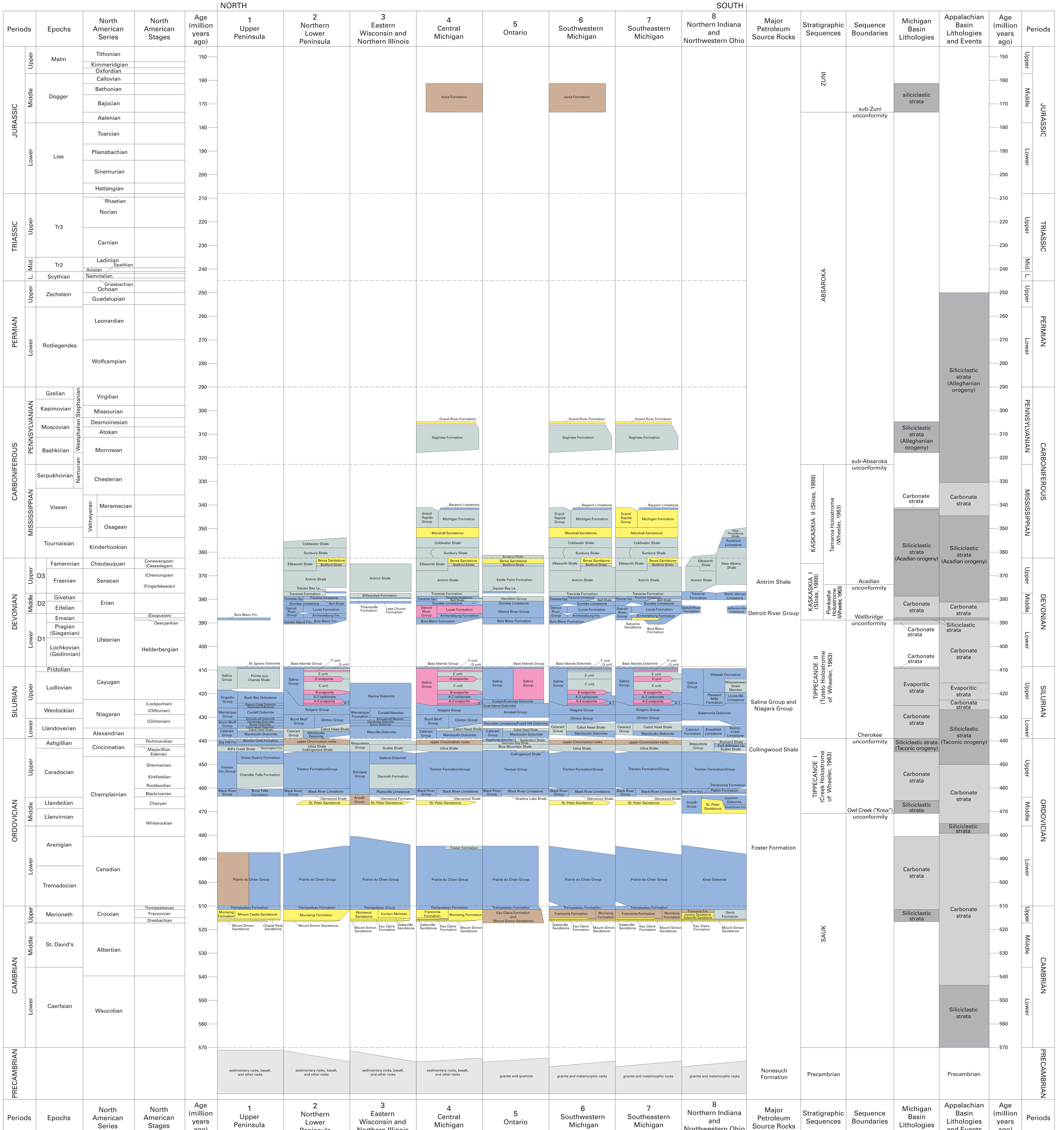

Figure 1.—Regional stratigraphy and petroleum systems of the Michigan basin, North America. Stratigraphic data are modified from American Association of Petroleum Geologists (AAPG) (1984), Johnson and others (1992), Sanford (1993), and Cross (1998). Stratigraphy of the adjacent Appalachian basin is from Swezey (2002). The time scale is taken from Harland and others (1990), with informal North American chronostratigraphic terms from AAPG (1984) added in parentheses. Sequences and sequence boundary locations are from Sloss (1963, 1988) and Wheeler (1963). Abbreviations used: Fm., Formation; Gp., Group; Ls., Limestone.

