MICHIGAN BASIN PROVINCE (063)

By Gordon L. Dolton

INTRODUCTION

The Michigan Basin Province of the United States includes the Lower Peninsula and eastern Upper Peninsula of the State of Michigan, the eastern counties of Wisconsin, twelve counties in northeast Indiana, five counties in northwest Ohio, and adjoining parts of the Great Lakes. The Michigan Basin is a classic interior cratonic basin whose edges are defined by a series of highs. Counterclockwise from the west, these are the Wisconsin Arch, the Kankakee Arch, the Findlay Arch of Ohio, Algonquin Arch of Ontario, and the Canadian Shield. Virtually the entire assessment province area of approximately 119,000 sq mi is underlain by sedimentary rock and encompasses the Michigan Basin of the United States and excludes only those small parts of the basin in Canada.

Oil and gas in the Michigan Basin are produced from reservoirs as young as Pleistocene and as old as Middle Ordovician. Oil was first found in the Canadian part of the basin in 1858 at Oil Springs on the west flank of the Algonquin Arch, Ontario. Trenton Group production was established in 1884 related to exploration of the Findlay Arch in Indiana, and production in Michigan was first established in 1886 in Devonian rocks at Port Huron field. The principal period of exploration of the basin in the United States did not begin until the 1920’s and resulted in discovery of many Mississippian and Devonian pools in large anticlinal features in the basin. This exploration reached its height during the 1930's and 1940's, followed by intensive exploration of the Silurian Niagaran pinnacle reef trends beginning in the 1970's and a surge of drilling for deep Ordovician reservoirs in the 1980's. Most recently, a high level of drilling has taken place in exploration of the Devonian Antrim Shale. More than 1,500 fields of all sizes have been discovered in the basin. Cumulative discoveries exceed 1.1 BBO and 3.4 TCFG to the end of 1990.

A combination of stratigraphy and structure allows a division of the Michigan Basin fields and prospects into 16 principal plays. The plays are distinguished by their trapping mechanism, reservoir type, and the age of their producing intervals. Fifteen conventional plays and two continuous-type unconventional plays are described. They are:

CONVENTIONAL PLAYS

6301	Anticline
6303	Mississippian Sandstone Gas
6304	Berea Sandstone Stratigraphic
6306	Devonian Carbonate Stratigraphic
6307	Northern Niagaran Reef
6308	Southern Niagaran Reef
6309	Offshore Niagaran Reef
6310	Burnt Bluff Stratigraphic
6311	Trenton-Black River
6312	Ordovician Sandstone Gas
6313	Pre-Glenwood Unconformity
6314	Cambrian
6315	Precambrian Rift
6317	Impact Structure
6318	Clinton

UNCONVENTIONAL PLAYS

6319	*Antrim Shale Gas, Developed Area*
3620	*Antrim Shale Gas, Undeveloped Area*

ACKNOWLEDGMENTS

Scientists affiliated with the American Association of Petroleum Geologists and from various State geological surveys contributed significantly to play concepts and definitions. Their contributions are gratefully acknowledged.

CONVENTIONAL PLAYS

6301. ANTICLINE PLAY

The Anticline Play consists primarily of structural accumulations in a series of northwest-trending anticlines that are clearly delineated in Devonian rocks; some of these features have had, most likely, a long history of growth. Production is mainly from Devonian reservoirs including the Traverse Lime, Dundee Limestone, and Detroit River Group; small amounts of oil and gas production is from pools in the Devonian Berea Sandstone, Silurian Salina carbonates, and Ordovician Trenton–Black River Groups. Salt solution structures, mainly in the southern and southwestern part of the basin, producing from Salina carbonate rocks and Devonian reservoirs, are included in this play. Principal production has been from the central and western parts of the basin. The area of the play is about 56,000 sq mi. For assessment purposes, nonassociated gas in shallow Mississippian reservoirs, in Silurian Clinton carbonate rocks, and in deep Ordovician sandstones is treated separately, although it sometimes occurs in anticlines that have shallow Devonian production.

Reservoirs: Production has mainly been from Devonian Traverse Limestone, Dundee Limestone, Detroit River Group, and Reed City Dolomite reservoirs. These Devonian reservoirs are mostly porous limestones and minor dolomitized limestones. Pay thicknesses average about 15 ft. Porosity ranges from about 5 to 17 percent and averages about 10–11 percent. Silurian Salina reservoirs, generally A–1 or A–2 in salt solution features, are dolomites that have intercrystalline porosity; they range from 2 to 69 ft in pay thickness and have porosities of about 12 percent. Incidental Ordovician Trenton-Black River formations produce in the structures from dolomitized limestone that is localized along fault and fracture trends related to structural development of the anticlines. Very small amounts of oil are trapped in Berea sandstones.

Source rocks: Oils from the Late Devonian Traverse Group are primarily from an unidentified Devonian source, with some possible contribution from Ordovician sources. In the Devonian Dundee Limestone, studies of oil geochemistry in the Michigan Basin by Volger and others (1981) suggest a relationship between these oils and those found in the Ordovician Trenton Group. Organic rich rocks within the Salina A–1 carbonate beds provide sources for the Silurian oils.

Timing and migration: The unusual chemistry of most Devonian oils suggests an Ordovician source, although such a source requires vertical migration through the Silurian evaporite sequence, and in adjoining Ontario, Canada, on the Algonquin and Findlay Arches, oils from Middle Devonian Dundee and Detroit River reservoirs have a character distinctive from Ordovician oils and are thought to have migrated from a Devonian source downdip in the basin (Powell and others, 1984). Ordovician source rocks could have begun generating oil as early as Silurian time, and Devonian source rocks may have been mature as early as Mississippian time. Generation and migration is generally favorable with reference to time of trap formation. Oil gravity in this play typically ranges between 30û and 50û API and averages around 42 degrees.

Traps: Traps are primarily anticlinal structures, but a significant number of combination traps are also included caused by porosity variation from stratigraphic and diagenetic variations within Middle Devonian rocks, primarily of the Traverse Limestone, Dundee Limestone, and Detroit River Group. Seals are shales, anhydrites, and dense carbonate rocks. Depth to production of the Devonian reservoirs is generally 1,000–5,400 ft; depth to production of the Ordovician Trenton-Black River reservoirs is as much as about 8,000 ft.

Exploration status: Commercial oil production from the large anticlinal features in the Michigan Basin was established in 1925 in Berea Sandstone at Saginaw Field, and the first significant Devonian production was established in 1927. Since that time, more than 360 fields have been discovered that are principally productive from Devonian reservoirs. About 70 of these are larger than 1 MMBO, and the largest, over 50 MMBO (Reed City field). This play includes most of the larger fields in the basin. Cumulative discoveries as of 1990 totaled approximately 560 MMBO and 200 billion cubic feet BCFG, not including nonassociated gas pools in Ordovician, Silurian, and Mississippian reservoirs, which are discussed separately. Drilling of major structures has been extensive and discovery rates are now very low. The accompanying exploration and production map shows the distribution of production in Devonian and Salina rocks.

Resource potential: The potential for further discoveries in the onshore areas is generally very low; however, a subset of this play consists of possible structural traps in a series of northwest-trending anticlines in the area occupied by Lake Huron and Lake Michigan. Although there are currently no discovered fields or production offshore and drilling is prohibited, extension of known onshore anticlinal trends suggests that there is offshore potential, especially beneath Saginaw Bay, Michigan. Undiscovered accumulations are anticipated, particularly in Devonian carbonate reservoirs, and much smaller undiscovered amounts are possible in Silurian and Ordovician rocks. Drilling depths of 1,500–8,000 ft are expected. Clinton carbonate and Prairie du Chien-St. Peter Sandstone nonassociated gas potential is assessed separately, but can be viewed, in part, as deep reservoir additions to old fields.

6303. MISSISSIPPIAN SANDSTONE GAS PLAY

The Mississippian Sandstone Gas Play consists of generally small, shallow Mississippian sandstone reservoirs on anticlinal structures in the central part of the Michigan Basin. Most of the production has been from the “Stray” sandstone of the Mississippian Michigan Formation and from the Marshall Sandstone. Most pools are accumulations on anticlines that produce from Devonian and older rocks. The area of the play is approximately 18,000 sq mi.

Reservoirs: Reservoirs are sandstones within a primarily clastic sequence, namely the "Stray" sandstone of the Mississippian Michigan Formation, the Mississippian Marshall Sandstone, and the Devonian–Mississippian Berea Sandstone. Although typically well developed, they show considerable stratigraphic variability. Thickness ranges from 5 to more than 30 ft, and averages about 15 ft. Porosity typically ranges from 9 to 19 percent, and averages about 15 percent.

Source rocks: Source of the gas is unclear, but the Late Devonian Antrim Shale is a likely source rock with some contribution from older rocks.

Timing and migration: Timing of migration is favorable and the charge is primarily gas, although a very small amount of oil is locally recorded.

Traps: Traps are primarily anticlinal structures, and the play is characterized by small, shallow sandstone reservoirs on these features in the central part of the basin. Several accumulations have stratigraphic overprints. Most are shallow accumulations on anticlines that produce from underlying Devonian and older rocks. Seals are interbedded shales and tight sandstones.

Exploration status: The play has produced from about 80 accumulations, mostly less than 6 billion cubic feet in size. Twelve pools are larger than 6 BCFG. The largest, Six Lakes Field, in Montcalm County, produced 52.6 BCFG before being converted to gas storage. Accumulations are relatively shallow, generally less than 2,600 ft deep. The play has been extensively explored since the first production in 1928, and more than 200 BCFG has been discovered. The last discovery of more than 6 BCFG was in 1945. The extent of exploration in this play is shown in the accompanying exploration and production map.

Resource potential: Little potential exists for undiscovered accumulations, and the play was considered virtually exhausted for potential accumulations larger than 6 BCFG.

6304. BEREA SANDSTONE STRATIGRAPHIC PLAY

The Berea Sandstone Stratigraphic Play is defined by accumulations stratigraphically trapped in Late Devonian-Early Mississippian Berea Sandstones in elongate nearshore deposits of the Bedford-Berea deltaic complex, the long axes of which parallel the old shoreline perpendicular to regional transport of sand from the east. Oil is trapped at updip ends of these bodies, where they are truncated by mud-filled channels, and within sandstones of the channel systems, where traps are formed by fine-grained abandoned channel deposits or cut-through fine-grained sediments. This play is on the east side of the Michigan Basin and has an area of approximately 16,000 sq mi.

