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ULLIN-FORT PAYNE, A MISSISSIPPIAN SHALLOW TO DEEP WATER CARBONATE TRANSITION IN A CRATONIC BASIN

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ABSTRACT

The Ullin Limestone (Mississippian) in the Illinois Basin is a light to medium gray, fine-grained skeletal mudstone to wackestone with beds of bryozoan and crinoid-rich grainstone and packstone. This lithofacies is widespread on the structurally higher parts of the La Salle anticline in Crawford and Jasper Counties, Illinois and adjacent areas of Indiana. This shallow to deep shelf facies grades laterally down the western slope of the La Salle anticline in Lawrence and Wabash Counties, Illinois, into the Fort Payne Formation through an intermediate facies. The intermediate facies consists of medium to dark gray lime mudstone which is actually a calcisiltite consisting of bryozoan, crinoids, and other fossil fragments that have been broken and abraded to the limit of recognizability.

The Fort Payne Formation in White County, Illinois, is a dark yellowish brown silicious lime mudstone interpreted to have been deposited in a deep-water basin. Bedding in the Fort Payne varies from irregular fine laminae to nodular bedded and burrowed. Silica is present as disseminated clay-sized quartz, chert nodules, and white quartz nodules. A small amount of crinoid debris is present.

Lateral continuity of beds from the shelf facies into the basinal facies can be demonstrated by correlation of electric log marker horizons. Total thickness of the interval is 122 to 153 m in Wabash and White Counties, Illinois.

Pre-existing depositional topography indicates that the Fort Payne was deposited in water approximately 300 meters deep. Most of the carbonate mud that makes up the Fort Payne was probably winnowed from the surrounding shallow shelves and transported to the center of the basin. Little indigenous carbonate was likely to have been produced at that depth. Silica could have been derived from silicious planktonic organisms, sponges, clay minerals, and clay-sized detrital quartz. Small quantities of organic matter and pyrite give the Fort Payne its characteristic dark color. Much of the Fort Payne is burrowed, not bioturbated, indicating limited bottom dwellers due to a dysaerobic depositional environment.
INTRODUCTION

Middle Mississippian (Valmeyeran) carbonates of the Illinois Basin exhibit two distinct lithofacies in southeastern Illinois (Figs. 1 and 2). The Ullin Limestone is a light colored, bryozoan-crinoidal grainstone to wackestone. The Fort Payne Formation is a dark colored, siliceous, lime mudstone to wackestone. The origin and depositional environment of the siliceous Fort Payne in Illinois was not adequately explained in previous studies (Lineback, 1966). Improved well control and cores obtained from the Fort Payne lithofacies in White County, Illinois, where the formation produces oil from fractured reservoirs, have provided new data that show the Ullin Limestone both grades laterally into and overlies the Fort Payne. Structural and depositional topography indicate that the Fort Payne lithofacies was deposited in a down-slope position relative to its Ullin equivalents. The rocks called Fort Payne in the Illinois Basin may or may not be stratigraphically or depositionally equivalent to other lithofacies known by the same name in Kentucky, Tennessee, Alabama, and elsewhere.

The purpose of this paper is to describe the lithologic and geophysical characteristics of the Ullin and Fort Payne lithofacies, to elaborate on their distribution and stratigraphic relationships, and to speculate on their depositional environments and the consequences of this evidence on interpretation of depositional conditions in not only the Illinois Basin, but other Middle Mississippian cratonic basins as well.

LITHOFACIES

Fort Payne Formation

The Fort Payne Formation is a dark gray to dark yellowish brown, fine grained, dense, siliceous limestone. Texturally the rock ranges from an unfossiliferous mudstone to a moderately fossiliferous
Figure 1. Stratigraphic sections of Valmeyeran rocks below Salem Limestone at four places in Illinois.

Figure 2. Area of Illinois studied for this report.
wackestone. A few thin beds of bioclastic packstone are also present, mostly in the uppermost portion of the unit. The composition of the rock is roughly 50% carbonate and 50% siliciclastic material, with the proportion of carbonate increasing upwards through the formation. The siliciolastic component is partly clay minerals, but is mostly very fine grained quartz. The quartz occurs as pervasive matrix silicification of chert nodules and lenses (Fig. 3A), as chert beds, and as dispersed silt and clay-sized particles. In some portions of the formation, particularly the lower part, the quartz silt is partly segregated into discrete beds and lenses, often with distinct sedimentary lamination, micro-cross bedding, or small scale ripple marks (Fig. 3B). These features attest to low velocity currents moving and sorting grains on the Fort Payne sea floor.