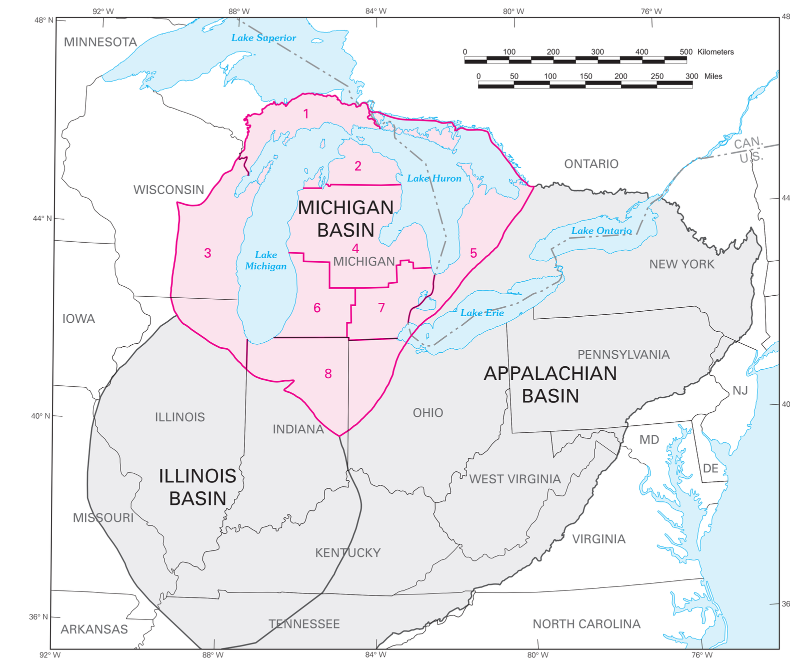

Figure 2.—Extent of the Michigan basin, shown in red, and of the Appalachian and Illinois basins, shown in gray. The Michigan basin is subdivided into eight regions, and the generalized stratigraphy of these eight regions is shown in figure 1. Column numbers in figure 1 correspond to region numbers in figure 2. Figure 2 is modified from American Association of Petroleum Geologists (AAPG) (1984) and Swezey and others (2005).

EXPLANATION OF LITHOLOGY

Although not designated as a separate lithology, some coal beds are present in Pennsylvanian strata in the Michigan basin.

- **Evaporite**
- **Carbonate rock or chert**
- **Sandstone**
- **Interbedded sandstone and mudstone**
- **Mudstone**
- **Section not present**

Petroleum Source Rocks of the Michigan Basin

Group 6: Devonian Antrim Shale and Devonian and Mississippian Ellsworth Shale
Group 5: Devonian Detroit River Group
Group 4: Silurian Niagara Group and Salina Group
Group 3: Ordovician Collingwood Shale and Upper Trenton Formation/Group
Group 2: Ordovician Foster Formation
Group 1: Precambrian Nonesuch Formation

Major Petroleum Plays of the Michigan Basin

Mississippian Michigan Formation
Devonian Berea Sandstone
Devonian Antrim Shale
Devonian Traverse Group
Devonian Dundee Limestone
Devonian Detroit River Group
Silurian A-1 Carbonate
Silurian Niagara Group
Silurian Burnt Bluff Group
Ordovician Trenton Formation/Group and Black River Group
Ordovician Prairie du Chien Group