The Bedford Shale and Berea Sandstone of eastern Michigan record the progradation of a major deltaic system into the basin from the east during Late Famennian or early Mississippian time. The dominant pattern of the Bedford Shale is one of deltaic distributary complexes entering the basin from the northeast, the main distributary dumping most of its load southeast of Saginaw Bay while another distributary flowed westward into the north-central part of the basin. Delta-front muds form an apron wedge that thins westward, and the upper part of the Bedford represents the closing phase of deposition in which the pattern shifted from one of deltaic input from the northeast to the southeast. Deposition closed with progradation of the Berea Sandstone which interfingers with and overrides the upper Bedford.

Distribution of the Berea follows the general pattern of Bedford sedimentation across the eastern margin and center of the Michigan Basin. According to Gutshick and Sandberg (1991), "short prongs of Berea Sandstone, deposited by feeder channels of the delta, project into the basin from the northeast, east, and southeast. In southwestern Ontario, one such Berea shoestring sandstone, more than 18 ft thick, was deposited in a channel cut through the Bedford Shale into the underlying Kettle Point Formation." Asseez (1969) stated that the western part of the Berea in Michigan is primarily a blanket sand and that laterally equivalent distributary and channel sands are present farther to the east.

A series of regressive fluvial-deltaic and shore-zone complexes is present along the eastern margin of the basin, and sandstones deposited in storm-dominated shelf environments are present to the west. Channels extend from northeast of the Michigan thumb area southwestward through the eastern part of the state and, according to Harrell and others (1991), apparently terminate in east-central Michigan close to longitude 84û W.

Reservoirs: The Berea Sandstone in eastern Michigan is generally light gray, mostly fine-grained, partly dolomitic, micaceous, pyritic sandstone that contains some interbeds of gray shale, especially in its lower parts. The reservoirs, although fine-grained in upper and lower parts, are sometimes medium- to coarse-grained in medial parts of the formation. In the Huron County area, the Berea Sandstone is as thick as 260 ft but it thins northwestward, westward, and southwestward. Reservoir thicknesses are much less and in the discovered fields generally range from 5 to 30 and typically from 10 to 20 ft. Porosities range from 7 to 24 percent and average about 12.5 percent.

Source rocks: Source rocks are probably the associated underlying Antrim Shale and some contribution is possible from the overlying Sunbury Shale. Older Devonian source rocks may also have contributed through vertical migration.

Timing and migration: Organic maturity in the Antrim is sufficient to have generated hydrocarbons peripheral to and within deeper parts of the central Michigan Basin (Cercone and Pollack, 1991; Dellapenna, 1991), and in the deep basin, the Antrim is well within the oil generative window at depths greater than about 2500 ft, (Gardner and Bray 1984; Cercone and Pollack, 1991). Vertical migration from older Devonian rocks is speculative. Oil in the play is sweet, and gravity ranges from 44û to 46û API. Traps were available at time of generation and migration.

Traps: Stratigraphic and combination traps have produced in northwest-trending linear sand bodies in the more permeable middle part of the Berea. These sand bodies probably accumulated as nearshore deposits with their long axes parallel to shore and normal to the southwestward regional transport of sand from the Ontario paleoriver system. Oil is trapped at updip ends of these bodies, where the sand bodies are replaced locally by mud-filled channels trending perpendicular to the bars, and is well documented at Williams, Larkins and New Lothrop Fields (Balthazor, 1991; Duszynski, 1991). Other trapping configurations can be hypothesized within both the nearshore and distributary facies, as well as within sandstones of the channel systems in which traps are formed by fine-grained abandoned channel deposits or cut-through fine-grained sediments. Trap timing is favorable relative to generation and migration of hydrocarbons. Drilling depths for these traps range generally from 1,500 to 2,600 ft.

Exploration status: The first Berea field was Saginaw field, a structural accumulation discovered in 1925. Small amounts of oil and gas have since been produced from the Berea in the Saginaw Bay area; however, recent discoveries have resulted in substantial new oil production in Midland and Bay Counties, and, according to Harrell and others (1991), from 1980 through 1986, more than 120 wells were drilled into these stratigraphic traps. Relatively few stratigraphic accumulations have been found to date, although there are a number of associated structurally controlled accumulations. The largest accumulation, Williams field, is about 5 MMBO known recoverable, possibly 7 MMBO when fully developed, but most discovered accumulations are less than a million barrels. Exploration status is shown on the accompanying exploration and production map, which, however, includes tests and production in the Berea on known structures.

Resource potential: The resource potential for this play is believed to be modest, and a relatively large number of generally small undiscovered accumulations are estimated.

6306. DEVONIAN CARBONATE STRATIGRAPHIC PLAY

The Devonian Carbonate Stratigraphic Play consists of accumulations controlled by stratigraphic and diagenetic variations within Middle Devonian rocks, primarily the Traverse Limestone, Dundee Limestone, and Detroit River Group. Depositional features such as bioherms and oolite banks are believed to be present both off- and on-structure. Local bioherms and biostromal buildups in the Traverse, Amherstburg, and Reed City offer trapping potential, and locally porous oolite banks are present in the Richfield. Dolomitization is also localized by fracture or fault trends, such as at Deep River and Pinconning fields, related in part to the northwest-southeast structural trend of the anticlines and an apparent conjugate set. The area of the play is approximately 56,000 sq mi.

Reservoirs: Reservoirs are porous limestones and, minor, dolomitized limestones. Reservoir facies are believed to occur both off- and on-structure, and they include local bioherms and biostromal buildups in the Traverse, Dundee, Amherstburg and Reed City and locally porous oolite banks in the Richfield. Dolomitization localized by fracture or fault trends provides reservoirs, as at Deep River and Pinconning fields. Reservoir thickness range from 5 to 60 ft and averages about 10 ft. Average reservoir porosity ranges from about 5 to 17 percent and averages about 10–11 percent.

Source rocks: Oils from the Traverse Group are primarily from an unidentified Devonian source, with some possible contribution from Ordovician source rocks. Studies of oil geochemistry by Vogler and others (1981) suggest a close relationship between oils in the Devonian Dundee Limestone and those in the Ordovician Trenton Group, and Vogler and others suggested vertical migration from Ordovician source rocks through the Silurian evaporite sequence into younger reservoirs. More recent work in adjoining Ontario, Canada, on the Algonquin and Finley Arches indicates, however, that the oils from Middle Devonian Dundee and Detroit River reservoirs have a distinctive character apart from Ordovician oils and probably migrated from a Devonian source downdip in the basin (Powell and others, 1984).

Timing and migration: Ordovician source rocks could have begun generating oil as early as Silurian time, and Devonian source rocks may have been mature as early as Mississippian time. Traps were in place at least during later stages and probably during principal stages of generation and migration.

Traps: Traps are caused by stratigraphic and diagenetic variations within Middle Devonian rocks. Seals are shales, anhydrites, or dense carbonate rocks. Local bioherms and biostromal buildups in the Traverse, Dundee, Amherstburg and Reed City offer particular trapping potential, such as in the South Buckeye field (Harrison, 1991), as do locally porous oolite banks in the Richfield. Dolomitization locally provides traps along fracture or fault trends, such as in the Deep River and Pinconning fields, and probably are related to the structural trend in the anticlines or a conjugate set (Hurley and Budros, 1990). Production in dolomitized fractured zones in the Dundee Formation at the Deep River and Pinconning fields and in the Dundee accumulations at Reed City and West Branch probably are in part similarly controlled.

Exploration status: The Deep River field is the largest accumulation at approximately 30 MMBO, and the West Branch is almost as large; however, most accumulations are small. Exploration in this play has been mostly incidental to exploration of the anticlinal trends. Exploration in the play is shown by the accompanying exploration and production map, which, however, includes all the extensive Devonian production in structural traps; data do not allow ready separation of the stratigraphically trapped components and are therefore shown together.

Resource potential: This play is lightly explored in off-structure areas, and significant potential for undiscovered resources is estimated. Most of these accumulations probably are small.

6307. NORTHERN NIAGARAN REEF PLAY

The Northern Niagaran Reef Play consists of onshore oil and gas accumulations trapped in pinnacle reefs of Niagaran (Middle Silurian) age within the northern segment of a circular trend of reefs in the Michigan Basin. Most of the productive reefs are about 50–400 acres in area and have 200–700 ft of relief. The play covers about 4,000 sq mi.

Reservoirs: Reservoir rocks within the reefs are dolomitized and have both intercrystalline and vugular porosity averaging about 8 percent. Occasionally overlying Salina Group A–1 carbonate rocks produce in association with the reefs. Pay thicknesses average about 70 ft, but vary greatly. Sealing is mostly by Salina Group evaporites encasing the reefs, and salt plugging of the reservoir is a significant problem in the eastern extremity of the play and along its basinward margin.

Source rocks: The Niagaran reef play produces an oil distinct from that found in other Michigan Basin accumulations. A strong phytane-over-pristane predominance and the lack of diasteranes indicates a carbonate source. Correlation of these oils and potential source rocks using carbon-isotope data shows that the A–1 carbonate units in the Salina Group are the principal source rocks; lesser contributions are from part of the Niagaran reef rocks themselves. Goodman (1991) also suggested that organic-rich rocks in the "Gray Niagaran" interreef areas and substrate are sources for oil and gas.

Timing and migration: Generation and migration may have begun as early as the Devonian. Accumulations are variously oil (with dissolved gas), oil with gas caps, and nonassociated gas, with gas preferentially downdip. The distribution of gas-filled versus oil- and gas-filled reservoirs suggest differential migration from a basinward source. Oil gravities are generally 39û to 50û API, and gas fields carry condensate, averaging around 80 NGL/MMCFG. Associated-dissolved gas to oil ratios commonly range from about 300 to 20,000 CF/bbl and average around 2,000.