Mobilization of silica was a very early diagenetic event, as shown by differential compaction of *Chondrites* burrows outside of many chert nodules (Fig. 3C). Fracturing of the chert nodules and deformation of fine, dark wispy laminations around the nodules also demonstrate that compaction of the mudstone matrix continued after the chert nodules became rigid. The dark laminations appear to be partly sedimentary in origin, possibly due to concentrations of organic matter (organic carbon content averages 0.5%), and partly are microstylolite swarms ("horsetail stylolites").

Bedding of the Fort Payne varies from even parallel and wavy parallel siliceous mudstones (Fig. 3B) to highly irregular nodular bedded rocks (Fig. 3D). Sedimentary structures, other than those noted above, are mostly limited to a restricted trace fauna of *Chondrites* and some possible *Zoophycos* burrows. In all cases the Fort Payne is burrowed, but not thoroughly bioturbated. Body fossils are sparse and are limited to finely fragmentedocrinid and bryozoan debris, siliceous spicules, and a few beds with coarse transported crinoid and brachiopod fragments (Fig. 3D). The dark coloration of the rock appears due to dispersed organic matter and dead oil (?), with some clay. The matrix of the rock also contains significant pyrite as scattered crystals and
framboids. All of the above evidence suggests low-oxygen conditions, corresponding to the dysaerobic zone as characterized by Byers (1977).

Geophysical characteristics of the Fort Payne Formation are typical of a dense, siliceous, slightly clayey carbonate. On resistivity logs the formation has extremely high or infinite resistivity at the top, lessening somewhat towards the base of the formation as clay content increases slightly. Spontaneous potential is usually deflected well to the right, although not as far as the shale base line. Compensated density and neutron porosity tools typically show very low porosity limestone, with a few units of separation noticeable on dual log suites (when run on a limestone matrix scale) because of the high silica content. The presence of clay influences the neutron log more than the density tool and tends to cancel out the matrix lithology effect.

Ullin Limestone

The Ullin Limestone is a light gray to light brownish gray, highly fossiliferous, medium to coarse grained limestone. The texture of this unit is dominantly a bioclastic packstone to wackestone (Fig. 4A), with considerable grainstone in the upper part of the formation (Fig. 4B). The composition of the rock is clean limestone; mostly lime mud with fragmented crinoids and bryozoans. The fauna is restricted and consists of over 90% crinoids, fenestrate bryozoans, and a few less common types of bryozoans. Minor components of the fauna are brachiopods, trilobite fragments, ostracodes, and very rare foraminifera. Non-skeletal components include pellets and some intraclasts. Conspicuously absent, in comparison to younger Mississippian formations, are calcareous algae, oolithically coated grains, and heavily micritized skeletals.

The Ullin is also siliceous like the Fort Payne, but to a much lesser degree. The lower part of the unit is very hard and some pervasive silicification has occurred. More common, however, are irregular chert nodules that tend to splay off and interfinger with the host limestone (Fig. 4C). Massive chert nodules similar to those in the
Figure 3. Typical lithologies of the Fort Payne Formation in Southern Illinois. All core photographs from the Superior Oil 30 E.S. Greathouse well, Sec. 4, T. 5 S., R. 14 W., White County, Illinois. White dot in corner of each slab is 2 cm in diameter.

A. Irregular chert nodule in matrix of silty, siliceous lime mudstone. (4073 ft)

B. Very silty and siliceous lime mudstone with wavy-lenticular laminations and small scale ripples. Lower Fort Payne. (4140 ft)

C. Patch silicification in silty lime mudstone, lower Fort Payne. (4130 ft) Note that Chondrites traces in the silicified areas (lighter colored) are only partly deformed and ovoid in cross-section, whereas burrows outside of the silicified area are completely flattened.