INTRODUCTION

Although more than 100 years of research have gone into deciphering the stratigraphy of the Michigan basin of North America, it remains a challenge to visualize the basin stratigraphy on a regional scale and to describe stratigraphic relations within the basin. Similar difficulties exist for visualizing and describing the regional distribution of petroleum source rocks and reservoir rocks. This publication addresses these difficulties by combining data on Paleozoic and Mesozoic stratigraphy and petroleum geology of the Michigan basin (fig. 1). Figure 2 shows the areal extent of this structural basin, and figure 1 presents these data in eight schematic chronostratigraphic sections arranged from north to south, with time denoted in equal increments along the sections. The stratigraphic data are modified from American Association of Petroleum Geologists (AAPG) (1984), Johnson and others (1992), Sanford (1993), and Cross (1998), and the time scale is taken from Harland and others (1990). Informal North American chronostratigraphic terms from AAPG (1984) are shown in parentheses. Stratigraphic sequences as defined by Sloss (1963, 1988) and Wheeler (1963) also are included, as well as the locations of major petroleum source rocks and major petroleum plays. The stratigraphic units shown in figure 1 are colored according to predominant lithology, in order to emphasize general lithologic patterns and to provide a broad overview of the Michigan basin. For the purpose of comparison, two columns on the right side of figure 1 show schematic depictions of stratigraphy and interpreted events in the Michigan basin and the adjacent Appalachian basin (location shown in figure 2).

GENERAL STRATIGRAPHY

Figure 1 shows the predominant lithologies for given areas within the Michigan basin. The oldest of these rocks is of Precambrian age and is overlain by Upper Cambrian siliciclastic strata that range in age from approximately 516 to 512 Ma. The Upper Cambrian siliciclastic strata, in turn, are overlain by uppermost Cambrian and Lower Ordovician carbonate and siliciclastic strata (~512–480 Ma). There is a distinct interval of siliciclastic strata (St. Peter Sandstone) that represents a relatively short duration (~471–465 Ma) within the overall package of Ordovician carbonate rocks. The St. Peter Sandstone is overlain by Middle and Upper Ordovician carbonate strata (~465–445 Ma). These carbonate strata are overlain by Upper Ordovician siliciclastic strata (~445–439 Ma), which exhibit a general basinwide pattern of finer grained rocks overlain by coarser grained rocks. The Upper Ordovician siliciclastic strata are overlain by Silurian strata (~439–408 Ma) of predominantly carbonate composition, which include a widespread interval of Upper Silurian evaporites (Salina Group; ~425–409 Ma). Likewise, the overlying Lower and Middle Devonian strata (~391–377 Ma) are predominantly carbonate, with some evaporites present in the central part of the basin. There is a distinct interval of siliciclastic rocks (Sylvania Sandstone) that represents a relatively short duration (~389–388 Ma) within the Lower and Middle Devonian carbonate package. The Lower and Middle Devonian carbonate strata are overlain by Upper Devonian to middle Mississippian siliciclastic strata (~377–342 Ma). A laterally extensive formation, the Berea Sandstone (~365–362 Ma), is present within Upper Devonian strata, and the lower Mississippian siliciclastic strata above the Berea Sandstone show a general coarsening-upward trend. The Upper Devonian to middle Mississippian siliciclastic strata are overlain by middle Mississippian carbonate strata (~342–341 Ma), which in turn are overlain by lower and middle Pennsylvanian siliciclastic strata (~318–305 Ma). The lower and middle Pennsylvanian siliciclastic strata are overlain by Middle Jurassic siliciclastic strata (~174–161 Ma).

As for correlations with the stratigraphic sequences of Sloss (1963, 1988) and Wheeler (1963), the Michigan basin contains the following five major sequences: Sauk, Tippecanoe, Kaskaskia, Absaroka, and Zuni. These five sequences are bounded by unconformities that have been identified across most of North America. The identification of these sequences provides a framework for stratigraphic correlations with other geologic basins and also provides a framework for discussing the respective influences of tectonic activity, climate, and sea level on the generation and preservation of strata. Additional unconformities of more local extent are present within the Michigan basin, but figure 1 shows only the major unconformities identified by Sloss (1963, 1988) and Wheeler (1963).