Traps: Traps are pinnacle reefs, which are very numerous and are in a trend approximately 12-20 mi wide across the northern part of the state. The productive part of the trend is approximately 6–10 mi wide. Most of the productive reefs are about 50–400 acres in area and have 200–700 ft of relief. Sealing is principally by Salina Group evaporites encasing the reefs. Anticipated drilling depths range from about 3,000 to 7,500 ft.

Exploration status: First production in the northern reef trend was established in 1952. However, the exploration history of this play is similar to that of the southern reef trend, being stimulated by sophisticated geophysical techniques that allowed effective definition of reef prospects beneath glacial drift and discovery of the first significant field in 1969. More than 700 reef fields have since been discovered, and prospects for further discoveries are good. Approximately one-third of the discovered fields are gas fields. The largest gas field is Grant 13 field, which has approximately 47 BCFG known recoverable, and the largest oil field is Chester 18A, which has about 14 MMBO known recoverable. Of those 113 oil fields larger than 1 million barrels known recoverable, the average size is approximately 2.4

MMBO; for 52 gas fields larger than 6 BCFG known recoverable, the size is 13.5 BCFG. Fields of all sizes have produced in excess of 300 MMBO and 1.4 TCFG.

Resource potential: Although the play is densely drilled, discovery rates remain high and significant undiscovered resources are estimated to be present. Overall, remaining accumulations are expected to be somewhat smaller than those that have been discovered.

6308. SOUTHERN NIAGARAN REEF PLAY

The Niagaran Reef Play consists of oil and gas accumulations trapped in pinnacle reefs of Niagaran (Middle Silurian) age that form a circular trend in the basin. Most of the productive reefs are about 40–300 acres in area and have 100–350 ft of relief. Sealing is primarily by Salina Group evaporites encasing the reefs The Southern Niagaran Reef Play refers to the southern onshore part of this trend and has an area of approximately 6,000 sq mi.

Reservoirs: Reservoir rocks within the reefs are dolomitized and have both intercrystalline and vugular porosity averaging about 8 percent. Pay thickness averages about 70 ft, but varies greatly. Occasionally, Salina Group A–1 carbonate rocks produce in association with the reefs.

Source rocks: The Niagaran Reef Play produces an oil distinct from that in other Michigan Basin accumulations. A strong phytane-over-pristane predominance and the lack of diasteranes indicates a carbonate source. Correlation of these oils and potential source rocks using carbon-isotope data shows that the A-1 carbonate units of the Salina Group are the principal source rocks; lesser contributions are from part of the Niagaran interreef rocks themselves.

Timing and migration: Generation could have begun as early as the Devonian. Oil gravities are from 26û to 49û API, averaging 40û, and gas to oil ratios average about 2200 CF/bbl. Liquids to gas ratios average around 38 BNGL/MMCFG for associated gas fields, and 11 BNGL/MMCFG for nonassociated gas fields.

Traps: Traps are pinnacle reefs in a tract that ranges from 15 to 40 mi in width. The productive part of the trend varies from about 6 to 35 mi in width. Reefs in the southern trend are generally shorter and broader than those in the northern trend, and most of the productive reefs in the southern trend range from about 40 to 300 acres in area and from 100 to 350 ft in vertical relief. Sealing is generally produced by Salina Group evaporites encasing the reefs. In the western part of the southern reef trend, virtually all reefs are water filed due to a lack of cap rock resulting from evaporite dissolution, and a few reefs within the normally productive part of the tend to the east are water filled due to similar breaching of evaporite cap rock and associated fracturing. Depths to production range from about 2,000 to 4,500 ft.

Exploration status: Hydrocarbons were first discovered in reefs in 1889 in Essex County, Ontario, Canada, and became more widely productive in the Canadian part of the basin and in St. Clair County, Michigan, in the early 1900's. First substantial production in Michigan was established at the Diamond Crystal Salt field in 1927. The modern exploration history of the play consists of two main phases. The first phase consisted of extension of the Silurian Guelph Formation reef trend of Ontario into southeastern Michigan. The second phase began in the late 1960's and was due to improvements in seismic techniques that allowed for effective resolution of reef prospects through glacial drift. About 300 fields have been discovered in the southern reef trend; both oil and gas have been found. Most of these fields are small, but more than 30 fields are larger than 1 MMBO or 6 BCFG known recoverable. Ray field is the largest nonassociated gas field, having about 36 BCF of known recoverable gas, and Columbus Sec. 3 is the largest oil field, having about 8.5 MMBO known recoverable. In terms of total hydrocarbons, Boyd-Peters field has about 17 MMBOE. Production from the Southern Niagaran Reef Play accounts for more than 90 MMBO and 600 BCFG.

Resource potential: Discoveries continue and prospects for further discoveries are good in that significant parts of the southern reef trend are undrilled. Accumulation sizes are expected to be similar, but overall somewhat smaller, than those already discovered.

6309. OFFSHORE NIAGARAN REEF PLAY (HYPOTHETICAL)

The Offshore Niagaran Reef Play consists of possible oil and gas accumulations trapped in pinnacle reefs of Niagaran (Middle Silurian) age within the offshore part of the reef trend in Lakes Michigan and Huron. The Offshore Niagaran Reef Play has an area of approximately 6,000 sq mi offshore in Lakes Michigan and Huron.

Reservoirs: Reservoir rocks within the onshore part of the reef trend are dolomitized and have both intercrystalline and vugular porosity averaging about 8 percent; they are believed to be present in the offshore. Pay thickness averages about 70 ft onshore.

Source rocks: The Niagaran reef plays produce an oil distinct from that in other Michigan Basin accumulations. A strong phytane-over-pristane predominance and the lack of diasteranes indicates a carbonate source. Correlation of these oils and potential source rocks using carbon-isotope data shows that Salina Group A–1 carbonate rocks are the principal source; lesser contributions came from part of the Niagaran reef rocks themselves.

Timing and migration: Generation could have begun as early as Devonian time.

Traps: Traps consist of pinnacle reefs in offshore extensions of both the northern and southern reef trends of Niagaran (Middle Silurian) age that altogether form a circular trend in the basin. Most of the producing onshore pinnacle reefs are about 50–200 acres in area and have 300–700 ft of relief. Pay thickness averages about 70 ft. Sealing is mostly by Salina Group evaporites encasing the reefs. Anticipated drilling depths range from about 2,000 to 7,000 ft.

Exploration status: No discoveries are recorded in the Great Lakes, although a very large number of accumulations have been recorded in adjoining onshore elements of these reef trends. Offshore drilling is now prohibited in both Lakes Michigan and Huron, although the reef trend undoubtedly extends into the offshore.

Resource potential: The resource potential is very good for both oil and gas. Field sizes should be similar to those discovered onshore, and a mix of oil and nonassociated gas fields is expected.

6310. BURNT BLUFF STRATIGRAPHIC PLAY (HYPOTHETICAL)

The Burnt Bluff Stratigraphic Play encompasses stratigraphic traps due to biohermal buildups and porosity pinchouts in carbonate rocks of the Lower Silurian Burnt Bluff Group in the northern Michigan Basin. Traps are believed to be primarily coral stromotoporoid reefs and buildups sealed by overlying rocks of the Manistique Group. Reservoirs are within the Hendricks Formation and consist of stromatoporoid reefal rocks, having primary intraparticle and interparticle porosity and open-shelf limestones having solution-generated porosity and dolomitization. This is a hypothetical play based on the general stratigraphic setting of observed bioherms within formation and hydrocarbons within the system.

Reservoirs: Reservoirs are within the Hendricks Formation and consist of stromatoporoid reefal rocks, having primary intraparticle and interparticle porosity, and open shelf limestones having solution-generated porosity and dolomitization, as noted by Harrison (1985). The Fletcher Pond and Hardwood Point Fields in Alpena County produce from coral-stromatoporoid reef facies in structural settings. The play is limited to the south by an increasingly deep-water open-marine facies lacking biohermal buildups.

Source rocks: Source rocks have not been positively identified for this play, but hydrocarbons are in the system, as evidenced by productive Burnt Bluff reservoirs in structural settings elsewhere, generally in offshore open-shelf reservoir facies.

Timing and migration: Timing of trap formation is favorable relative to hydrocarbon generation and migration. Oil is anticipated in shallow parts of the play and gas in deeper basinal areas.

Traps: Traps are stratigraphic and believed to be primarily coral stromotoporoid reefs and buildups sealed by overlying rocks of the Manistique Group. Depths generally range from 1,500 to 9,000 ft.

Exploration status: This is a hypothetical play based on general stratigraphic setting, observed bioherms within the formation and hydrocarbons within the system. Although the Burnt Bluff Formation produces oil or gas from structural traps, this hypothetical play is defined for stratigraphic traps only. The exploration status map indicates where this formation is now productive in structural settings within the play area; these maps are constructed by stratigraphic unit rather than by trap type.

Resource potential: Based on the general stratigraphic setting, observed bioherms within formation and hydrocarbons within the reservoir system, the play is believed to have potential for undiscovered resources. The accumulations are expected to be small, and at this time a substantial risk is assigned to the play based mostly on the unknown effectiveness of traps and seals.

6311. TRENTON-BLACK RIVER PLAY

The Trenton-Black River Play is characterized by hydrocarbon accumulations in stratigraphic traps in dolomitized limestone reservoirs within the Upper and Middle Ordovician Trenton and Black River Groups. The play includes the largest field in the Michigan Basin (the Albion-Pulaski-Scipio trend), as well as the oldest production. Rocks of these groups are present throughout the Lower Peninsula and in parts of the Upper Peninsula and Wisconsin, but, to date, almost all discoveries have been from the southern part of the Lower Peninsula of Michigan and the adjoining parts of Indiana and Ohio. The discovered oil and gas pools are primarily stratigraphic traps caused by porosity and permeability variations in dolomitized limestone, that are probably localized by fault and fold trends related to the northwest-southeast structural trend of the anticlines. The area of the play is approximately 72,000 sq mi, both on- and off-shore.

Reservoirs: The typical reservoir rock is dolomite having intercrystalline, vuggy, and (or) fracture porosity and generally in narrow linear trends cut vertically through the involved formations, localized along fault and fracture trends that probably are related to the northwest structural trend of the anticlines and to the fault and fracture zones on their flanks. In some intervals, vugs, fractures, and even caverns are abundant. Pay thickness varies greatly but averages about 30 ft; lesser development of dolomitization away from these zones near the top of the formation is locally productive, especially on the Findlay Arch.