D. Chert nodules and very coarse crinoidal debris in dark lime mudstone, typical of upper Fort Payne. (3976 ft)
Figure 4. Typical lithologies of the Ullin Limestone in Southern Illinois. Core photographs A, B, and C are from the Spartan Petroleum #1 T. Hasse well, Sec. 12, T. 1 S., R. 13 W., Wabash County, Illinois. White dot in corner is 2 cm. in diameter. Photo D is from the Marathon Oil #43 Miller Core, Sec. 19, T. 4 N., R. 12 W., Lawrence County, Illinois.

A. Skeletal wackestone with large, mostly intact fenestrate bryozoan fronds aligned parallel to bedding. This facies is typical of the lower part of the Ullin Limestone and the non-grainstone intervals of the upper Ullin. (3280 ft)

B. Crinoid-bryozoan grainstone typical of the upper Ullin Limestone or "Harrodsburg" facies. Most core samples of this lithology appear massive or only faintly laminated, but outcrop and quarry exposures reveal abundant low angle cross-bedding. (3302 ft)

C. Partially silicified (whitish areas) medium to fine grained crinoid-bryozoan packstone. This style of silicification is typical of most Ullin Limestone cores. (3308 ft)

D. Chert nodules in bryozoan wackestone with discontinuous wavy laminations. This lithology is characteristic of the lower Ullin and is similar to the upper part of the Fort Payne Formation. It differs mainly in that the matrix is less siliceous than in the Fort Payne and bioclastic debris is more abundant. (2219 ft)
Fort Payne also are found in the finer grained lithologies of the Ullin (Fig. 4D). The degree of silicification and abundance of chert decreases somewhat upwards through the Ullin, although in some cores the uppermost Ullin beds beneath the Salem Limestone are extensively silicified.

Sedimentary structures within the finer grained wackestone and packstone lithologies are restricted to disrupted laminations and burrows. The burrowing is a general mixing of the sediment and individual trace types have not been identified. Considerable low angle cross bedding is found within the grainstone intervals of the Ullin, especially in the upper part of the formation. Although it is difficult to identify cross bedding in most small diameter cores from the central portion of the basin, the cross-bedded nature is prominent and widespread in outcrops and quarry exposures. Even where current activity was strongest, however, there are no associated exposure surfaces, intertidal deposits, oolitic coatings, or even extensive rounding of grains. The lack of these features suggests subtidal deposition of the grainstones as moving sand waves or dune fields.

The geophysical characteristics of the Ullin are typical of very clean, moderate porosity limestone. In some areas the upper portion of the Ullin contains considerable primary interparticle porosity, up to 13%, in intervals many tens of feet to over 100 feet in thickness. The upper Ullin typically has moderate to high resistivity, depending on its porosity, and spontaneous potential is deflected far to the left. Gamma ray logs are especially useful in separating the Ullin from the overlying Salem Limestone, as the Ullin contains virtually no clay or organic matter and gamma ray response is absolutely minimal. Density porosity and neutron porosity tools show clean limestone with porosity varying from 0 to 15%. There is no appreciable dolomite within the formation. The lower part of the Ullin may grade into or interfinger with the upper Fort Payne, with corresponding intermediate log response through the transition zone.
STRUCTURE

The structurally deepest part of the Illinois Basin lies in an area centered on White and Hamilton Counties, Illinois (Fig. 5). This part of the basin is also called the Fairfield Basin. The basin floor is gently undulating and slopes upward to the north through Wayne, Edwards, Wabash, Richland, and Jasper Counties. The basin is bounded on the southeast by the northeasterly trending Wabash Valley Fault System, on the northeast by the northwesterly trending La Salle Anticline, and on the west the -923 m (-3,000 ft) contour line (top Devonian) marks the boundary between the western shelf and the deep basin. The Fairfield Basin is bounded on the south by the east-west trending Cottage Grove and Shawneetown Fault Systems, which separate it from a second sub-basin in extreme southern Illinois and western Kentucky that is known as the Moorman Syncline (Krausse and Treworgy, 1979).

Mississippian depositional patterns indicate that the major structural elements of the basin were active at that time. The deeper part of the basin received the greater thickness of sediment, and sediment thins towards the western shelf and over the La Salle Anticline.

