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PETROGRAPHIC ANALYSIS OF DIAGENETIC TRENDS AND POROSITY TYPES IN THE UPPER SMACKOVER FORMATION, SOUTHWESTERN ARKANSAS

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North Little Rock, Arkansas
2024

OFFICE OF THE STATE GEOLOGIST

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Petrographic analysis of diagenetic trends and porosity types in the upper Smackover Formation, southwestern Arkansas

Ciara Mills

ABSTRACT

The upper sequence of the Jurassic Smackover Formation in the subsurface Gulf Coastal Plain of southern Arkansas consists primarily of ooid grainstones, which serve as substantial hydrocarbon and brine reservoirs. Petrographic analyses of these grainstones provide critical information for interpreting reservoir quality and therefore are useful for hydrocarbon and brine exploration. Thin sections of the upper Smackover Formation taken from cores in seven wells from seven oil fields in Miller, Lafayette, and Columbia counties in southwestern Arkansas were analyzed for trends in primary porosity type and diagenetic features, including cementation, dissolution, replacement, and compaction.

The seven wells were grouped into three diagenetic zones that generally correlate with Moore and Druckman's (1981) original study. Samples from the northern zone (Paup Spur, Midway, and McNeil East fields) often exhibited secondary moldic and intraparticle porosity as well as early equant calcite mosaic cement occluding interparticle pore space. Ooids were either fully or partially dissolved or completely recrystallized. Compaction features were not prevalent. Porosity in the southern zone (Walker Creek and Atlanta fields) was predominantly primary interparticle, and ooids were either micritized or partially replaced with very fine calcite. Early calcite rim cement was common but did not completely occlude interparticle space. Medium to coarse calcite spar was the most common porosity-occluding cement. Compaction features such as pressure solution contacts and stylolites were common. The transitional zone (Mt. Vernon and Kress City SE fields) had diagenetic characteristics of both the northern and southern zones.

There were no conclusive results of the mechanisms behind these diagenetic patterns since this study did not involve geochemical data. Future work should include trace element and isotope geochemistry to determine original ooid mineralogy and diagenetic settings.

INTRODUCTION

The purpose of this study is to provide a detailed petrographic analysis of the upper Smackover Formation across three counties and seven fields to reveal post-depositional trends that can be used to predict reservoir quality for hydrocarbons and element-rich brines across southern Arkansas. Multiple petrographic, diagenetic, and porosity analyses of upper Smackover reservoir rocks were conducted in previous studies that often focused on specific fields (Becher and Moore, 1976; Brock and Moore, 1981; Wagner and Matthews, 1982; Druckman and Moore, 1985; Bliefnick and Kaldi, 1996). Other than a comprehensive study by Moore and Druckman (1981), research that documents diagenetic and porosity trends across multiple Smackover fields is generally lacking.

The Upper Jurassic (Oxfordian) Smackover Formation is a shallow marine carbonate sequence in the subsurface of the northern margin of the Gulf of Mexico Basin (Fig. 1). In Arkansas, it consists of two members: a lower, dark, dense limestone with argillaceous bands and an upper oolitic to chalky limestone (Vestal, 1950). The porous oolitic limestones of the upper member have been active targets for hydrocarbon production in southern Arkansas since the 1930s due to their favorable reservoir rock qualities. In addition to hydrocarbons, the upper Smackover Formation contains brines with significant concentrations of bromine and alkali metals (Moldovanyi and Walter, 1992). In recent years, the high concentrations of lithium in these brines have garnered attention due to increased global demand for lithium batteries used in electric vehicles and portable electronics.