Source rocks: The Ordovician oils form a group with the Devonian Dundee oils and have a distinctive chemical composition of Ordovician oils from various localities worldwide. A probable source rock is the Utica Shale (Upper Ordovician) or associated Collingwood Shale, whose correlative in the Canadian part of the basin, the Collingwood Member of the Lindsay Formation, is organic rich and has been suggested, where mature downdip, as the probable source of the Canadian Ordovician oils (Powell and others, 1984). The Utica is of good source-rock quality to the south in Ohio, although geochemical analyses in Michigan suggest that quality diminishes rapidly to the north into the basin (Moyer, 1982; Hiatt, 1985) and, in central and northern parts of the basin, may not be sufficient for generation and expulsion. However, the Collingwood Shale has been identified as a source rock in the northern part of the basin (Hiatt and Nordeng, 1985). Other workers have suggested source beds within the underlying Glenwood, Foster, or Trempealeau.

Timing and migration: Utica Shales and older possible source beds could have been thermally mature as early as Silurian time. Such rocks are now clearly within the gas window in deeper parts of the basin. Oil produced in this play ranges from 39û to 43û API and has gas to oil ratios averaging approximately 1,600 CFG/bbl.

Traps: The play consists of stratigraphically controlled accumulations within the Upper and Middle Ordovician Trenton and Black River Groups. The discovered oil and gas pools are stratigraphic traps resulting from porosity and permeability variations in dolomitized limestone; the larger fields are localized along fault trends related to the northwest-southeast structural grain of the anticlines and associated faults which probably are along reactivated basement faults, though they commonly lack significant displacement; a conjugate fracture set is suggested at Dover and Colchester fields in Canada and also in Devonian rocks at several places in Michigan. Seals are provided by the Utica Shale and by impermeable Trenton carbonate rocks. Depths of discovered fields are fairly shallow; most produce from less than 5,000 ft. Undiscovered accumulations are expected to be somewhat deeper and could locally be as deep as 10,000 ft.

Exploration status: The play includes the largest field in the Michigan Basin (the Albion-Pulaski-Scipio trend), as well as the earliest production (dating from 1884) which was from a few small pools at the southern edge of the basin. In 1957, the Albion-Pulaski-Scipio trend was discovered in south-central Michigan. This trend, which forms the largest field in the basin, contains approximately 128 MMBO known recoverable and dominates the production statistics for the basin. The second largest field, Stoney Point, discovered in 1983, is approximately 20 MMBO. To date, more than 60 Trenton-Black River fields have been discovered. Of these, only four contain more than 1 MMBO. Cumulative production in the play, as of 1989, was more than 130 MMBO and more than 230 BCF of associated-dissolved gas.

Resource potential: The sparseness of drilling in the play allows for significant exploration potential. The key question is whether any large traps similar to the Albion-Pulaski-Scipio trend are present, or if the undiscovered resources are distributed mainly in small fields (<1 MMBO or <6 BCFG) similar to other discoveries in the play.

6312. ORDOVICIAN SANDSTONE GAS PLAY

The Ordovician Sandstone Gas Play includes nonassociated gas and condensate trapped in Middle Ordovician sandstone reservoirs variously attributed to the Prairie du Chien Group, St. Peter Sandstone, Jordan Sandstone, and Bruggers Sandstone and to sandstones within the overlying Glenwood Formation. These sandstones extend over much of the central part of the basin Traps are structural and, in some cases, associated with production from overlying shallow reservoirs. The play area is about 60,000 sq mi.

Reservoirs: Middle Ordovician sandstones are as thick as about 1,200 ft in the central part of the basin, and thin to the margins. The sandstone is a silica-cemented clean quartz sandstone, having a porosity of about 10 percent, and is lithologically somewhat similar to the St. Peter Sandstone. The unit is of probable Middle Ordovician age (White Rockian age of Repetski and Harris, 1981), and is overlain by a major unconformity (Bricker and others, 1983; Fisher and Barratt, 1985). Although the precise correlation is uncertain, some authors attribute these sandstones to the St. Peter Sandstone (Catacosinos and others, 1991; Barnes and others, 1992). Unequivocal St Peter Sandstone is limited to southwestern Michigan (Bricker and others, 1983), and assignment of the subject sandstone to Bruggers Sandstone (Fisher and Barratt, 1985) or to an unnamed uppermost member of the Prairie du Chien is reasonable in light of age and rock relationships. Sandstones in the overlying Middle Ordovician Glenwood Formation produce in association with the older Ordovician sandstones, and for assessment purposes, are considered with them. A complex diagenetic history is indicated, and effective porosity may be controlled in part by diagenetic interactions between the quartz grains and the associated clay assemblage. As noted by Fowler and Schaefer (1991), the unit contains a variety of shallow marine facies and, particularly in the southern two-thirds of the state, the sandstone is interlayered with sandy, dark dolomite of low porosity that can act to isolate the individual sandstone layers into separate reservoirs. This reservoir variability is particularly well documented at Rose City field (Schneider and others, 1991). Reported reservoir thickness range from 10 to more than 400 ft. Porosity of the productive intervals range from 5 to 20 percent and averages about 10–12 percent.

Source rocks: The precise source rock is unknown, but a source in the Ordovician is suspected, possibly in the Glenwood Formation or in the Foster Formation of the Prairie du Chien Group (Fisher and Barratt, 1985) or in the underlying Late Cambrian Trempealeau Formation. Such rocks are in the gas-generation realm in most of the basin. More speculative, and so far undocumented, are source rocks of Precambrian age, as have been suggested by Seglund (1989).

Timing and migration: Traps were in place at time of generation and migration of source rocks. The known traps are gas charged, and the produced gas has a NGL/gas ratio of approximately 25 bbl/MMCF.

Traps: The basic trapping mechanism is probably due to a combination of factors. Virtually all production is found on anticlines, and most discoveries have been as deep pools within fields already producing from Devonian and shallower reservoirs. Nevertheless, porosity and permeability variations at least partly control productivity. Many of these deep structural closures grew during Ordovician and Lower Silurian. The associated younger structures represent a later phase of folding, possibly augmented by compactional drape over the earlier features.

Exploration status: This play is the most recent of the major exploration plays in the Michigan Basin; the first discovery was in 1981. Since then, more than 60 nonassociated gas accumulations have been discovered, accounting for more than 700 BCF known recoverable gas; 34 accumulations are probably larger than 6 BCFG. Pools include the deepest production to date in the Michigan Basin and range from about 7,800 to 12,000 ft in depth. Approximately two-thirds of these are new pools within older producing fields. Because of the recency of the discovery of these accumulations, their actual size is not well known; the largest is probably the Conners Marsh field, containing more than 80 BCF of known recoverable gas.

Resource potential: Because of very sparse drilling below the Devonian in the central part of the Basin, potential for additional gas discoveries is excellent. Porosity control by diagenesis could further increase the undiscovered gas potential by adding the possibility of off-structure stratigraphic traps, although this purely hypothetical element was not quantitatively estimated.

6313. PRE-GLENWOOD UNCONFORMITY PLAY (HYPOTHETICAL)

This hypothetical play consists of possible stratigraphic traps associated with the pre-Glenwood unconformity. The Ordovician St. Peter, Prairie du Chien, Foster formations and Cambrian Trempealeau formation and older rocks are truncated at the southern margin of the Michigan Basin. Stratigraphic traps are postulated to be present at this unconformity and may consist variously of truncation, paleorelief, and localized porosity development at or near the surface of unconformity. Structure would provide additional hydrocarbon localization. Stratigraphic entrapment is also possible where the sandstones are interbedded with carbonates within the older rocks.

Reservoirs: Reservoirs are variously sandstones of the Bruggers-Prairie du Chien and St. Peter intervals and carbonate rocks of the Prairie du Chien, Foster and Trempealeau and older formations. Seals are the overlying fine-grained rocks of the Glenwood Formation.

Source rocks: Source rocks are possibly unidentified organic-rich beds within the older Paleozoic sequence, possibly Glenwood, Foster (Prairie du Chien), or Trempealeau Formations. Organic-rich rocks have been noted in the Foster Formation (Fisher and Barratt, 1985).

Timing and migration: Traps would have been present at the time of generation and migration of hydrocarbons. In deeper areas, supposed source rocks would be in a gas-generation realm; however, oil has been discovered in shallow Glenwood reservoirs in a few places in the basin, such as at Lime Lake field (Arndt, 1991).

Traps: Stratigraphic traps are speculated to be present at the basal Glenwood unconformity and may consist variously of truncation, paleorelief, and localized porosity development at or near the surface of unconformity. Structure would provide additional hydrocarbon localization. Stratigraphic entrapment is also possible where the sandstones are interbedded with carbonates within the older rocks (Fisher and Barratt, 1985). Some production may be anticipated in the immediately overlying Glenwood interval due to local porosity development, folding, or draping over relief of the underlying surface (Dolly and Busch, 1972; Arndt, 1991). Depths to traps are expected to range from 2,000 to 7,500 ft and average around 3,000 ft.

Exploration status: This is a hypothetical play and, at present, there is no production within the confines of the Michigan Basin; however, in north-central Ohio, the Trempealeau is productive in a somewhat analogous setting involving paleorelief at the Knox unconformity (Dolly and Busch, 1972).

6314. CAMBRIAN PLAY (HYPOTHETICAL)

This is a speculative play primarily involving Cambrian reservoirs in basement-controlled structural traps, both within and without recognized anticlinal trends in younger rocks and encompassing broad areas of the basin and its shelves.

Reservoirs: The objective section is the Cambrian section, consisting of dolomites of the Trempealeau Formation and Franconia Formation and sandstones of the Galesville or Mt. Simon Formations. Quality of reservoirs is relatively unknown; however, the apparent low rock density of possible reservoir sandstones suggests some effective porosity.

Source rocks: Source rocks are hypothetical. Indigenous Cambrian hydrocarbon source rocks are not demonstrated. Speculative source rocks for the play could be present within the Trempealeau Formation or within the overlying Ordovician, and deep source rocks have been hypothesized within the underlying Precambrian rift. Nevertheless, the presence of adequate source rocks for this play is unknown and is considered to carry a very high risk.

