Chapter 1

Mississippian Oolites and Petroleum Reservoirs in the United States—An Overview

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ABSTRACT

A coincidence of tectonic, eustatic, and geochemical conditions resulted in substantial deposits of oolitic limestone during later Mississippian time in the continental United States. These oolitic limestones have formed petroleum reservoirs with favorable primary and secondary recovery characteristics. Significant potential reserves in stratigraphic traps remain to be discovered and developed in these reservoirs.

INTRODUCTION

Mississippian rocks of the continental U.S. have been the subject of two previous compilation volumes by the USGS (Craig and Connor, 1979; U.S. Geological Survey, 1979), both concentrating on the Mississippian system as a whole, the former on Mississippian and Pennsylvanian stratigraphy and the latter on the paleotectonic history of the Mississippian. However, there has not been a publication specifically emphasizing Mississippian oolitic rocks. Geologists have reported oolitic limestones in Mississippian rocks in many areas of the United States for years, but Wilson (1975, p. 283) may have been the first to point out that oolites are especially common in Early Carboniferous (Mississippian) strata of the Northern Hemisphere. Wilkinson et al. (1985) first presented quantitative evidence of oolite abundance in Mississippian rocks, and Handford (1988) reported that the most widespread time of oolitic limestone deposition on the North American continent was during the Mississippian.

With the recent emphasis on global-scale geologic processes, we recognize that attention must be given to Mississippian oolitic deposition on a broader scale, seeking to understand the factors that influenced and controlled oolitic deposition at that time. A prerequisite to interpreting worldwide depositional patterns of Mississippian oolitic rocks is to study these deposits at both the regional and the continental scales. The abundant occurrence and widespread distribution of Mississippian oolitic rocks, and the wealth of available subsurface information, make the North American continent a fitting choice on which to focus this attention. In addition, Mississippian oolites are economically important for North America because they form significant petroleum reservoirs and are especially important today because they are largely stratigraphic traps, which represent the most promising exploration targets in mature basins where most of the positive structural features have been drilled.

The purpose of this chapter is to present an overview of Mississippian oolites in the continental United States based on stratigraphy, depositional setting, and their significance as petroleum reservoirs. We hope that this general treatment will lead to greater understanding of these fascinating rocks and encourage additional research.

MISSISSIPPIAN STRATIGRAPHY

Mississippian stratigraphy for most of the continental United States (Figure 1) has been generalized into the chart shown in Figure 2. This compilation was based on eight of the COSUNA (Correlation of Stratigraphic Units of North America) charts published by the American Association of Petroleum Geologists. Specific citations are noted in the figure caption. Our intent in this compilation is not to present an exhaustive analysis of Mississippian stratigraphy, but rather to review the occurrence and correlation of Mississippian carbonate rocks, especially those units reported in the literature as containing oolitic limestones. The chart in Figure 2 reflects this bias in that terrigenous clastic units are not broken out individually, but are shown only by general distribution. The widespread occurrence of the Late Devonian through Early Mississippian organic shale in most basins and the extensive Early Mississippian chert of the Appalachian basin are noted on the chart. Mississippian evaporite units, however, are named along with the carbonate units because of the often intimate association of these rock types.

Some regions where oolitic limestones are either not reported in the literature or are of minor occurrence, such as the Black Warrior basin of Mississippi and Alabama and the Great Basin of western Utah, are not represented in the chart to conserve space. The stratigraphy of the Black Warrior basin is similar to that shown for the northern Alabama portion of the southern Appalachian basin. The Great Basin