In the Michigan basin, the Sauk Sequence is bounded at the base by the unconformity between the Precambrian basement and the overlying Cambrian siliciclastic strata, and at the top by the Owl Creek unconformity, which lies at the base of the St. Peter Sandstone and equivalent units. Sloss (1963, 1988) divided the Sauk Sequence into three units (Sauk I, Sauk II, and Sauk III), but only the Sauk II and Sauk III units are present in the Michigan basin. The Sauk II–Sauk III boundary is associated with the transition from the Late Cambrian Dresbachian Stage to the younger Late Cambrian Franconian Stage, but the exact lithostratigraphic boundary is not well documented and therefore is not shown in figure 1. The ages of the St. Peter Sandstone and the underlying Owl Creek ("Knox") unconformity in the Michigan basin are not the same as the ages in the adjacent Appalachian basin [compare figure 1 with Swezey (2002, fig. 1)], although additional biostratigraphic control may show that the St. Peter Sandstone and the underlying unconformity are of approximately the same ages in both basins.

The Tippecanoe Sequence is bounded at the base by the Owl Creek unconformity and at the top by the Wallbridge unconformity, which lies at the base of the Sylvania Sandstone and equivalent units. The Tippecanoe Sequence was divided by Sloss (1988) into a lower unit (Tippecanoe I) and an upper unit (Tippecanoe II). Wheeler (1963) referred to the strata of this lower unit as the Creek Holostrome, and he referred to the upper interval as the Tutelo Holostrome. In the Michigan basin, the boundary between these two Tippecanoe units is an unconformity between the Upper Ordovician Maquoketa Group (and stratigraphically equivalent upper Cincinnatian rocks) and the overlying Lower Silurian Manitoulin Dolomite (and the stratigraphically equivalent Brassfield Limestone and Mayville Dolomite). Although Wheeler (1963) named this unconformity the "Taconic discontinuity," Dennison and Head (1975) later proposed that the name be replaced by "Cherokee unconformity," which is a Native American name (similar to the names of the Sloss and Wheeler sequences) and does not imply an association with the Taconic orogeny.

The Kaskaskia Sequence, which lies above the Tippecanoe Sequence, is bounded at the base by the Wallbridge unconformity and at the top by the sub-Absaroka unconformity, which is associated with the Mississippian-Pennsylvanian boundary. More recent work, however, suggests that the sub-Absaroka unconformity is actually of early Pennsylvanian age (Ettensohn, 1994). The Kaskaskia Sequence was divided by Sloss (1988) into a lower unit (Kaskaskia I) and an upper unit (Kaskaskia II), with the boundary between the two units being "near the close of Devonian time" (Sloss, 1988, p. 35). In figure 1, this Kaskaskia I–Kaskaskia II boundary is shown at the base of the Berea Sandstone. Wheeler (1963) also divided the strata between the Wallbridge unconformity and the sub-Absaroka unconformity into two units, referring to the lower unit as the Piankasha Holostrome and the upper unit as the Tamaroa Holostrome. However, the boundary between these two units designated by Wheeler is not the same as the Kaskaskia I–Kaskaskia II boundary of Sloss. Wheeler (1963) indicated that the boundary between the Piankasha Holostrome and the Tamaroa Holostrome is the Acadian unconformity, which is found within the Upper Devonian Antrim Shale in the Michigan basin.

The Absaroka Sequence, which lies above the Kaskaskia Sequence, is bounded at the base by the sub-Absaroka unconformity and at the top by the sub-Zuni unconformity, which is equivalent to the J-2 unconformity (Pipiringos and O'Sullivan, 1978; Swezey and Kocurek, 1992) of the Western Interior of North America. The Absaroka Sequence was divided by Sloss (1988) into a lower unit (Absaroka I), a middle unit (Absaroka II), and an upper unit (Absaroka III). In the Michigan basin, however, only Absaroka I strata (Pennsylvanian Saginaw Formation and Grand River Formation) have been preserved.

The Zuni Sequence, which lies above the Absaroka Sequence, is bounded at the base by the sub-Zuni unconformity and at the top by the sub-Tejas unconformity, which is of Paleocene age (not shown in figure 1). The Zuni Sequence was divided by Sloss (1988) into a lower unit (Zuni I), a middle unit (Zuni II), and an upper unit (Zuni III). In the Michigan basin, however, only Zuni I strata (Middle Jurassic Ionia Formation) have been preserved.