BORDEN SILTSTONE

The New Albany Shale Group (Devonian-Mississippian) contains black organic-rich shale and greenish gray shale deposited under anaerobic and dysaerobic conditions respectively (Cluff and others, 1981). Subsidence and slow sedimentation in the Late Devonian and Early Mississippian resulted in development of a deep-water sediment-starved basin in southeastern Illinois (Lineback, 1966, 1967). When the conditions responsible for deposition of the New Albany ended in the Early Mississippian (Kinderhookian), carbonate deposition resumed on the western shelf of the basin. The Burlington and Keokuk Limestones (Middle Mississippian, Valmeyeran) are over 100 m (300 ft) thick near
Figure 5.
Structure on top of Devonian. Contour interval 500 ft (152 m) below MSL.

Figure 6. Thickness of Borden Siltstone. Contour interval 100 ft (30 m) with added 50 ft (15 m) isopach.
their eastern limits in the basin and formed a prograding bank or steep ramp facing a deep-water sediment-starved basin in southeastern Illinois (Lineback, 1981). Only a few centimeters of shale and limestone were deposited in southeastern Illinois while the Burlington and Keokuk were being deposited in western Illinois.

Deltaic siltstone was spreading westward and southward from Michigan and Ohio into Indiana and Kentucky at the same time that the Burlington and Keokuk were being deposited in Illinois. The Borden Siltstone was deposited in south central Indiana, but did not extend into the sediment-starved basin in southeastern Illinois. Eventually, a delta-like tongue of Borden Siltstone extended westward across central Illinois and effectively terminated carbonate deposition in Western Illinois (Swann and others, 1965; Lineback, 1966).

The Borden Siltstone thins 30 to 60 m (~100 to 200 ft) over the La Salle Anticline in southeastern Illinois and is over 183 m (600 ft) thick in western Effingham, Marion, Jefferson, and Franklin Counties (Fig. 6). The Borden thins rapidly southward and eastward to less than 30 m (100 ft). The zone of rapid thinning between the 183 and 30 m (600 and 100 ft) isopachs is interpreted as the last formed foreset slope of the Borden delta. Basinward of the 30 m (100 ft) isopach line the unit is called the Springville Shale and represents the bottomset deposits of the delta. Only a few centimeters of micritic limestone and shale were deposited at places in Wayne and Hamilton Counties during deposition of the entire Burlington, Keokuk, and Borden Formations. The topset beds of the Borden and the equivalent bottomset beds in Marion and Wayne Counties are presently vertically separated by more than 183 m (600 ft). Pre-compaction water depths beyond the foreset slope were probably in excess of 300 m (~1000 ft) in Wayne, Hamilton, and White Counties (Lineback, 1966).
FORT PAYNE FORMATION

The deep water area in southeastern Illinois and adjacent parts of Indiana was surrounded on three sides by Borden foreset slopes. This topographic basin was filled with carbonate sediment divisible into two main lithofacies. The Fort Payne is a dark colored, siliceous, lime mudstone that is thickest (122 to 152 m, 400 to 500 ft) in Wabash, Edwards, and White Counties (Fig. 7). The Fort Payne is not present on the La Salle Anticline nor in parts of Wayne and Hamilton Counties (Fig. 7). More than 61 m (200 ft) of dark colored siliceous carbonate are present in places on the foreset slope of the Borden Delta in Jefferson and Marion Counties.

ULLIN LIMESTONE

The Ullin Limestone is a light colored bryozoan-crinoid limestone. It is thin where the Fort Payne is thick and is more than 244 m (800 ft) thick in Wayne and Hamilton Counties where the Fort Payne is absent (Fig. 8). Local thick areas of Ullin in Wayne County may represent Waulsortian mound development. The Ullin thins to 30 m (100 ft) or less on the top of the Borden delta and is 152 m (500 ft) thick on the La Salle Anticline in Crawford County.

COMBINED ULLIN AND FORT PAYNE

The individual thickness of the Ullin and Fort Payne are reciprocal and irregular, giving an odd appearance to the thickness maps of the two formations. The combined thickness of the two formations is more regular and follows the form of the deep Fairfield Basin and thins reciprocally towards the Borden (Fig. 9). This combined interval appears to have filled the basin left in southeastern Illinois by Borden Deposition.
Figure 7. Thickness of Fort Payne Formation. Contour interval 100 ft (30 m).