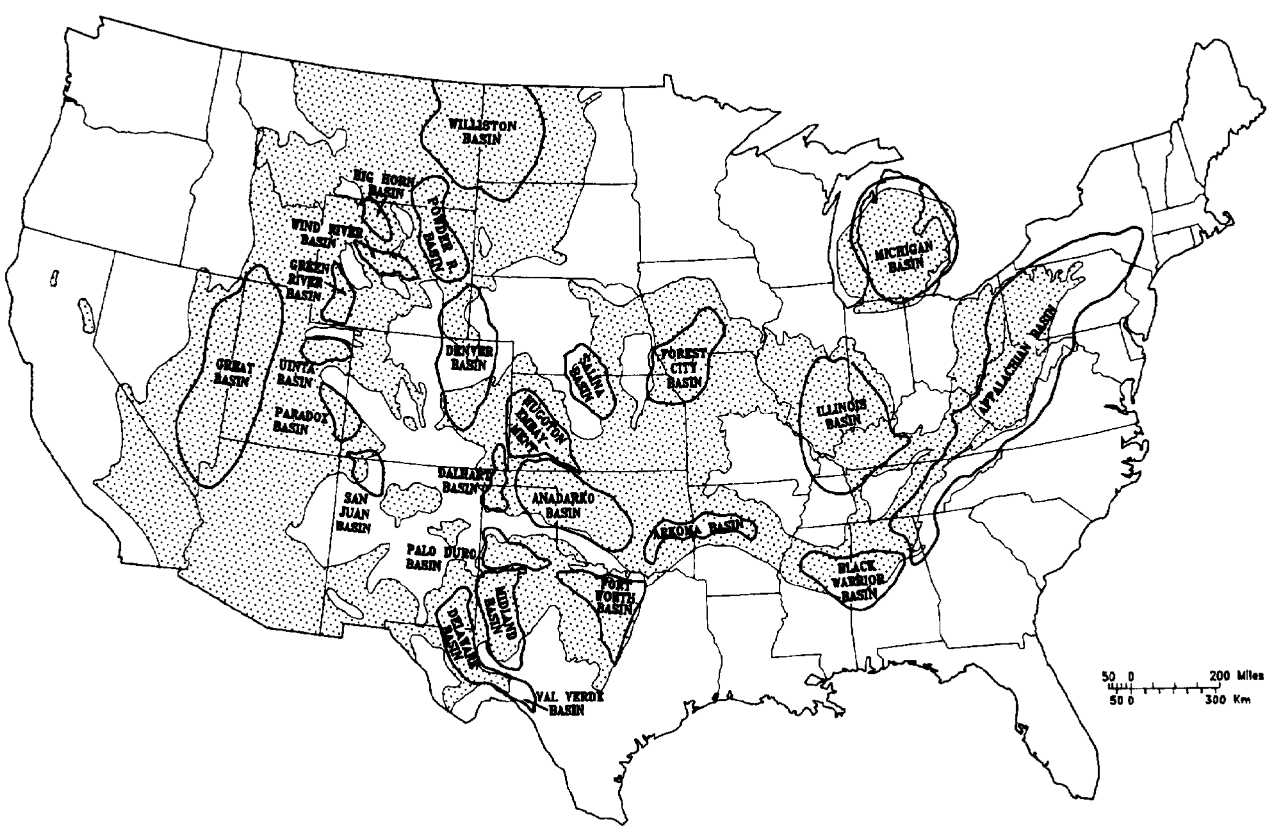


Figure 1. Map of United States showing general distribution of Mississippian rocks (stippled pattern) and location of major sedimentary basins referred to in text and on Figure 2. Basin outlines are somewhat generalized and do not necessarily correspond to Paleozoic or present configurations. Areas not labeled, but referred to on Figure 2, include: Cincinnati arch (separates Appalachian and Illinois basins), mid-continent (general area including Forest City, Arkoma, Anadarko, and Salina basins), Hardeman basin (eastern end of Palo Duro basin), Permian basin (Midland and Delaware basins and intervening area), SW platform (southern New Mexico and Arizona), and northern Rocky Mountains (area between and including Green River, Wind River, Big Horn, and Powder River basins). Compiled and modified from various sources, but primary source for outcrop distribution was Craig and Connor (1979).

stratigraphy is complex, but the western portion is primarily represented by the Joana Limestone (Osagian to Meramecian), whereas the eastern portion has terminology similar to the San Juan and Paradox basins of the Four Corners area and to the Uinta basin. Also, the Fort Worth basin of central Texas is not treated separately because it contains the Osagian Chappel Limestone that is equivalent to part of the Boone Formation and the Sycamore Limestone of Oklahoma and to the Osage Limestone and the Chappel limestones of the Palo Duro basin.

Southern New Mexico presented particular problems because of considerable stratigraphic variation, especially with regard to the large age span of the Lake Valley Formation. The column for the Sacramento Mountains was arbitrarily chosen to be representative for that area. In north-central New Mexico the Arroyo Penasco Group contains oolitic limestone in the lower Chesterian (A.K. Armstrong, personal communication, 1990) but was not included in the chart.

A limited area of oolitic rocks also occurs as a carbonate facies of the Osagian Ellsworth Shale in the southwestern part of the Michigan basin (Cohee, 1979) but is not included in the chart.

Stratigraphic names generally apply to the area under which they are shown on the chart, but column lines were intentionally omitted because names may overlap from one area to another. The placement of names on the chart should be used only as a general guide as to where a given name is used; undue significance should not be given to exact placement of names on the chart.

Following the format of the COSUNA charts, the Mississippian has been divided (from oldest to youngest) into four North American stages: Kinderhookian, Osagian, Meramecian, and Chesterian. In the Illinois basin area, Valmeyeran is used in place of the combined Osagian and Meramecian, but this usage is not shown on the chart to avoid clutter. Also, the position of the boundary between the Meramecian and Chesterian has come under review. When the COSUNA charts were compiled, the boundary was placed at the correlative position of the top of the Ste. Genevieve Limestone in the mid-continent and Illinois basin areas based on megafossils. However, Maples and Waters (1987) have recommended that the boundary be lowered to the correlative position between the Ste. Genevieve and St. Louis limestones based on microfossil zonation. Both positions are shown on the chart as dashed lines.

SETTING FOR OOLITE DEPOSITION

Any discussion of Mississippian oolites in the United States needs to consider the following characteristics of Mississippian rocks in general and Mississippian limestones in particular: (1) limestones are a volumetrically significant component of Mississippian rocks throughout most of their extent in the United States (Figure 2), and oolitic facies are an important constituent of these limestones, especially when compared to skeletal frame-building constituents that are rare in the Mississippian; (2) Mississippian oolitic limestones are more abundant in Meramecian and early Chesterian rocks (Figure 3) (Ettensohn, this volume); (3) Mississippian oolitic limestones are generally not dolomitized except locally; and (4) the texture of the ooid grains is predominantly radial, indicating that they were originally calcite (Wilkinson et al., 1985).

Even for modern ooid deposition, the exact nature of the formation of individual ooids and the role of biologic activity are uncertain. However, it is generally accepted that ooid deposits form in shallow water environments regularly agitated by waves and/or currents (see summary discussion in Tucker and Wright, 1990, p. 3–8). Extensive sequences of oolitic limestone such as those in the Mississippian required that large expanses of these high-energy environments be maintained over long periods of time. Additional environmental requisites for oolitic deposition would have been minimal siliciclastic input and generally warm temperatures (relatively low-latitude settings). Today these particular environmental conditions are favored by many organisms, especially frame-builders, but in order for extensive deposits to form during the Mississippian there must have been some controls over organic proliferation. In modern environments these controls are generally either a lack of upwelling nutrient supply or poisoning by non-normal marine waters (hypersaline or hyposaline). During Mississippian time, controls on organic proliferation may have included eustatic changes as well (see discussion below).