Timing and migration: Maturation of source rocks, if present, should be, in principle, well timed with reference to trap formation.

Traps: Traps are considered to be primarily structural, however, some stratigraphic traps related to facies porosity variations may be present.

Exploration status: No oil or gas discoveries have been made in the part of the Michigan Basin in the United States. The only Cambrian production is from Ontario, Canada, on or near the axis of the Algonquin Arch at the eastern edge of the basin; production is from stratigraphic traps in dolomite and porosity pinchouts or from fault blocks in dolomite (Reszka, 1991).

Resource potential: This play carries a very high risk because of the lack of demonstrated adequate source rocks and the tenuous nature for inferring their presence.

6315. PRECAMBRIAN RIFT PLAY (HYPOTHETICAL)

This hypothetical play consists of the occurrence of nonassociated gas in Precambrian sedimentary rocks associated with a major buried rift system, probably an arm of the Mid-Continent rift system. More than 5,290 ft of pre-Mt. Simon red beds have been penetrated at Sparks and others 1-8, Gratiot County, and beds of similar age have been encountered at Beaver Island, where more than 810 ft of sandstone, siltstone, and shale, marine and fluvial in origin, are reported. Reservoirs are estimated to be fluvial, and lacustrine sandstones and source rocks are hypothesized to be fine-grained lacustrine or paludal rift sediments. Reservoirs are thought to be primarily within the sag sequence overlying the Mid-Keweenawan synrift sedments. Source rocks, if present, are presumed to be in the Nonesuch Formation of the Oronto Group of the Keweenawan Supergroup, or its equivalent, as in the Upper Peninsula of Michigan and in northern Wisconsin. Because of their generally deep structural settings, the source rocks are believed to be mostly in the thermal zone of gas generation, and any liquids originally present would have been converted to gas. Traps are conceived as fault-bounded blocks containing reservoir rocks in structural closures and stratigraphic combinations with porosity pinch-outs and reservoir truncations. The area of the play is approximately 5,400 sq mi.

Reservoirs: Reservoirs are believed to be fluvial and lacustrine sandstones of uncertain quality, probably mostly within the sag sequence overlying the Mid-Keweenawan synrift sediments. Fowler and Kuenzi (1978) indicated that the composite sequence in the Sparks test contains approximately 40 percent sandstone and 60 percent mudstone, and they interpreted the environment associated with these sequences to be a combination of turbidity and low-velocity clear water currents and pelagiac precipitation associated with a broad, subsiding rifted-marine basin. Catacacosinos and Daniels (1981) argued for continental deposition in a lacustrine environment, whereas Ojakanges and Morey (1982) suggested a fluvial origin. At Beaver Island, possibly equivalent strata, consisting of more than 810 ft (240 m) of sandstone, siltstone, and shale, have been reported variously as "granite wash," marine, and fluvial (Catacosinos, 1991).

Source rocks: Source rocks are hypothesized to be fine-grained lacustrine or paludal sediments. They are not documented within the Michigan Basin proper, but if present, are presumed to be equivalents of the Nonesuch Formation of the Oronto Group of the Keweenawan Supergroup, as in the Upper Peninsula of Michigan and in northern Wisconsin.

Timing and migration: Because of their generally deep structural settings, possible source rocks are believed to be mostly in a gas-generative realm, and any liquids originally present would have been converted to gas. In the shallowly buried Lake Superior region, where little overburden has been removed, Nonesuch source rocks passed from the thermal zone of oil generation into the thermal zone of gas generation by Early Paleozoic (Yarus and others, 1987). In much of the Michigan Basin proper, rocks deeper than about 7,000 ft are generally in the gas generation zone (Gardner and Bray, 1984; Cercone and Pollack, 1991). Timing of trap formation relative to hydrocarbon migration was probably favorable; however, early generated hydrocarbons may have escaped from the system.

Traps: Traps are postulated to be folds and fault-bounded blocks containing reservoir rocks and stratigraphic combinations, including porosity pinch-outs and reservoir truncations; however, the internal structure of the Michigan arm of the Midcontinent rift is not well understood. Because of its approximately normal rather than parallel orientation to the Grenville Front, possibly related to the principal stress of the compressional phase in the Midcontinent rift arm, the structural fabric may differ from that area, lack the strong inversion, and not be optimal for entrapment. Traps are anticipated to be products mostly of the compressional phase of rift deformation near the end of the Proterozoic. Seals are hypothesized to be fine-grained clastic rocks associated with the reservoirs. A significant problem may be the integrity of traps and seals within this ancient faulted system for retention of hydrocarbons.

Exploration status and resource potential: This is a purely hypothetical play with very high risk. No hydrocarbons have been encountered in this arm of the rift. Drilling depths generally range from 6,000 to more than 20,000 ft.

6317. IMPACT STRUCTURE PLAY

During the Phanerozoic, the Earth has been subject to nearly random bombardment by asteroids and comets and by occasional comet showers. Structures created by impacts provide a unique and known habitat for hydrocarbon entrapment in the Michigan Basin.

Reservoirs: Reservoirs may be provided by those Devonian, Silurian, and Ordovician limestones, dolomites, and clastic rocks which are productive elsewhere in the basin, and by unique reservoirs resulting directly from the impact itself, including shattered or brecciated rock, fall back and ejecta of various ages and lithology, and from local reservoir developments associated with the post impact history of the individual feature. An inferred impact structure in Cass County produces from limestones of the Traverse Group, which are draped over a rim structure of Late Ordovician rocks.

Source rocks: Potential source rocks are of Ordovician, Silurian, and Devonian ages, seen elsewhere in the basin. Oils from the Devonian Traverse Group elsewhere in the basin, and productive at the Cass County feature, are attributed to an unidentified Devonian source, with some possible contribution from Ordovician sources.

Timing and migration: Generation and migration of hydrocarbons from source rocks was favorable with reference to trap formation. API gravity at the Calvin 28 field, in a very shallow part of the basin, is approximately 20û.

Traps: A variety of trap types are known or conceived in association with impact structures. Initial crater configurations and sizes are imposed at the time of impact, depending on size, mass, composition, velocity, and angle of incidence of the impacting body and the character of the impacted rocks. These features are modified by subsequent erosional and depositional processes. Central uplifts of shattered rocks, where present, may afford traps and reservoirs for hydrocarbons. Uplift, faulting, rotation, and slumping associated with formation of crater rims may also provide traps. Closures also may be productive in rocks that are folded over rims or central uplifts of impact structures. At the Cass County feature, production is primarily from Traverse Lime draped over the rim structure.

Exploration status: The number of remaining impact features in Michigan is unknown. The first discovery at an impact feature in the basin was in 1978 at Juno Lake field on the Cass County structure. The Cass County feature in the Michigan Basin is of apparent Late Ordovician age and is productive from the Devonian Traverse Lime and Sylvania Sandstone in four separate fields along the crater rim; the largest of these accumulations is at Calvin 28, discovered 1980, which had produced more than 300,000 BO by 1984 (Milstein, 1988).

Resource potential: This is a very high risk play and depends on the presence of an additional impact structure containing an accumulation of minimum size in the Michigan Basin. Exploration of similar features in other basins has yielded fields larger than 20 MMBO; however, the probability of occurrence of an additional undiscovered accumulation larger than 1 MMBO or 6 BCFG in the Michigan Basin is considered slight.

6318. CLINTON PLAY

The Clinton Structural Play consists of gas reservoirs in Clinton carbonate rock in structural traps within the northern and deeper parts of the Michigan Basin. Most of the discoveries have been deep pool additions to older fields, however, some undrilled anticlinal features offer opportunity for undiscovered accumulations.

Reservoirs: Reservoirs are dolomites that produce in structures common with the deeper reservoirs, typically open-shelf limestones that have solution-generated porosity and dolomitization. Open-marine dolomitized micritic limestone produces at the Goodwell field; porosity ranges from 3 to 12 percent, and averages 6 percent in an interval of 35 ft. The formation also locally produces from coral-stromatoporoid reef facies in structural settings, such as at the Fletcher Pond and Hardwood Point fields in Alpena County. The play is limited to the south by the increasing argillaceous content of the reservoir formation. Porosity varies within fields, and in some instances porosity is high in off-crestal positions.

Source rocks: Source rocks have not been positively identified for this play, but hydrocarbons are in the system, as evidenced by productive Clinton reservoirs. A Silurian or Ordovician source rock is suspected.

Timing and migration: Timing of trap formation is favorable relative to hydrocarbon generation and migration. Suspected source rocks are in the gas-generation thermal realm in most of the basins, and known accumulations are gas. The produced NGL/gas ratio is approximately 13 bbl/MMCF.

Traps: Accumulations are considered to be in structural traps and are located mostly as deep pools in anticlines that are ordinarily producing also at shallow Devonian or deeper Prairie du Chein levels. Traps range from about 4,500 ft to more than 9,000 ft.

Exploration status: Although one of the most recent plays in the basin, the Clinton Play can be attributed almost entirely to discovery and development of deep pools within known fields. Only one accumulation, Fletcher Pond, is outside the bounds of a known field. Six pools have been discovered that exceed 6 BCFG in size. The largest of these may be either Goodwell, containing approximately 18 BCFG, or Big Rapids, a more recent discovery of uncertain size.

Resource potential: Some undrilled structural closures undoubtedly remain and offer opportunity for undiscovered accumulations.

UNCONVENTIONAL PLAYS

Continuous-Type Plays

6319. ANTRIM SHALE GAS PLAYS, DEVELOPED AREA
6320. ANTRIM SHALE GAS PLAYS, UNDEVELOPED AREA (HYPOTHETICAL)

The Antrim Shale Gas Plays consist of gas accumulation within fractured Antrim shales of Late Devonian age. Besides the Antrim proper, the play includes parts of the Ellsworth Shale in western Michigan and Bedford Shale in eastern Michigan. The play probably is bounded to the west by the low organic content of the Ellsworth Shale and the loss of thick organic-rich Antrim Shale tongues. Trapping in part may be controlled by hydrodynamic flow and water block at the subcrop. Gas presumably was generated during early catagenesis. Organic maturity within the Antrim Shale is sufficient to have generated gaseous hydrocarbons peripheral to and within deeper parts of the central Michigan Basin. Production probably is feasible only where the shales are sufficiently fractured, and it is mostly confined to the black shale facies (Lachine and Norwood Members) of the Lower Antrim, with principal development in Antrim, Otsego, and Montmorency Counties, and to a lesser extent, Kalkaska, Crawford, and Oscoda Counties. The area of the play is approximately 39,000 sq mi.