Figure 8. Thickness of Ullin Limestone. Contour interval 100 ft (30 m).
Figure 9. Thickness of combined Ullin Limestone and Fort Payne Formation. Contour interval 100 ft (30 m).

Figure 10. Location of cross sections.
The Fort Payne Formation and Ullin Limestone appear to be reciprocal lithofacies within a carbonate basin fill. Three cross sections show that the Fort Payne both grades laterally into and is overlain by the Ullin (Fig. 10). The Ullin on the La Salle Anticline grades laterally southwestward and down structure into the Fort Payne (Fig. 11). The gradation takes place between between Sec. 27, T. 3 N., R. 12 W. and Sec. 25, T. 3 N., R. 13 W., at the western edge of the La Salle structure. The La Salle is believed to have been a positive feature during the Mississippian because units thin over it. Resistivities increase basinward in the Fort Payne and spontaneous potential logs are deflected to the right, indicating the increase in siliceous content. Individual medium to coarse sand-sized fossil fragments can be identified in the Ullin. Fossil fragments become finer basinward and finally become too small to be identifiable in the Fort Payne. The color changes from light brownish-gray in the Ullin to dark yellowish-brown in the Fort Payne. Siliceous content increases basinward over the transition zone.

On the west side of the thick tongue of Fort Payne, the formation thins depositionally with minor lateral interfingering (Fig. 12). Individual markers within the Fort Payne dip westward and the units between them thin. The Ullin thickens reciprocally. Extra thick Ullin sections in Sec. 27, T. 2 S., R. 8 E. and Sec. 3, T. 2 S., R. 7 E. possibly mark sites of Waulsortian-style buildups. Too few wells exist to show their geometry. The lower part of the Ullin is cherty and the upper part is rich in crinoids and bryozoans.

The Fort Payne lithofacies also occurs on the eastern foreset slope of the Borden delta (Fig. 13). Siliceous, silty dark colored carbonate with high resistivity is present as a thick lens lying on the last Borden foreset and does not obviously grade laterally into either the Borden or the Ullin lithologies.
Figure 11. Cross section A-A' showing lateral gradation of Ullin Limestone into the Fort Payne Formation on the western flank of the La Salle Anticline.
Figure 12. Cross section B-B' showing westward thinning of the Fort Payne Formation and reciprocal thickening of the Ullin Limestone.
Figure 13. Cross section C-C' showing presence of a Fort Payne like lithofacies on the foreset slope of the Borden Delta in Jefferson County, Illinois.
DEPOSITIONAL ENVIRONMENTS

The carbonate textures of the Ullin and Fort Payne, if separated from the topographic constraints imposed by prior deposition and regional structure, are not particularly diagnostic. Certain constraints apply to the Mississippian of the Illinois Basin, however, and serve to distinguish two types of carbonate-producing environments that are separated primarily by a difference in water depth.

The Ullin Limestone and its deeper water depositional equivalent, the Fort Payne Formation, are characterized by a normal marine salinity fauna that is restricted in diversity. The abundance of crinoids and fenestrate bryozoans in the Ullin is similar to Middle Mississippian carbonates in various parts of the world. The lack of sedimentary rounding, calcareous algae, foraminifera, and oolites sets the Ullin apart from the overlying Salem Limestone which has those features plus a more diversified fauna and demonstratable intertidal and supratidal sedimentary features in places. Thus we reach the conclusion, supported by basinal topography, that the carbonate of the Ullin was produced in relatively deep water and the Salem carbonate was produced in shallow water. Quantitative values on water depth are problematic and hinge on the depth at which calcareous algae and benthonic foraminifera may occur in a moderately agitated normal marine carbonate environment. The oolite-coated grain grainstone and associated Salem lithofacies were probably deposited in water less than 30 m (100 ft) deep and mostly in water less than 10 m (30 ft) (Cluff and Lineback, 1981; Cluff, 1984). The Ullin carbonate may not have been subphotic, but may have been formed primarily in water 50 to 100 m (~150-300 ft) deep at its shallowest and, of course, was largely deposited in water more than 300 m (~1000 ft) deep.