Modern ooids are predominantly aragonite rather than calcite. The concept that ancient ooid mineralogy might have been significantly different than the modern was raised by Sandberg (1975) and expanded upon by MacKenzie and Pigott (1981), Sandberg (1983), and Wilkinson et al. (1985), the latter being the most comprehensive. Each of these studies is concerned with the cycling through geologic time of ooid mineralogy between aragonite and calcite, and with possible controls for this cycling: climate, atmospheric, or ocean chemistry, and global sea level. Wilkinson et al. (1985) showed that there were four times of peak ooid deposition in geologic history (Figure 3)—Late Cambrian, Late Mississippian, Late Jurassic, and Holocene. When compared to a first-order sea level curve (Figure 3), it is clear that peak ooid production occurred during times when overall sea level was either rising or falling, rather than at times when sea level was at a maximum (highstands) or minimum (lowstands). Wilkinson et al. (1985) concluded that global changes in sea level, related to crustal processes and pCO_2 (vapor pressure of CO_2, which controlled carbonate concentrations in the atmosphere and the oceans), are the primary controls over both ooid mineralogy and abundance. During times of

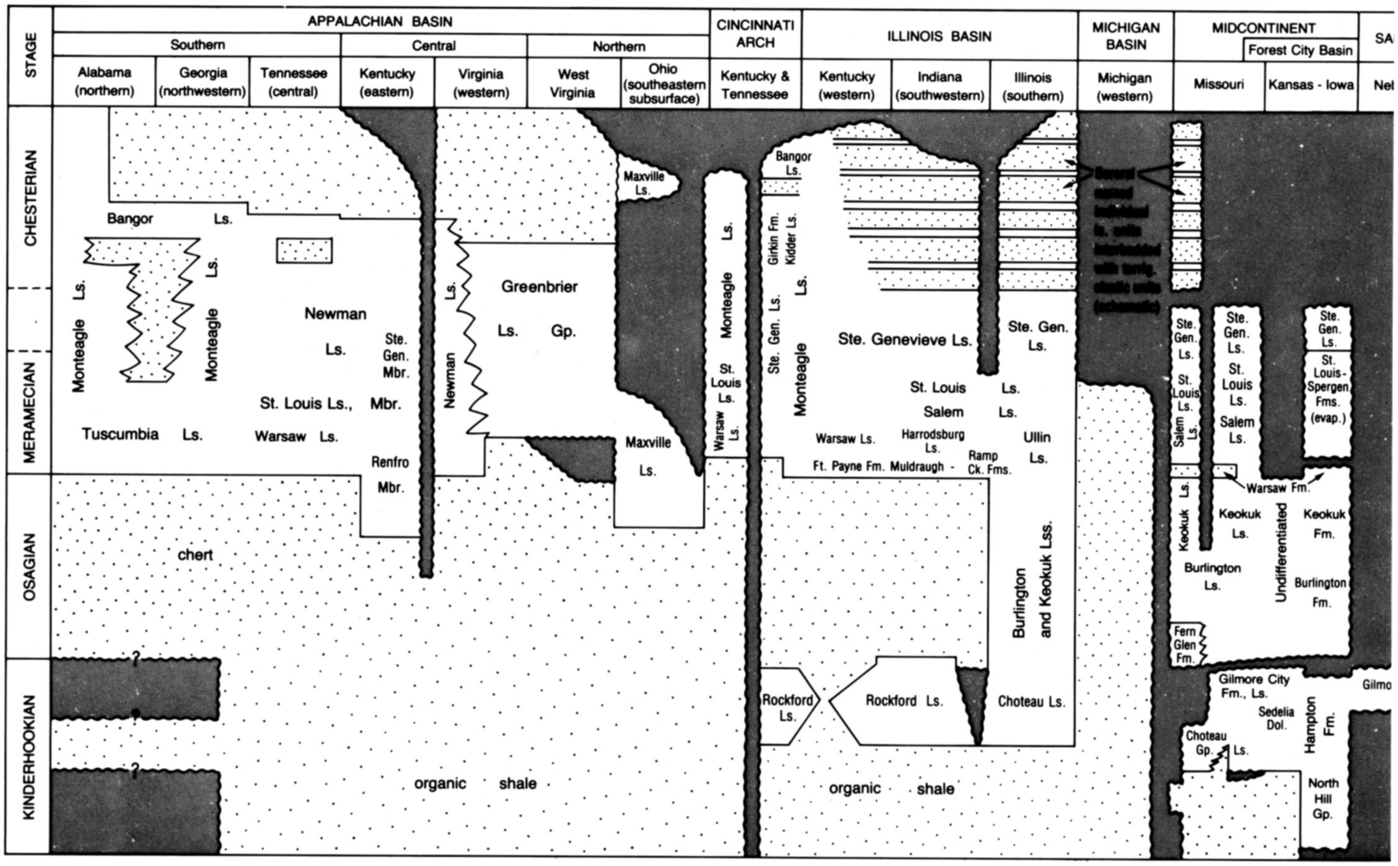
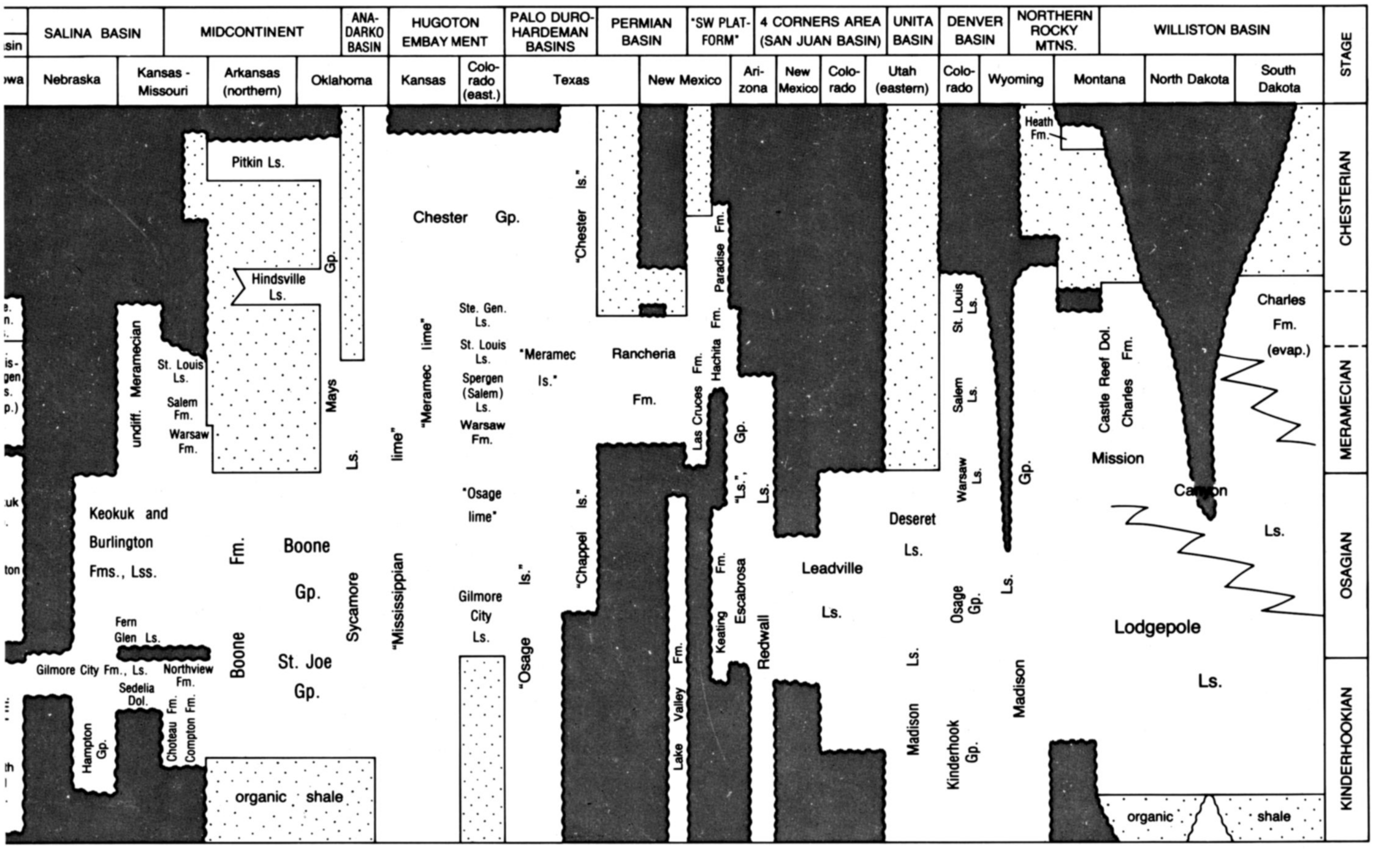