Reservoirs: The formation is as thick as 800 ft and fractured shales provide reservoirs and conduits for production. Gas is sorbed within the shale, dissolved in the bitumen, and stored in matrix porosity, but production probably is feasible only where the shales are sufficiently fractured to allow adequate flow, and is mostly confined to the black shale facies (Lachine and Norwood Members) of the Lower Antrim, with principal development in Antrim, Otsego, and Montmorency Counties and to a lesser extent, Kalkaska, Crawford, and Oscosa Counties.

Source rocks: The "black facies" of the organic-rich Antrim Shale has an organic content ranging from less than 1 to 25 percent, averaging about 8 percent. It is hydrogen rich and oil prone. Thermal maturity of the shale is sufficient to have generated gaseous hydrocarbons peripheral to and within deeper parts of the central Michigan Basin (Cercone, 1984, 1991; Dellapenna, 1991). The shales are well within the oil generative window at depths greater than about 2,500 ft, based on data reported by both Cercone (1991) and Gardner and Bray (1984). This position may provide opportunity for oil recovery and at the same time place an effective floor on the gas play, even though gas is present.

Timing and migration: Generation of hydrocarbons probably began in Pennsylvanian time during subsidence of the basin, and both oil and gas are found in the Antrim reservoirs. The gas is believed to represent an early stage of catagensis.

Traps: Gas probably is mostly absorbed. Trapping may be controlled in part by hydrodynamic flow and water block at the subcrop of the formation (Maness and others, 1993). Controls of fracturing are not well understood and have been attributed to tectonism, flexuring over underlying Silurian reefs, differential loading by glacial drift, and fracture dilation due to glacial unloading. Economic recovery of gas is mostly confined to Upper Black and Lower Black (Lachine and Norwood Member) shale facies of the Lower Antrim, capped by Upper Antrim and Middle gray (Paxton Member) beds, respectively. The prospective formation is generally less than 3,300 ft deep.

Exploration status: Production generally ranges between 1,200 and 2,000 ft but is reported at almost 2,600 ft in Crawford County and at 3,200 ft in Missaukee County. Production at Otsego Field began in 1940, but intensive development in the play has been since 1986. Principal exploration and development activity and discoveries have been in Antrim, Otsego, and Montmorency Counties but include, to a lesser extent, Kalkaska, Crawford, and Oscosa Counties. Well production typically ranges from 25 to 150 MCFGPD. Scattered gas wells are recorded in Missaukee, Wexford and Jackson Counties. Outside of these areas, the formation has not been successfully produced, although it commonly contains sufficient organic content.

Resource potential: Although in-place resource potential of this play may be large, economic deliverablility of the resource is very poorly understood.

REFERENCES

Arndt, B.P., 1991, Lime Lake field, *in* Wollensak, M.S., ed., Oil and gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 485-492.

Aseez, A.O., 1969, Paleogeography of the Lower Mississippian rocks of the Michigan Basin: American Association of Petroleum Geologists Bulletin, v. 53, no. 1, p. 127-135.

Balthazor, D.A., 1991, Williams field, *in* Wollensak, M.S., ed., Oil and gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 14-27.

Barnes, D.A., Lundgren, C.E., and Longman, M.W., 1992, Sedimentology and diagensis of the St. Peter Sandstone, central Michigan Basin, United States: American Association of Petroleum Geologists Bulletin, v. 76, no. 10, p. 1507-1532.

Bricker, M.D., Milstein, R.L., and Reszka, C.R., 1983, Selected studies of Cambro-Ordovician sediments within the Michigan Basin: Geological Survey Division, Michigan Department of Natural Resources, Report of Investigation 26, 54 p.

Brown, L., Jensen, L., Oliver, J., Kaufman, S., and Steiner, D., 1982, Rift structure beneath the Michigan Basin from COCORP profiling: Geology, v. 10, p. 645-649.

Budai, J.M., and Wilson, J.L., 1991, Diagenetic history of the Trenton and Black River Formations in the Michigan Basin, *in* Catacosinos, P.A., and Daniels, P, A., eds, Early sedimentary evolution of the Michigan Basin: Geological Society of America Special Paper 256, p. 73-88.

Burgess, R.J. (ed), 1969, Symposium on Michigan Oil and Gas Fields: Michigan Basin Geological Society, Lansing, 198 p. (Reprinted in 1991, with map updates, as Oil and gas field manual of the Michigan Basin, v. 1 [Oil & Gas Field Symposium]: East Lansing, Michigan Basin Geological Society, 198 p., 38 p. supplement, Proration of Michigan Gas Update).

Cannon, W.F., Green, A.G., Hutchinson, D.R., Lee, Myung , L., Milkereit, B., Behrendt, J.C., Halls, H.C., Green, J.C., Dickas, A.B., Morey, G.B., Sutcliffe, R., and Spencer, C., 1989, The North American Midcontinent Rift beneath Lake Superior from Glimpce seismic reflection profiling: Tectonics, v. 8, no. 2, p. 305-332.

Catacosinos, P.A., 1981, Origin and stratigraphic assessment of Pre-Mt. Simon clastics (Precambrian) of Michigan Basin: American Association of Petroleum Geologists Bulletin, v. 65, no. 9, p. 1617-1620.

Catacosinos, P.A., and Daniels, P.A., 1991, Stratigraphy of Middle Proterozoic to Middle Ordovician formations of the Michigan Basin, *in* Catacosinos, P.A., and Daniels, P, A., eds, Early sedimentary evolution of the Michigan Basin: Geologial Society of America Special Paper 256, p. 53-71.

Catacosinos, P.A., and Daniels, P.A., eds, 1991, Early sedimentary evolution of the Michigan Basin: Geologial Society of America Special Paper 256, 248 p.

Catacosinos, P.A., Daniels, P.A., and Harrison W.B., 1991, Structure, stratigraphy, and petroleum geology of the Michigan Basin, *in* Leighton, M.W., Kolata, R.D., Oltz, D.F., and Eidel, J.J., eds, Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 561-601.

Cercone, K. R., 1984, Thermal history of Michigan Basin: American Association of Petroleum Geologists Bulletin v. 68, no. 2, p. 130-136.

Cercone, K.R., and Budai, J.M. eds., 1985, Ordovician and Silurian rocks of the Michigan Basin and its margins: Michigan Basin Geological Society Special Paper 4, 196 p.

Cercone, K.R., and Pollack, H.N., 1991, Thermal maturity of the Michigan Basin, *in* Catacosinos, P.A., and Daniels, P, A., eds, Early sedimentary evolution of the Michigan Basin: Geological Society of America Special Paper 256, p. 1-11.

Chandler, V.W., McSwigen, P.L., Morey, G.B., Hinze, W.J., and Anderson, R.R., 1989, Interpretation of seismic reflection, gravity, and magnetic data across Middle Proterozoic Mid-Continent Rift System, Northwestern Wisconsin, Eastern Minnesota, and central Iowa: American Association Petroleum Geologists Bulletin v. 73, no. 3, p. 261-275.

Charpentier, R.R., 1987, A summary of petroleum plays and characteristics of the Michigan Basin: U.S. Geological Survey Open-File Report 87-450-R, 33 p.

Cole, G.A., Drozd, R.J., Sedivy, R.A., and Halpern, H.I., 1987, Organic geochemistry and oil-source correlations, Paleozoic of Ohio: American Association Petroleum Geologists Bulletin v. 71, no. 7, p. 788-809.

Colquhoun, S., 1991, Ordovician Period--Trenton-Black River, *in* Wollensak, M.S. (ed), 1991, Oil & gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 293-296.

Crowley, K., 1991, Burial and thermal history of the Michigan Basin from fission tract ages and vitrinite reflectances: Geological Society of America Abstracts with program, p. A251-252.

Curtis, J. B., Manger, K.C., Richard K. Vessell-David K. Daves and Associates, Inc., 1991, Geologic factors affecting Antrim Shale gas production; I, Stratigraphy and geochemistry, [abs.], *in* Michigan--Its geology and geologic resources, A Second Symposium, 1991: Geologic Survey Division, Michigan Department of Natural Resources, East Lansing, Program and Abstracts, p. 8.

Daniels, P. 1991, Ordovician Period--Glenwood and Pre-Glenwood: *in* Wollensak, M.S., ed, Oil and gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 319-320.

Daniels, P.A., and Elmore, R.S.D., 1988, Upper Keweenawan rift-fill sequence, Mid-Continent Rift System, Michigan: Michigan Basin Geological Society, 1988 Field Trip, Houghton, Michigan, p. 81-94.

Decker, A.D., 1993, Gas content and log derived gas-in-place calculations for the Antrim Shale, Michigan Basin, [abs.] *in* Michigan--Its geology & geologic resources, A Third Symposium, 1993: Geologic Survey Division, Michigan Department of Natural Resources, East Lansing, Program and abstracts, p. 1-2.

Decker, A.D., Coates, J-M., and Wicks, D., 1992, Stratigraphy, gas occurrence, formation evaluation and fracture characterization of the Antrim Shale, Michigan Basin: GRI Topical Report 92/0258: prepared by Advanced Resources International, Inc, for Gas Research Institute, Chicago, Contract No. 5091-213-2305, 101 p.

Decker, A.D., Wicks, D.E., and Coates, J-M., 1993, Gas content measurements and log based correlations in the Antrim Shale: GRI Topical Report 93/0293; prepared by Advanced Resources International, Inc, for Gas Research Institute, Chicago, Contract No. 5091-213-2305, 51 p. and appendices.

Dellapenna, T.M., 1991, Sedimentological, structural, and organic geochemical controls on natural gas occurrence in the Antrim Formation in Otsego County, Michigan: Kalamazoo, Western Michigan University, M.S. thesis, 147 p.