The Ullin formed an irregular carbonate ramp grading basinward into the Fort Payne lithofacies at the base of the ramp (Fig. 14). There were no shelf edge reefs or shoals to interrupt sediment flow. Waulsortian mounds, if present, were small and located down slope. The
most significant flaw in this model is the question of why the Ullin does not grade laterally into shallow shelf Salem-like lithofacies on the top of the Borden delta. The topset part of the delta would likely have been a shallow shelf environment as the sea transgressed across it, unless the end of Borden deposition was caused by a rapid rise in sea level. A relative sea level rise of 200 feet would have been enough to drown the Borden topset plain in water too deep for Salem type lithologies to be deposited, except in far western Illinois, 200 miles from the study area. The Ullin-Salem transition could have been caused by a sudden sea level fall of the same magnitude.

Rapid sea level change in the Mississippian of the Illinois basin is supported by the presence of Salem-type lithologies and benthonic foraminifera in a thin bed of oolites in the lower part of the Keokuk Limestone in western Illinois (Cluff and Lineback, 1981; J. W. Baxter, pers. comm., 1984). The Burlington-Keokuk is predominantly a crinoid and bryozoan-rich carbonate and may also have been deposited in a deep shelf platform environment. The platform underwent a brief and abrupt sea level fall and Salem lithologies and fauna were deposited.

The rapid fall in sea level at the end of Ullin deposition may account for the abrupt vertical change in lithofacies into the Salem that takes place basinwide in spite of the fact that the Ullin is an upward-shallowing sequence. Without a sea level fall, the contact would have been more gradational than observed.

Vail-type sea level curves are not very reliable at this scale in the Paleozoic, but sea level fluctuations could occur at this time without much record being preserved in the shallower depositional environments because this was the time of maximum marine inundation of the continent and much of the shallow record lies beyond present erosional limits of the Mississippian. Similar sea level changes took place in the Williston Basin at the same time causing vertically alternating subtidal and supratidal deposits to form in the Mission Canyon and Charles Formations.
SYNTHESIS

If the water in Wayne and White Counties was 300 or more meters (-1000 ft) deep at the end of Borden Siltstone deposition (Fig. 14), it is unlikely that any significant amount of carbonate would have been produced on the sea floor because it would have been below the photic zone. Yet the region contains 244 m (800 ft) or more of carbonate rock. Much of the carbonate must have originated in relatively shallow shelf environments elsewhere and have been transported into the deep-water basin. Relatively little pelagic carbonate production took place in the Paleozoic (Scholle, 1977).

After Borden deltaic sedimentation ceased, the delta subsided and became a vast shallow carbonate shelf. Possibly the area of the La Salle Anticline, south of the limit of Borden deposition, was also shallow enough for rapid carbonate production. Excess fine carbonate was winnowed from the zones of production and swept off the shelf and into the deep-water basin.

The deep water lithofacies of the Fort Payne has a high silica content, dark color, sparse skeletals and trace fossils, all characteristic of presumed deep-water carbonate deposition (Wilson, 1969, 1975). The basin waters were likely dysaerobic during deposition of the Fort Payne, an environmental condition continuing in southeastern Illinois from the time of deposition of the New Albany Shale (Cluff and others, 1981). The environment of deposition caused the carbonate of shelf origin to take on its present dark color and high silica content. The silica may in part be spicular or pelagic, but most derived originally from the same clastic source as the Borden delta. The quartz was mobilized during early diagenesis into pervasive replacements of the carbonate matrix. The Fort Payne lithologically and depositionally resembles the Paine Member of the Lodgepole Formation (Mississippian) in central Montana (Smith, 1977).
Figure 14. Diagrammatic models for Fort Payne and Ullin deposition.
The dysaerobic conditions evident in the Fort Payne ended before the prograding carbonate bank filled the basin. Ullin Limestone in Wayne and Hamilton Counties was deposited in water just as deep as the Fort Payne lithofacies (Fig. 14), but the water was aerobic and the carbonate remained light colored. The lower Ullin in that area contains chert, but pervasive replacive mobilization of silica, that characterizes the Fort Payne, is generally absent in the Ullin. As the Ullin carbonate filled the basin along basinward dipping depositional slopes, the shelf area rapidly expanded and hastened filling.

REFERENCES