Figure 2. Stratigraphic correlation chart for Mississippian units for most of the United States. Refer to Figure 1 for location of areas noted along the top of the chart. Compiled from 219 columns contained in the following COSUNA charts: Ballard et al. (1983), Hills and Kottlowski (1983), Patchen et al. (1985a, b), Shaver (1985), Adler (1987), Mankin (1987), and Kent et al. (1988). Only names of carbonate (as well as evaporite) units are

emergence, the volume of shallow water carbonate deposited is generally smaller because the size of shallow water environments is limited. During times of submergence, organic carbonate production is high, making conditions most favorable for extensive carbonate deposition (Figure 3), and terrigenous clastic input is low; but pCO_2 levels probably limited the amount of abiotic (i.e., ooid) carbonate that could be produced (Wilkinson et al., 1985). The lack of detailed studies, however, leaves many questions about this aspect of carbonate sedimentation unanswered (see Eluik, 1987, and Wilkinson et al., 1987, for further discussion).

During Mississippian time, widespread oolitic sedimentation occurred because physical and chemical conditions were optimum for ooid production and because competition from organisms available to produce organic buildups was low (Figure 3). In addition, tectonic events during Meramecian and early Chesterian time in the United States produced broad expanses of shallow water at low paleolatitudes (Ettensohn, this volume). Thus, tectonism combined with both the lack of organic carbonate production by framework-building organisms and the apparent proper pCO_2 to control atmospheric and oceanic carbonate levels provided ideal conditions for widespread deposition of predominantly calcitic ooids.

Highstands of sea level also show general correspondence with increased dolomite abundance (Figure 3). No specific mechanism for dolomitization is implied by this relationship (Given and Wilkinson, 1987), but the relationship is consistent with the observation noted earlier that Mississippian oolites are generally not dolomitized, whereas Cambrian and Jurassic oolitic carbonate rocks commonly are. These dolomitized oolitic limestones formed during times of overall sea level rise that were followed by times of maximum emergence (with favorable conditions for widespread dolomitization), whereas Mississippian oolites formed during an overall sea level drop that was followed by maximum submergence (with unfavorable conditions for widespread dolomitization).



shown. Stippled pattern represents the distribution of terrigenous clastic units. The boundary between the Meramecian and Chesterian is shown dashed in two positions to reflect possible revision. See text for more detailed discussion.

PETROLEUM SIGNIFICANCE

Petroleum Occurrences in Mississippian Oolites

Significant occurrences of hydrocarbon production from Mississippian oolitic rocks are present in four areas in North America: (1) the Ste. Genevieve Limestone of the Illinois basin, (2) several Middle and Late Mississippian formations in the Anadarko basin and Hugoton embayment, (3) the Greenbrier and Monteagle limestones of the Appalachian basin, and (4) the Madison Group of the Williston basin.

A review of petroleum reservoirs in Mississippian oolites, especially contrasting their occurrence and characteristics in geographically separated basins with unique histories of petroleum industry activity, is difficult. The literature and records of petroleum production contain so many differences in terminology, available information, research motives, and interpretations, all intertwined with the historical progression of our knowledge of oolitic rocks, that this review is by necessity constrained to be general in nature and rather limited in its conclusions.

The most oil-prolific and most thoroughly studied area of Mississippian oolite reservoirs is the Illinois basin. Oolitic reservoirs are the predominant reservoir type in the Ste. Genevieve Limestone, which accounts for an estimated 18% of the basin's cumulative production, or approximately 743 million barrels of oil (Cluff and Lineback, 1981; Howard, 1991; Mast and Howard, 1991). The Ste. Genevieve oolite grainstone reservoirs are encased in impermeable limestone. The reservoirs, known informally as "McClosky sands," are widely distributed throughout the basin (see Zuppann, Figure 1, this volume). Oil in the McClosky was discovered in 1907, in Lawrence County, Illinois (Blatchley, 1913), along the regionally prominent LaSalle anticlinal belt (see Bandy, Figure 1, this volume). During the first 50 years of Ste. Genevieve oil production, it was not uncommon for wells to initially produce at rates greater than 500 BOPD. Even today some wells are still completed for more than 200 BOPD.