Dolly, E.D., and Busch, D.A., 1972, Stratigraphic, structural, and geomorphologic factors controlling oil accumulation in Upper Cambrian strata of central Ohio: American Association Petroleum Geologists Bull. v. 56, n. 12, p. 2335-2368.

Droste, J.B., and Shaver, 1977, Synchronization of deposition of Silurian reef-bearing rocks on Wabash platform with cyclic evaporites of Michigan Basin, *in* Fisher, J.H., ed., Reefs and evaporites--Concepts and depositional models: American Association of Petroleum Geologists Studies in Geology 5, p. 93-109.

Droste, J.B., and Shaver, R.H., 1985, Comparative stratigraphic framework for Silurian reefs-Michigan Basin to surrounding platforms, *in* Cercone, K.R., and Budai, J.M., eds., Ordovician and Silurian rocks of the Michigan Basin and its margins: Michigan Basin Geological Society Special Paper 4, p. 73-93.

Duszynski, J., 1991, New Lothrop field, *in* Wollensak, M.S., ed., Oil and gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 7-14.

Fisher, J.H., and Barrett, M.W., 1985, Exploration in Ordovician of Central Michigan Basin: American Association of Petroleum Geologists, v. 69, no. 12, p. 2065-2076.

Fisher, J.H., Barrett, M.W., Droste, J.B., and Shaver, 1988, Michigan Basin, *in* Sloss , L.L., ed, Sedimentary Cover--North American craton: Boulder, Colorado, Geological Society of America, The Geology of North America, v. D-2, p. 361-382.

Fowler, J.H., and Kuenzi, W.D., 1978, Keweenawan turbidites in Michigan (deep bore hole red beds); a foundered basin sequence developed during evolution of a protoceanic rift system: Journal of Geophysical Research, v. 83, p. 5833-5843.

Fowler, J.H., and Schaefer, S.F., 1991, Burdell field, *in* Wollensak, M.S., ed., Oil and gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 343-352.

Friedman, G.M., and Kopaska-Merkel, D.C., 1991, Late Silurian pinnacle reefs of the Michigan Basin, *in* Catacosinos, P.A., and Daniels, P, A., eds, Early sedimentary evolution of the Michigan Basin: Geological Society of America Special Paper 256, p. 89-98.

Gardner, W.C., 1974, Middle Devonian stratigraphy and depositional environments in the Michigan Basin: Michigan Basin Geological Society Special Papers, no. 138 p.

Gardner, W.C., and Bray, E.E., 1984, Oils and source rocks of Niagaran reefs (Silurian) in the Michigan Basin, *in* Palacas, J.G. ed, Petroleum geochemistry and source rock potential of carbonate rocks: American Association of Petroleum Geologists Studies in Geology 18, p. 33-44.

Gill, D., 1979, Differential entrapment of oil and gas in Niagaran pinnacle-reef belt of northern Michigan: American Association of Petroleum Geologists, v. 63, no. 4, p. 608-620.

Gill, D., 1994, Niagaran reefs of northern Michigan; part 1: Exploration portrait: Journal of Petroleum Geology, v. 17, no. 1, p. 99-110.

Goodman, W.R., 1991, Silurian Period--Northern and Western Niagaran, *in* Wollensak, M.S., ed., Oil and gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 103-106.

Gunn, G.R., 1988, Stratigraphy, reservoir characteristics of Berea Sandstone in Michigan Fields: Oil and Gas Journal, v. 86, no. 10, p. 57-60.

Gutschick, R.C., and Sandberg, C.A., 1991a, Late Devonian history of Michigan Basin, *in* Catacosinos, P.A., and Daniels, P.A., eds, Early sedimentary evolution of the Michigan Basin: Geological Society of America Special Paper 256, p. 181-202.

Gutschick, R.C., and Sandberg, C.A., 1991b, Upper Devonian biostratigraphy of Michigan Basin, *in* Catacosinos, P.A., and Daniels, P.A., eds, Early sedimentary evolution of the Michigan Basin: Geological Society of America, Special Paper 256, p. 155-179.

Harrell, J.A., Hatfield, C.B., and Gunn, G.R., 1991, Mississippian system of the Michigan Basin; stratigraphy, sedimentology, and economic geology, in Catacosinos, P.A., and Daniels, P.A., eds, Early Sedimentary Evolution of the Michigan Basin: Geological Society of America, Special Paper 256, p. 202-220.

Harrison, W.B., 1985, Lithofacies and depositional environments of the Burnt Bluff Group in the Michigan Basin, *in* Cercone, K.R., and Budai, J.M., eds., Ordovician and Silurian rocks of the Michigan Basin and its margins: East Lansing, Michigan Basin Geological Society Special Paper 4, p. 85-108.

Harrison, W.B.,1991, Devonian Period, *in* Wollensak, M.S., ed, Oil & gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 29-30.

Hiatt, C.R., and Nordeng, S., 1985, A petrographic and well log analysis of five wells in the Trenton-Utica transition, *in* the northern Michigan Basin, in Cercone, K.R., and Budai, J.M. eds., Ordovician and Silurian rocks of the Michigan Basin and its margins: East Lansing, Michigan Basin Geological Society Special Paper 4, p. 33-43.

Hinze, W.J., Kellogg, R.L., and O'Hara, N.W., 1975, Geophysical studies of basement geology of Southern Peninsula of Michigan: American Association of Petroleum Geologists Bulletin, v. 59, p. 1562-1584.

Holgarth, C.G., and Sibley, D.F., 1985, Thermal history of the Michigan Basin: evidence from conodont color alteration indices, *in* Cercone, K.R., and Budai, J.M., eds., Ordovician and Silurian rocks of the Michigan Basin and its margins: Michigan Basin Geological Society Special Paper 4, p. 45-57.

Huh, J.M., Briggs, L.I., and Gill, D., 1977, Depositional environments of pinnacle reefs, Niagaran and Salina Group, northern shelf, Michigan Basin, *in* Fisher, J.H., ed., Reefs and evaporites-concepts and depositional models: American Association of Petroleum Geologists Studies in Geology 5, p. 1-21

Hurley, N.F., and Budros, R., 1990, Albion-Scipio and Stoney Point Fields--U.S.A., Michigan Basin, *in* Beaumont, E.A., and Foster, N.H., Stratigraphic traps I: American Association of Petroleum Geologists Treatise of Petroleum Geology, Atlas of Oil and Gas Fields, p. 1-37.

Illich, H.A., and Grizzle, P.L., 1985, Thermal subsidence and generation of hydrocarbons in Michigan Basin--Discussion: American Association of Petroleum Geologists Bulletin, v. 69, no. 9, p. 1401-1403.

Keith, B.D., 1986, Reservoirs resulting from facies-independent dolomitization--Case histories from the Trenton and Black River carbonate rocks of the Great Lakes area, *in* Friedman, G.M., ed., Carbonates and evaporties, Northeast Science Foundation Inc., v. 1, no. 1, p. 74-82. (Also published in Keith, B.D,. ed., 1989, The Trenton Group (Upper Ordovician Series) of eastern North America: American Association of Petroleum Geologists Studies in Geology 29, p. 267-276.]

Keith, B.D., and Wickstrom, L.H., 1992, Lima-Indiana Trend--U.S.A., Ohio and Indiana, *in* Foster, N.H., and Beaumont, E.A., Stratigraphic traps III, American Association of Petroleum Geologists Treatise of Petroleum Geology, Atlas of Oil and Gas Fields, p. 347-367.

Kuuskraa, V.A., Wicks, D.E., and Thurber, J.L., 1992, Geologic and reservoir mechanisms controlling gas recovery from the Antrim Shale: Society of Petroleum Engineers, Annual Technical Conference and Exhibition, 67th , SPE 24883, p. 209-224.

Lillienthal, R.T., 1978, Stratigraphic cross-sections of the Michigan Basin: Michigan Geologic Survey Division Report of Investigation 19, 36 p., 89 plates.

Longman, M.W., and Palmer, S.E., 1987, Organic geochemistry of Mid-Continent Middle and Late Ordovician Oils: American Association of Petroleum Geologists Bulletin, v. 71, no. 8, p. 938-950.

Maness, T.R., Maness, D.J., and Bailey, D.J., 1993, The Otsego (Michigan) Antrim Shale gas field: Unconventional Reservoir, unconventional trapping mechanism, *in* Michigan--Its Geology & Geologic Resources, A Third Symposium, 1993: Geologic Survey Division, Michigan Department of Natural Resources, East Lansing, Program & Abstracts, unpaged.

Manger, K.C., and Curtis, J.B., Geologic influences on location and production of Antrim Shale gas: Gas Research Institute, Devonian Gas Shales Technology Review, v. 7, no. 2, p. 5-16.

Manger, K.C., Oliver, S.J.P., 1991, Geologic factors affecting Antrim Shale gas production II - Geologic mapping and fracture analysis, *in* Michigan--Its Geology and Geologic Resources, A Second Symposium, 1991, Geologic Survey Division, Michigan Department of Natural Resources, East Lansing, Program and Abstracts, p. 12.

Matson, M.M., 1991, Silurian Period: Southern Niagaran, *in* Wollensak, M.S., ed, Oil & gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 175-178.

Matthews, R.D., 1993, Review and revision of the Devonian-Mississippian stratigraphy in the Michigan Basin, *in* Roen, J.B., and Kepferle, R.C., eds., Petroleum geology of the Devonian and Mississippian black shale of eastern North America: U.S. Geological Survey Bulletin 1909, p. D1-D85.

McGuire, D.R., 1991, Charlton 19 Project, *in* Wollensak, M.S., ed, Oil & gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 31-44.

McGuire, D.R., and Oliver, J.P., 1988, Devonian shale gas production in the Michigan Basin: Gas Research Institute, Eastern Devonian Gas Shales Technology Review, v. 5, no. 2 and 3, p. 28-40.

McMurray, M.G., 1985, Geology and organic geochemistry of Salina A-1 carbonate oil source-rock lithofacies (upper Silurian), southwestern Ontario, Canada: Ontario, University of Waterloo, M.S. thesis.