Petroleum Source Rocks

The names of Michigan basin petroleum source rocks (rocks from which petroleum is derived) are taken from Swezey and others (2005). These source rocks, which are presented in figure 1, fall into six distinct groups according to stratigraphic occurrence. Group 1 is the Precambrian Nonesuch Formation. Group 2 is the Lower Ordovician Foster Formation. Group 3 consists of shale within Upper Ordovician strata (Collingwood Shale and shale in the upper Trenton Formation/Group). Group 4 consists of shale associated with the Upper Silurian Niagara Group and Salina Group. Group 5 consists of shale associated with the Lower and Middle Devonian Detroit River Group (Amherstburg Formation and Lucas Formation). Group 6 consists of Upper Devonian and lower Mississippian shale (Antrim Shale and Ellsworth Shale).

Most of the petroleum source rocks in the Michigan basin are thought to have generated thermogenic oil and gas. Much of the gas in the Devonian Antrim Shale, however, is of biogenic origin (Martini and others, 1996, 1998). Non-biogenic gas within the Antrim Shale may have been derived by means of vertical leakage from older petroleum source rocks (Hatch and others, 2005).

Petroleum Plays

A petroleum play is defined as a group of drilling prospects having similar geologic characteristics that control production (Magoon and Dow, 1994; Patchen, 1996). Plays are commonly designated in terms of stratigraphy, although play names can also be modified by reference to type of petroleum trap. The major petroleum plays in the Michigan basin include sandstone, carbonate, and shale. The plays are distributed more widely throughout the stratigraphic sections than the source rocks, but most of the plays do show some stratigraphic proximity to the source rocks.

DISCUSSION

The lithostratigraphy of the Michigan basin is strikingly similar to that of the Appalachian basin, and thus it appears that the two basins have had a similar history and have responded in a similar manner to changes in tectonics, sea level, and climate. Notable exceptions to this lithostratigraphic similarity are the Cambrian strata, which are primarily sandstone in the Michigan basin and primarily carbonate in the Appalachian basin. Except for this Cambrian sandstone in the Michigan basin, much of the remaining Paleozoic record within the Michigan basin and the Appalachian basin is composed of carbonate strata. Accordingly, the two basins are essentially carbonate basins, with the appearance of non-carbonate strata denoting unusual events.

Most of the siliciclastic strata in the Michigan basin are traditionally interpreted as being associated with tectonic events in the Appalachian basin (for example, see Quinlan and Beaumont, 1984). The Upper Ordovician to Lower Silurian siliciclastic strata are associated with the Taconic orogeny, the Middle Devonian to middle Mississippian siliciclastic strata are associated with the Acadian orogeny, and the Pennsylvanian siliciclastic strata are associated with the Alleghanian orogeny. Jurassic strata in the Michigan basin are coincident with extension and rifting of the Atlantic Ocean. Cecil and others (2003, 2004), however, have suggested that climate also exerts an important control on lithostratigraphy. Additional support for the role of climate is suggested by the observation that the three Appalachian orogenies (Taconic, Acadian, and Alleghanian) are approximately coincident with the three major glaciations that occurred during the Paleozoic (as described by Crowell, 1999).

For each package of siliciclastic strata associated with an orogeny, there is a major unconformity (sequence boundary) within the siliciclastic package in the Michigan basin. However, these unconformities (Cherokee, Acadian, and sub-Absaroka) are not located exactly at the base of the respective siliciclastic packages, nor are they necessarily located at the top of major coarsening-upward or fining-upward trends.

Comparing the stratigraphic records of the Michigan and Appalachian basins, it appears that Upper Ordovician and Upper Devonian siliciclastic strata began to accumulate in the Appalachian basin before they began to accumulate in the Michigan basin. In both instances, subsidence in the Appalachian basin may have initially trapped siliciclastic sediments in that basin, allowing carbonate sediments to continue accumulating in the Michigan basin. Eventually, however, siliciclastic sediments extended beyond the Appalachian basin and into the Michigan basin, shutting down carbonate production and leading to an overall change from carbonate accumulation to siliciclastic accumulation in the Michigan basin. A similar sequence of events may have occurred during the late Mississippian, but the stratigraphic record of this time has been removed from the Michigan basin by the sub-Absaroka unconformity.