The Monteagle Limestone of northern Tennessee and south-central Kentucky and the roughly equivalent Greenbrier Limestone of West Virginia contain

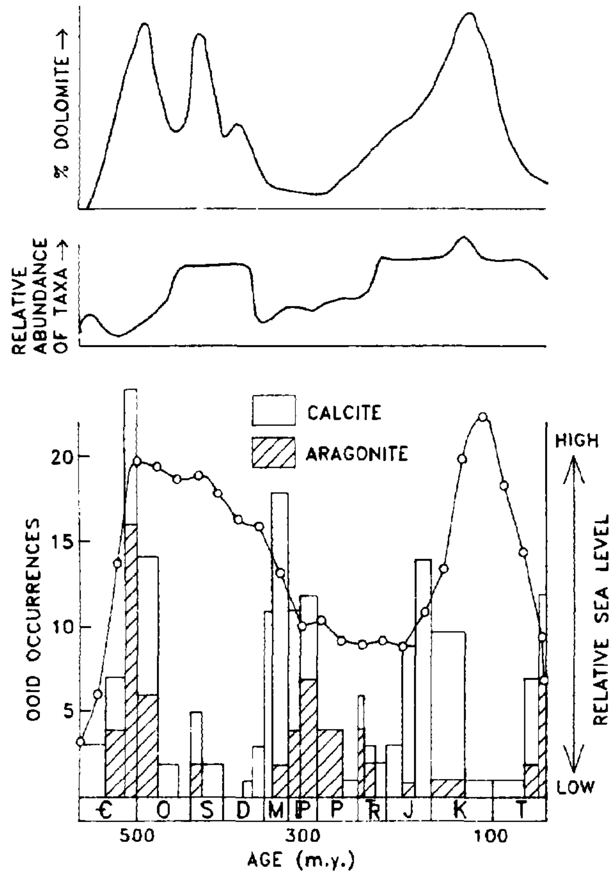


Figure 3. Plot of the distribution of documented oolite occurrences and original mineralogy through geologic time as compared to a first-order sea level curve (line connecting circles). After Wilkinson et al. (1985). Also shown (normalized to the same approximate geologic time scale) are plots of generalized relative abundance of the primary organisms (different taxa) of carbonate buildups (modified from James, 1983) and dolomite abundance plotted as calculated percent dolomite (modified from Given and Wilkinson, 1987). Of interest here are the general correlations of abundances of oolitic limestone, carbonate buildup organisms, and dolomite as they relate to the first-order sea level curve.

many oolitic hydrocarbon reservoirs that are predominantly gas-bearing. Gas wells completed in the Monteagle Limestone tend to have initial tests in the low hundreds of mcfgd per day. According to Youse (1964), some early Greenbrier gas wells had open-flow tests of 20 mmcf per day, and one well was reported with cumulative production in excess of 9 bcf of gas.

The Chester section in the Anadarko basin and the St. Louis and Ste. Genevieve limestones in the Hugoton embayment contain significant oolitic petroleum reservoirs, although they are fewer and less widely distributed than reservoirs in the Ste. Genevieve in the Illinois basin. Because hydrocarbon production in the Anadarko basin and Hugoton embayment comes from a number of different reservoir facies, and because production from oolitic reservoirs is not specifically reported as such, we cannot reasonably estimate the volume of oil production attributable to the oolitic facies. An example that illustrates the quality of these oolitic reservoirs is the Damme field in the Hugoton embayment, Kansas. The Damme field has produced more than 13 million barrels of oil, mostly from oolitic/skeletal grainstones in the St. Louis Limestone (Schmidlapp, 1959; Handford, 1988). The initial potential for the discovery well at Damme field was 1795 BOPD from an oolitic zone in the St. Louis (Schmidlapp, 1959). Asquith (1984) mapped at least four distinct oolite reservoirs within the Chester interval in Beaver County, Oklahoma, in the northwest portion of the Anadarko basin (see Figure 4). These reservoirs contained 41 wells that each have cumulative gas production greater than 1 bcf (Asquith, 1984).

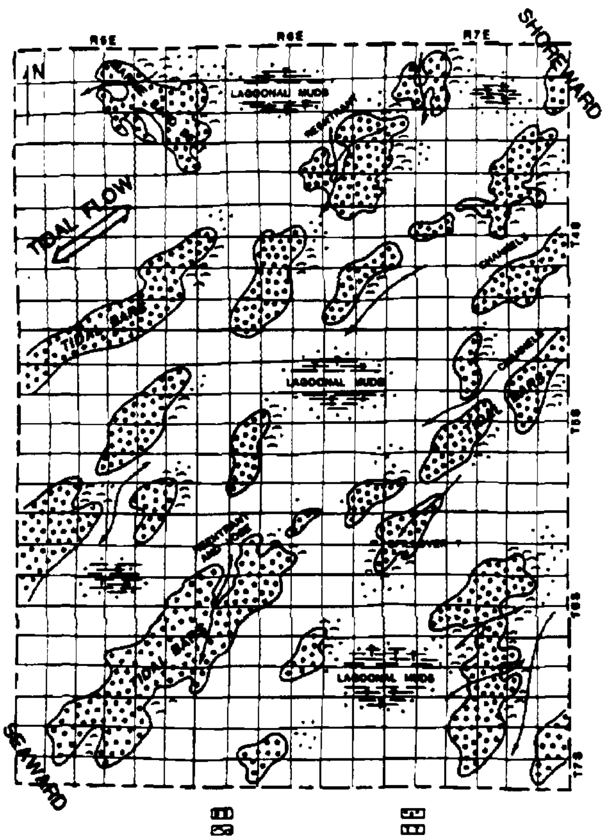
Carbonate rocks of the Madison Group have been active exploration targets in the Williston basin since the early 1950s. Within this prolific oil-producing interval, oolitic rocks are common and oolitic grainstones have often been described as reservoir host rocks (early examples include Berg, 1956; Stanton, 1956; Harrison and Larson, 1958; Smith et al., 1958). However, porosity types related to dolomitization, fracturing, dissolution, and other host lithologies are also common in Madison Group reservoirs (Kent, 1987). The relative importance of specifically oolitic facies to hydrocarbon occurrence in the Williston basin has yet to be reported.

