	
Prairie du Chien Cut	Wisconsin		Outcrop	PdC	X	X	
Prairie du Chien Cut			Outcrop	PdC	X		

Well or Outcrop Name	County	Footages	Sample Type	Lith. Interval	T-S	XRD	SEM
Prairie du Chien Cut			Outcrop	PdC	X		

Specific locations for Michigan Wells are given in Appendix A.

PdC = Prairie du Chien Group

Numerous samples were collected on 2 subsequent trips to Wisconsin, none of which were used for anything other than hand observation.

Illinois wells are in addition to lithology from published literature.

Indiana well samples are provided for information only. Well locations were requested to remain confidential.

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