Meyers, P.A., Rullkotter, J., and Marzi, R., 1991, Organic geochemical reassessment of petroleum sources and thermal history in the Michigan Basin, *in* Michigan--Its Geology and Geologic Resources, A Second Symposium, 1991: Geologic Survey Division, Michigan Department of Natural Resources, East Lansing, Program & abstracts, p. 14

Michigan Geological Survey Division, 1989, Michigan's Oil and Gas Fields 1985 and 1986: Geological Survey Division, Michigan Department of Natural Resources, OFR 89-1, 310 p.

Milstein, R.L., 1988, Impact origin of the Calvin 28 cryptoexplosive disturbance, Cass County, Michigan: Geological Survey Division, Michigan Department of Natural Resources, Report of Investigation 28, 33 p.

Moyer, R.B., 1982, Thermal maturity and organic content of selected Paleozoic formations--Michigan Basin: Lansing, Michigan State University, M.S. thesis, 62 p., 19 plates.

Nicol, J.E., and Oliver, S.J.P., 1991, Reservoir characterization of the Antrim Shale, *in* Michigan--Its Geology and Geologic Resources, A Second Symposium, 1991: Geologic Survey Division, Michigan Department of Natural Resources, East Lansing, Program & abstracts, p. 15.

Nunn, J.A., Sleep, N.H., and Moore, W.E., 1984, Thermal subsidence and generation of hydrocarbons in Michigan Basin: American Association of Petroleum Geologists Bulletin v. 68, no. 3, p. 296-315.

Ojankanges, R.W., and Morey, G.B., 1982, Keweenawan sedimentary rocks of the Lake Superior region--A summary, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 157-164.

Oliver, S.J.P., 1991, GRI's Antrim Shale research project, *in* Michigan--Its Geology and Geologic Resources, A Second Symposium, 1991: Geologic Survey Division, Michigan Department of Natural Resources, East Lansing, Program & abstracts, p. 16.

Oliver, S.J.P., Coates, J.M., Kelafant, J.R., Kuuskraa, V.A., Brandenburg, C.F., 1989, Improved production strategies for the Antrim Shale of the Michigan Basin, *in* Michigan--Its Geology and Geologic Resources, A Symposium, 1989: Geologic Survey Division, Michigan Department of Natural Resources, East Lansing, Program & Abstracts, p. 20.

Powell, T.G., Macqueen, R.W., Barker, J.F., and Bree, D.G., 1984, Geochemical character and origin of Ontario oils: Bulletin of Canadian Petroleum Geology, v. 32, no. 3, p. 289-312.

Prouty , C.E., 1989, Trenton exploration and wrenching tectonics--Michigan Basin and environs, *in* Keith, B.D,. ed., 1989, The Trenton Group (Upper Ordovician Series) of eastern North America: American Association of Petroleum Geologists Studies in Geology no. 29, p. 207-236.

Pruitt, J.D., 1983, Comment on "Comparison of Michigan Basin crude oils" by Vogler and others: Geochimica et Cosmochimica Acta, v. 47, p. 1151-1159.

Reed, J.D., Illich, H.A., and Horsfield, B., 1986, Biochemical evolutionary significance of Ordovician oils and their sources: Organic Geochemistry, v. 10, p. 347-358.

Repetski, J., and Harris, A., 1981, Report on referred fossils, Lower and Middle Ordovician, Ogemaw County, Michigan: U.S. Geological Survey internal report, 13 p.

Reszka, Carl R., 1991, The Michigan Basin, *in* Sloss, L.L., ed, Economic Geology, U.S.: Geological Society of America, Decade of North American Geology, v. p-2, p. 287-300.

Roberts, P.A., 1991, 1990 Antrim Shale drilling and production statistics: Gas Research Institute, Devonian Gas Shales Technology Review, v. 7, no. 2, p. 50-55.

Rullkotter, J., Myers, P.A., Schaefer, R.G., and Dunham, K.W., 1986, Oil generation in the Michigan Basin--A biological marker and carbon isotope approach, *in* Leythaeuser, D., and Rullkotter, J., eds, Advances in organic geochemistry 1985: Organic Geochemistry, v. 10, p. 359-375.

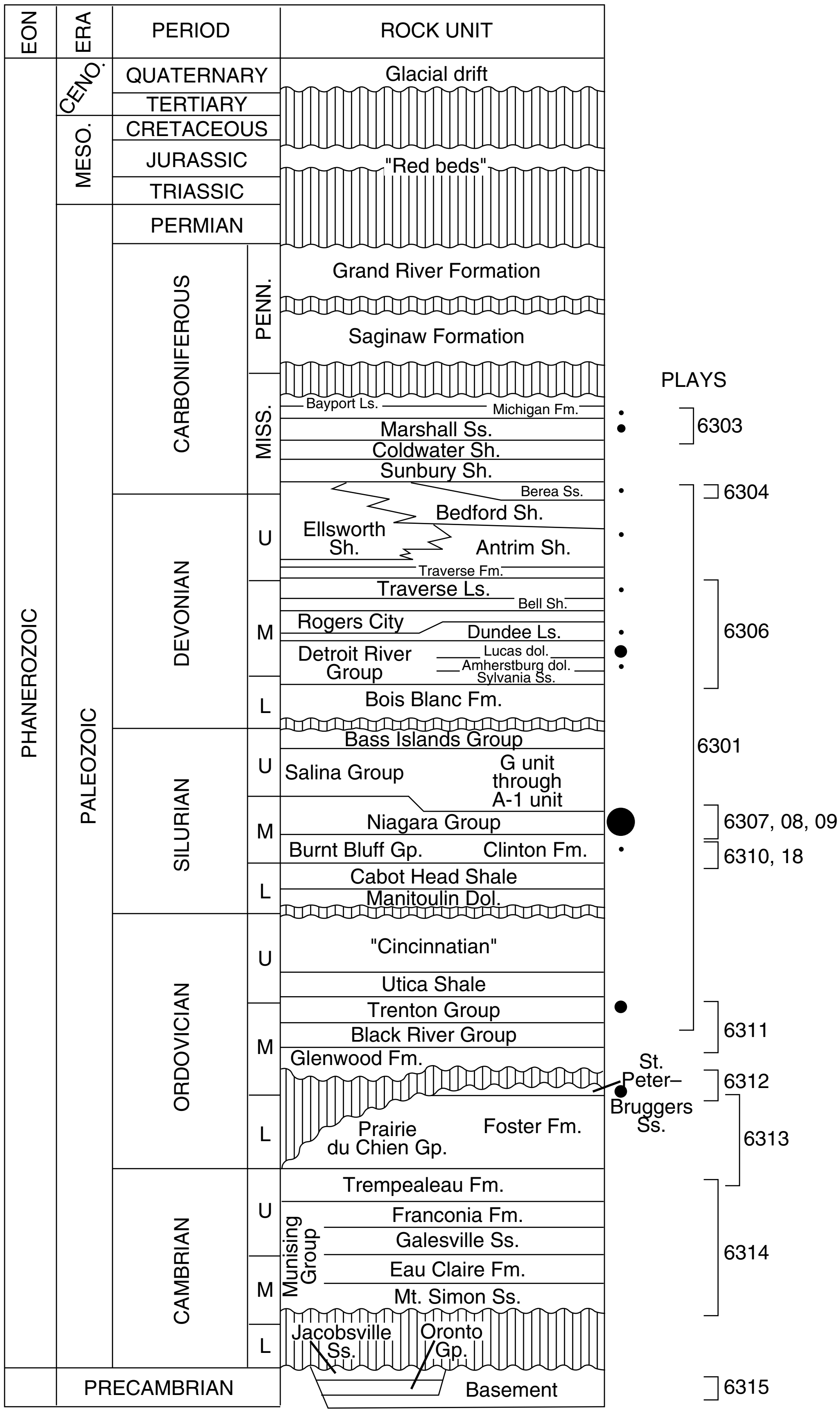
Schneider, J.J., Tinker, C.N., and Ching, P.D., 1991, Rose City Field, *in* Wollensak, M.S., ed., Oil and gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, p. 431-440.

Seglund, J.A., 1989, Midcontinent rift continues to show promise as petroleum prospect: Oil and Gas Journal, v. 87, no. 20, p. 55-58.

Smith, G.L., Byers, C.W., and Dott, R.H., 1992, Sequence stratigraphy of the Lower Ordovician Prairie Du Chien Group on the Wisconsin Arch and the Michigan Basin: American Association of Petroleum Geologists Bulletin, v. 77, no. 1, p. 49-67.

Vogler, E.A., Meyers, P.A., and Moore, W.A., 1981, Comparison of Michigan Basin crude oils: Geochimica et Cosmochimica Acta, v. 45, p. 2287-2293.

Wollensak, M.S., ed, 1991a, Oil and gas field manual of the Michigan Basin, v. 2: East Lansing, Michigan Basin Geological Society, East Lansing, Michigan, 502 p.


EON
ERA
PERIOD
ROCK UNIT
PHANEROZOIC
CENO.
MESO.
PALEOZOIC
PRECAMBRIAN
QUATERNARY
TERTIARY
CRETACEOUS
JURASSIC
TRIASSIC
PERMIAN
CARBONIFEROUS
PENN.
MISS.
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
U
M
L
Glacial drift
"Red beds"
Grand River Formation
Saginaw Formation
Bayport Ls.
Michigan Fm.
Marshall Ss.
Coldwater Sh.
Sunbury Sh.
Berea Ss.
Bedford Sh.
Ellsworth Sh.
Antrim Sh.
Traverse Fm.
Traverse Ls.
Bell Sh.
Rogers City
Dundee Ls.
Detroit River Group
Lucas dol.
Amherstburg dol.
Sylvania Ss.
Bois Blanc Fm.
Bass Islands Group
Salina Group
G unit through A-1 unit
Niagara Group
Burnt Bluff Gp.
Clinton Fm.
Cabot Head Shale
Manitoulin Dol.
"Cincinnatian"
Utica Shale
Trenton Group
Black River Group
Glenwood Fm.
St. Peter–Bruggers Ss.
Prairie du Chien Gp.
Foster Fm.
Trempealeau Fm.
Munising Group
Franconia Fm.
Galesville Ss.
Eau Claire Fm.
Mt. Simon Ss.
Jacobsville Ss.
Oronto Gp.
Basement
PLAYS
6303
6304
6301
6306
6307, 08, 09
6310, 18
6311
6312
6313
6314
6315