Mississippian Oolite Reservoirs

Understanding the potential shapes and distribution of target reservoirs is necessary to effectively explore for and develop any type of reservoir. Reservoir geometries of Mississippian oolites are of particular interest for several reasons: (1) patterns of reservoir geometry are readily apparent in Mississippian oolitic reservoirs; (2) differences in geometry, especially orientation of oolitic facies, have been considered a major distinguishing feature in depositional models, based on both modern and ancient oolitic deposits; and (3) oolite-body geometry has long been an important aspect of research related to Mississippian oolites, resulting in new ideas and significant contributions to the literature.

Comparing oolitic hydrocarbon reservoirs from the different basins, perhaps the most striking similarity is that those in the Illinois basin, the mid-continent area, and the Appalachian basin tend to occur in stratigraphically recurring trends of subparallel, elongate porosity bodies (Figure 4). This circumstance stems directly or indirectly from depositional controls affecting oolitic sedimentation.

A distinction must be made between a three-dimensional body of porosity (porosity body) that may form a reservoir and the three-dimensional sediment facies (sediment body) to which it may corre-



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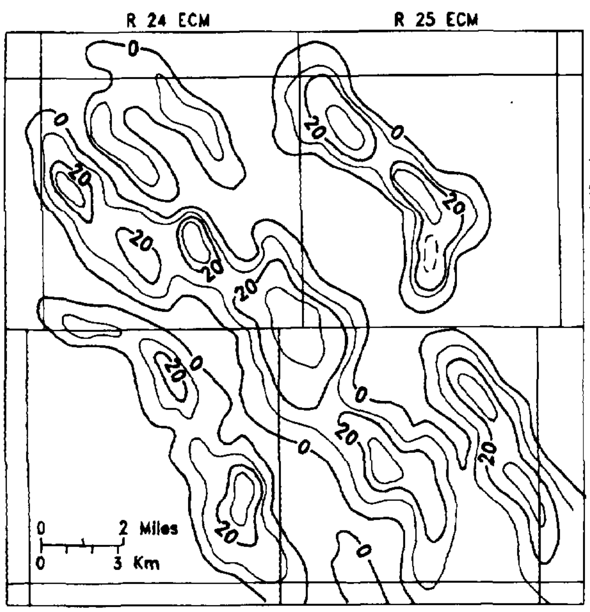

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Figure 4. Examples of trends of subparallel, elongate oolite bodies typical of Mississippian oolitic sequences in the Illinois basin, the mid-continent area, and the Appalachian basin. (A) Paleogeographic map showing distribution of Ste. Genevieve oolite bodies (McClosky "B" time) in Hamilton County, Illinois (from Tharp, 1983). (B) Isoporosity (≥6%) map of upper Chester oolite bodies in north-central Oklahoma. Contour interval: 10 ft (modified from Asquith, 1984). Maps made by Zuppann in 1982 show similar trends of oolite bodies in the Monteagle Limestone of northern Tennessee in the Appalachian basin. These maps were sold, and their whereabouts are unknown.

spond. In some places the relationship between these two appears quite strong, but elsewhere it does not. In northern Tennessee, for instance, there appears to be extremely close agreement between elevated porosity values and the presence of oolitic facies in the Monteagle Limestone. This conclusion is based on examination of a core (Medeiros, 1984) and extensive examination by Zuppann of Monteagle well cuttings, many at the well site. The latter study found virtually a one-to-one correspondence between the presence of ooids in the samples and markedly increased porosity as indicated by density logs. Similarly close approximations have been documented in the St. Louis Limestone in Kansas (Handford, 1988).

In other areas, however, cementation and diagenetic alteration may occlude porosity to the point that oolitic facies may be no more porous than adjacent facies; or porosity may be developed in nonoolitic facies associated with oolitic rocks. Swann and Bell (1958), for instance, stated that most of the Ste. Genevieve oolites in the Illinois basin are "rather well cemented" and differ from the loosely cemented lenses typical of reservoir-quality oolites in that formation. Youse (1964) reported well-developed oolitic zones that were uniformly tightly cemented in the Greenbrier Limestone of West Virginia and eastern Kentucky. Tightly cemented oolites are apparently even more common in the Williston basin, where the diagenetic history is complex and significantly affects reservoir quality in Mississippian rocks (Kent, 1987). This may account for the absence in the literature of maps showing the distribution and geometries of oolite bodies in that basin.

Interpreting porosity of oolite bodies in the subsurface is also complicated because porosity may also be developed in facies adjacent to the oolitic rock. Choquette and Steinen (1980) described extensive reservoirs in dolomitized mudstones subjacent to oolitic bodies in the Ste. Genevieve at North Bridgeport field, in Illinois (see Bandy, this volume). They interpreted this non-supratidal dolomitic porosity to have resulted from influx of meteoric waters via permeability pathways present in the porous oolitic deposits. Thus, in addition to porous oolite facies, these dolomitic reservoirs are significant exploration targets.

The presence of tightly cemented oolites, as well as porosity development in facies other than the oolitic rock, presents problems in delineating oolite sediment bodies in the subsurface by mapping porosity distribution as recorded on geophysical logs.

Unfortunately, this is often the only possible method of inferring geometries of the original sediment bodies in most areas, because geophysical logs are far more commonly available than cores and reliable sample information. So this method cannot be avoided, but a certain degree of generalization must be accepted in the resulting interpretations of depositional geometries.

Oolite-Body Geometry

Controlling Factors

Ball (1967) observed that elongate oolite sand bodies are common in Holocene marine deposits in the Bahamas and proposed models that explained why they may be preferentially oriented either parallel with or perpendicular to depositional strike. He described two major types of oolite shoals: (1) marine sand belts, oriented parallel with the slope break; and (2) tidal bar belts, which, although oriented parallel with slope break, contain oolite bodies that are oriented perpendicular to the slope break because of locally amplified tidal currents directed up- and downslope.