In addition to the major packages of siliciclastic strata, there are two minor packages of siliciclastic strata that accumulated in the Michigan basin: the St. Peter Sandstone at approximately 471 to 465 Ma, and the Sylvania Sandstone at approximately 389 to 388 Ma. These two sandstones are present within predominantly carbonate strata and are not associated with significant fining-upward or coarsening-upward trends. Furthermore, they represent relatively short durations and are not associated with major orogenies. These sandstones may owe their origin primarily to changes in climate and (or) sea level. A likely scenario is that the two sandstones are of eolian origin, or that they originally were eolian sediments that were subsequently redeposited in a subaqueous environment (Berkey, 1906; Grabau, 1940; Summerson and Swann, 1970; Dott and others, 1986).

Carbonate rocks are present between the three major siliciclastic packages associated with orogenies. The Silurian-Devonian carbonate package is unusual, however, because it contains extensive evaporite accumulations (Salina Group and Detroit River Group). These evaporites are thought to have formed in sabkha and shallow-water environments (Briggs, 1958; Gardner, 1974; Droste and Shaver, 1977; Catacosinos and others, 1990), which could have developed as the result of climate change and (or) restricted circulation within the basin.

Some of the Michigan basin petroleum source rocks (Nonesuch Formation, Foster Formation, and Antrim Shale and Ellsworth Shale) are associated with siliciclastic strata, whereas other petroleum source rocks (Collingwood Shale, Niagara Group and Salina Group, and Detroit River Group) are associated with carbonate strata. Nevertheless, the recognition of six discrete groups of petroleum source rocks provides a context for evaluating hydrocarbon resources of the Michigan basin in terms of six petroleum systems (in the sense of Magoon and Dow, 1994). The existence of different petroleum systems within the Michigan basin is supported by data from Hatch and others (2004), who described several stratigraphically limited gas populations having distinct geochemical characteristics.

In summary, the Michigan basin of North America contains Paleozoic and Mesozoic strata ranging from Cambrian to Jurassic in age (fig. 1). These strata represent parts of the Sauk, Tippecanoe, Kaskaskia, Absaroka, and Zuni Sequences of Sloss (1963, 1988) and Wheeler (1963). Michigan basin strata are characterized by distinct lithologies that persisted geologically on the order of tens of millions of years. Most of the Upper Cambrian strata (~516–512 Ma) are predominantly siliciclastic. The uppermost Cambrian to Ordovician strata (~512–445 Ma) are predominantly carbonate. The uppermost Ordovician strata (~445–439 Ma) are predominantly siliciclastic, associated with the Taconic orogeny. The Silurian to Middle Devonian strata (~439–377 Ma) are predominantly carbonate (with evaporites). The Upper Devonian to middle Mississippian strata (~377–341 Ma) are predominantly siliciclastic, associated with the Acadian orogeny. Carbonate rocks (~342–341 Ma) are present within middle Mississippian strata. The Pennsylvanian strata (~318–305 Ma) are predominantly siliciclastic, associated with the Alleghanian orogeny. The Jurassic strata (~174–161 Ma) are siliciclastic, coincident with extension and rifting of the Atlantic Ocean. Lithologic variability on the order of tens of millions of years is correlated with tectonic activity in combination with climatic changes, whereas lithologic variability of shorter duration (<10 million years) may have been caused by changes in climate or sea level or both (without necessarily a major tectonic influence).

The petroleum source rocks fall into six groups according to stratigraphic occurrence. These six groups consist of the Precambrian Nonesuch Formation, the Lower Ordovician Foster Formation, the Upper Ordovician Collingwood Shale and shale within the upper Trenton Formation/Group, the Upper Silurian Niagara Group and Salina Group, the Lower and Middle Devonian Detroit River Group, and Upper Devonian and lower Mississippian shale (Antrim Shale and Ellsworth Shale). The petroleum plays are more widely distributed throughout the stratigraphic sections than the source rocks, suggesting that there has been much migration of petroleum. The recognition of six discrete groups of petroleum source rocks suggests that there are at least six different petroleum systems within the Michigan basin.

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