We see no need to review the details of these and more recent models, which has been done quite effectively by Handford (1988). Ball (1967) presented these two models as end-member models of oolite shoals deposited at a shelf break, the main variable distinguishing the two being relative tidal influence. Following Ball's (1967) observations on modern oolite-body orientations, his models were soon applied to subsurface oolite bodies, and orientations of ancient bodies relative to depositional strike has been, and continues to be, discussed. However, Hine (1977) noted that in the Bahamas tidal bar belts and marine sand belts can coexist along the same bank edge in response to multiple generations of oolitic sedimentation under different environmental conditions. Therefore, the meaning of oolite-body orientations may not be all that simple to evaluate in paleoenvironmental reconstructions of ancient rocks.

Models based on modern occurrences in the Bahamas may not be entirely applicable to Mississippian rocks because the Bahamian deposits are situated on the edge of a prominent shelf break, which does not appear to have been the case for most areas of the United States during the Mississippian. Extensive Mississippian oolite sedimentation occurred on broad ramps such as the eastern shelf of the Illinois basin, which had a regional depositional slope of less than 0.5 ft per mi (0.2m per km) (Carr, 1973). However, the concept that the relative interplay between depositional topography and tidal and other currents defines the orientation and distribution of oolite shoals is entirely appropriate, and the record of Mississippian rocks suggests that these factors combined in a variety of ways to control the distribution and geometries of oolite bodies.

The main role of depositional topography in oolitic sedimentation, assuming the presence of environments otherwise suitable for ooid growth, is to bring the bottom depth up to a shallow enough level to create higher-energy environments necessary for ooids to form (typically less than 3 m in modern settings, according to Tucker and Wright, 1990). Bands of oolitic sediment should be parallel with local depositional strike, just as they are in both the marine sand belt and the tidal bar belt models of Ball (1967). If tidal currents are sufficiently strong, then the oolitic deposit might be dissected into bars with a different orientation. Also, if the crest of a depositional topographic high falls within the range of ooid production, then the oolitic sediment might be localized over the crest and generally assume the shape of the crest.

The primary factors that control the geometry of oolite bodies, i.e., depositional strike and prevailing tidal (or other) currents, tend to create elongate oolite sediment bodies with preferred orientations, explaining why trends of parallel oolite reservoirs are so common in the Mississippian. The influence of these factors would also tend to persist through time and through relative changes in sea level, explaining why parallel elongate bodies recur at different stratigraphic levels.

Of course, the relative influence of topography and tidal currents varied from basin to basin during the Mississippian and from one locality to another within each basin. Local conditions and depositional controls worked in some instances to form oolite bodies with unusual shapes or with abnormal orientations. Features such as ooid-filled channels (Bandy, 1991), spillover lobes, eolian oolitic accumulations, local structural irregularities, and shifting depositional environments account for oolite bodies with anomalous geometries and orientations.

Geometry of Reservoirs

The trail of research relating to oolite reservoir geometries has some interesting milestones in studies of Mississippian rocks. Reviewing this progress helps to gauge our present level of knowledge about the shape and distribution of Mississippian oolites and underscores the large gap between what we know and what we could know about this subject.

Prior to 1949 oolite reservoirs discussed in the literature were typically described by phrases such as "vertically and laterally variable lenses of oolitic rock." The reservoirs were generally depicted on structure maps using the top of the oolite as a mapping horizon (for example, Blatchley, 1913; Bell and Piersol, 1932; Bybee, 1948). This method does infer the oolite-body geometry to a certain extent because the structure on top of the oolite lens typically has positive relief, providing it has not been removed by subsequent structural movement. However, the true three-dimensional shape of a reservoir is not portrayed by a structure map, and details such as thickness variations, convex-downward geometries, composite reservoirs, and effects of post-depositional structural changes are not discernible on structure maps. Investigators generally acknowledged that the mapped reservoirs contained multiple oolite lenses, but they did not isolate and map the individual bodies of porosity.

Connolly (1949), in his unpublished M.S. thesis, was apparently the first to map an ancient oolite body (a continuous lens of oolite rock) in the subsurface (Carr, 1973). In his interpretation, Connolly used slice maps and fence diagrams to depict the geometry of two Ste. Genevieve oolite bodies at the Passport field in Illinois (see Zuppann, this volume). Significantly, he also compared these subsurface oolitic zones to "sub-parallel, bar-like" oolitic accumulations of the modern Bahamas as described by Rich (1948).

The first recorded use of isopach maps to show geometries of subsurface oolite bodies was apparently by Truitt (1951), who mapped parts of two oolite bodies in the Ste. Genevieve at Spencer field in southwestern Indiana. Like Connolly, his work was also part of an unpublished thesis. It was not until Nuttall (1968) and Sparks (1968) that the first portrayals of individual ancient oolite bodies were published in the literature; both reported on field studies of Ste. Genevieve reservoirs in the Illinois basin. Thereafter, isopach maps of oolite bodies and oolitic reservoirs have often been used to interpret Mississippian oolites. Among these important papers is Carr's (1973) study of Ste. Genevieve oolite bodies in the Illinois basin, a landmark work on Mississippian oolite-body geometries. A large part of an oolite body was exposed in a quarry, allowing direct observation. Carr mapped three subsurface oolite petroleum reservoirs as well and compared their geometries with the Holocene Bahamian models of Ball (1967). Another paper, by Choquette and Steinen (1980), also on the Ste. Genevieve in the Illinois basin, showed geometries of several oolite bodies occurring at two stratigraphic levels in the Bridgeport field area in Illinois. They described facies relationships between oolite grainstones and adjacent dolomite facies. Also, Handford (1988) mapped the St. Louis B-zone at Damme field in the Hugoton embayment in southwestern Kansas and discussed suitable depositional models.

Now that interest in oolite-body geometries has increased and oolite-body geometries are routinely mapped in the literature, what should be the direction of future research? Most reports that show geometries of Mississippian reservoirs are limited to local accumulations such as a single field or a small group of fields. Now research with greater geographic and stratigraphic scope is needed so that the occurrences and distribution of many oolite bodies can be related to each other and to their basin setting. For entire basins containing Mississippian oolite reservoirs, there may not be even a single oolite body mapped in the literature, the Williston basin being the most conspicuous. Probably more than 100 oolite bodies (mostly gas-bearing) occurring at eight or more stratigraphic levels have been mapped by Zuppann in the Monteagle Limestone of northern Tennessee (these proprietary maps are no longer available to the authors), but no one has described the geometry of more than a single field in any published study.

Only when the details of local oolite accumulations are applied to the larger picture will we be able to understand the controls that affect each individual oolite deposit and to understand patterns of oolite-body geometries within each basin. Until that knowledge is obtained, the geometries of Mississippian oolite reservoirs in different basins will remain difficult to compare.

Reservoir Characteristics

There has always been a fascination with oolitic reservoirs, perhaps in part because they are similar to terrigenous sandstone reservoirs. They consist of more or less round grains formed into discrete bodies by wave or current activity. Geologists may assume that oolite-body geometries and pore-system characteristics can be interpreted using terrigenous sandstone reservoirs as analogs. Although they are far more common and have been studied in more detail than their oolitic counterparts, terrigenous sandstone reservoirs may not be analogous in terms of either their geometries or their pore systems. First, ooid grains are typically deposited quite near their site of formation, whereas marine deposits of terrigenous sandstones have been transported over considerable distances. The depositional factors therefore affecting sand-body geometries of autochthonous oolite accumulations may be substantially different from those associated with allochthonous terrigenous sandstone deposits. Second, as noted in the previous section, the geometry of oolite reservoirs may be difficult or impossible to determine using available subsurface information.

An important consideration for oolitic reservoirs is the critical role played by diagenesis in preserving or modifying porosity systems. The pathway of diagenesis in a simplistic sense progresses from the reduction of primary interparticle porosity through cementation and chemical compaction to the creation of secondary moldic, vuggy, or intercrystalline porosity (or some combination) through dissolution and recrystallization. The often complex variety of porosity networks that results from this process is important not only to the formation of a reservoir but also to the quality of its performance.

Some insight into pore systems of ancient oolite reservoirs may be gained by noting simpler intergranular pore systems in Holocene ooid and pelletoidal sands from the Bahama Banks that were measured for porosity and permeability (Enos and Sawatsky, 1981). Porosity values ranged from 40 to 48% and permeabilities from 25,000 to 54,000 md. These porosity values are at or near the upper limit (48%) expected for minimal packing of spherical grains (Graton and Fraser, 1935). It is interesting that capillary pressure data from these Holocene samples indicated that approximately 17% of this pore volume was related to porosity with entry diameters smaller than 1 μm. These fine pores presumably are between the aragonite needles that form the ooid and pelletoidal grains (Enos and Sawatsky, 1981). Cementation of Holocene ooid sand on Joulters Cay in the Bahamas was reported by Halley and Harris (1979). Porosities of the cemented oolite are in the same range as that of the ooid sand reported by Enos and Sawatsky (1981), between 40 and 50%. The Halley and Harris study indicated that early vadose and phreatic cementation does not substantially affect the amount of porosity, but permeabilities were substantially reduced by even relatively minor amounts of cement. Exact comparisons between the permeability measurements by Enos and Sawatsky (1981) and by Halley and Harris (1979) are not possible due to differences in measuring techniques, but the amount of permeability reduction appears to be several orders of magnitude.

Oolitic limestone reservoirs may contain fairly simple intergranular pore systems with good porosity (10 to 20%) and permeability (tens to hundreds md). However, diagenesis may also create more complex pore systems. Moldic pore systems (high porosity and low permeability) are typical of many Jurassic Smackover reservoirs which are also commonly dolomitic. Bimodal pore systems are characterized by micritized ooids with intercrystalline microporosity and coarser grained macroporosity between the grains. Oolitic bimodal porosity reservoirs have been documented in the Ste. Genevieve in Kentucky (Asquith, 1986).

General treatments of porosity in carbonate reservoirs are available (Moore, 1989; Chilingarian et al., 1992), but little information has been presented about Mississippian oolite reservoirs. The best sources of data on porosity and permeability from cores of Mississippian oolitic reservoirs are two Marathon Oil Company studies on Ste. Genevieve reservoirs in Illinois (Choquette and Steinen, 1985; Manley et al., this volume). At North Bridgeport field (Choquette and Steinen, 1985), Ste. Genevieve reservoirs occur in both microcrystalline dolomite and oolitic limestone. Porosity in the oolitic reservoir ranges from 3.8 to 28.8%, with an average of 13.7%. The permeability ranges from 0.1 to greater than 9500 md, with an average of 250 md (Choquette and Steinen, 1985). At Willow Hill field (Manley et al., this volume), only the oolitic limestone reservoir facies is present, and porosity ranges from 6.0 to 17.2%, with an average of 12.7%. Permeability ranges from 0.1 to 228 md, with an average of 113 md (Manley et al., this volume). Following the classification system of Wardlaw and Cassan (1978), the recovery efficiency for carbonate reservoirs can be estimated by knowing the amount of porosity and the nature of the pore system. For North Bridgeport and Willow Hill fields, estimated recovery efficiencies would be on the order of 40 to 45% for intergranular porosity that averages 13 to 14%. There are no published figures on recovery efficiency from Ste. Genevieve reservoirs in the Illinois basin, but this level of recovery efficiency (40 to 45%) seems to conform to the general consensus for Ste. Genevieve reservoirs. As a rule these reservoirs also seem to respond well to waterflooding, but reservoir heterogeneity is often a major problem for operators trying to establish an efficient waterflood.

SUMMARY

Mississippian oolitic limestone reservoirs represent an important petroleum resource for several reasons: (1) depositional and tectonic controls operated together to make oolitic limestones a significant component of Meramecian and lower Chesterian rocks in several petroleum-producing areas of the United States; (2) there is potentially a large undrilled petroleum resource remaining in stratigraphic traps (probably concentrated at relatively shallow depths) in Mississippian oolites; and (3) these oolitic reservoirs tend to have favorable characteristics for good recovery efficiency for both primary and secondary production. The combination of these factors makes oolitic reservoirs an especially attractive target for our domestic oil industry.

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