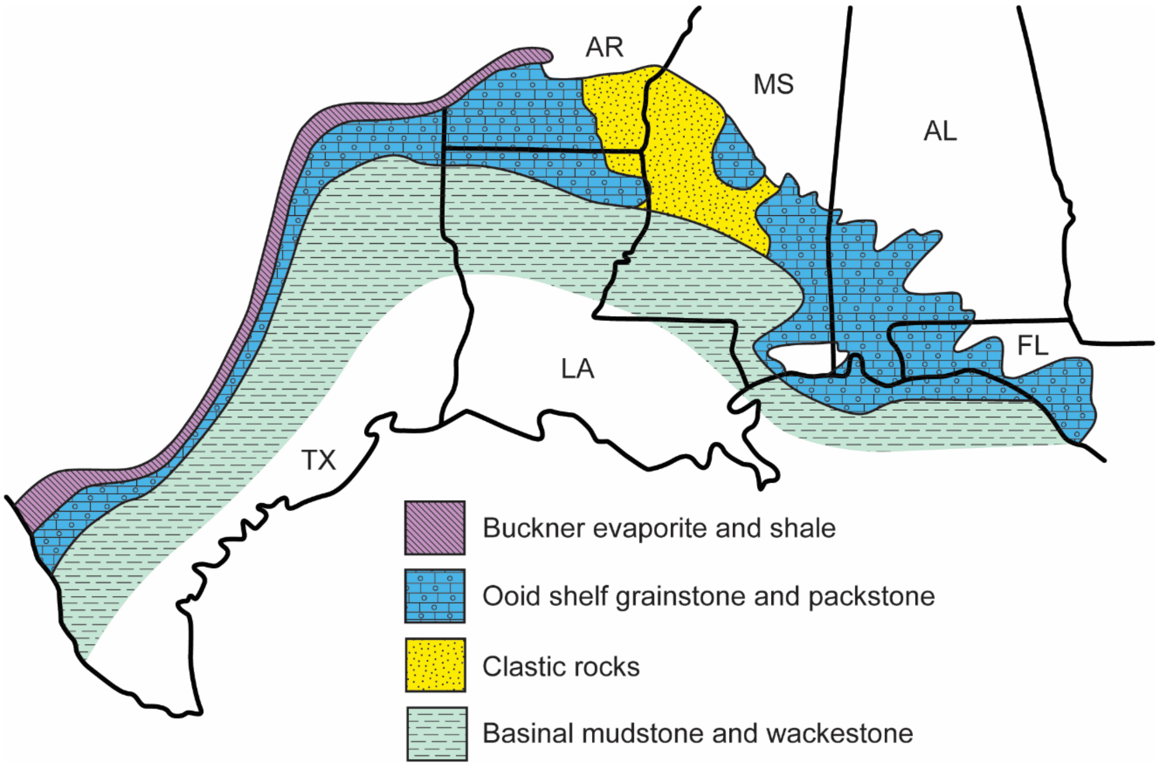

Figure 1. Generalized map of Buckner and Smackover rock types in the northern Gulf of Mexico Basin. Modified after Crevello and Harris, 1984.

GEOLOGIC SETTING

The Gulf of Mexico Basin formed during the Mesozoic breakup of Pangea following the Ouachita Orogeny. Siliciclastic "red beds" of the Late Triassic Eagle Mills Formation were the first basin deposit to accumulate in south Arkansas during the Mesozoic (Scott et al., 1961; Salvador, 1987). Middle Jurassic evaporite deposits of the Werner-Louann sequence were deposited unconformably on the Eagle Mills, and formed in an arid sabkha environment in large, shallow hypersaline lakes during a period of restricted seawater influx (Fig. 2, Hazzard et al., 1947; Salvador, 1987, 1991; Snedden and Galloway, 2019). Widespread marine transgression followed in the Late Jurassic, depositing the Norphlet and Smackover Formations. The Smackover Formation represents a marine sequence accumulated on a tectonically stable, low-angle ramp on the northern margin of the Gulf of Mexico Basin (Ahr, 1973; Salvador, 1987; Snedden and Galloway, 2019). In south Arkansas, the Smackover Formation is split into two distinct members:

a lower dark, dense limestone with argillaceous bands and an upper member composed of porous oolitic grainstone to chalky limestone (Imlay, 1949; Vestal, 1950; Akin and Graves, 1969). The lower member was deposited in a deep shelf, low-energy system and the upper member in a high-energy, shoaling-upward system (Budd and Loucks 1981; Moore, 1984; Salvador, 1991). Sediment loading during Smackover deposition prompted contemporaneous faulting and migration of the underlying Louann salt basinward, forming anticlines and faults generally parallel to the ancient shoreline (Bornhauser, 1958; Hughes, 1968; Bishop, 1973). Oolite-rich shoal deposits often formed on the resulting structural highs (Akin and Graves, 1969; McGraw, 1984). These shoals transitioned conformably to evaporites (primarily nodular and bedded anhydrite) and mudstone in the Buckner Member of the Haynesville Formation and were likely deposited in shoreward hypersaline coastal lagoons or sabkhas (Dickinson, 1968; Moore, 1984; Salvador, 1991).

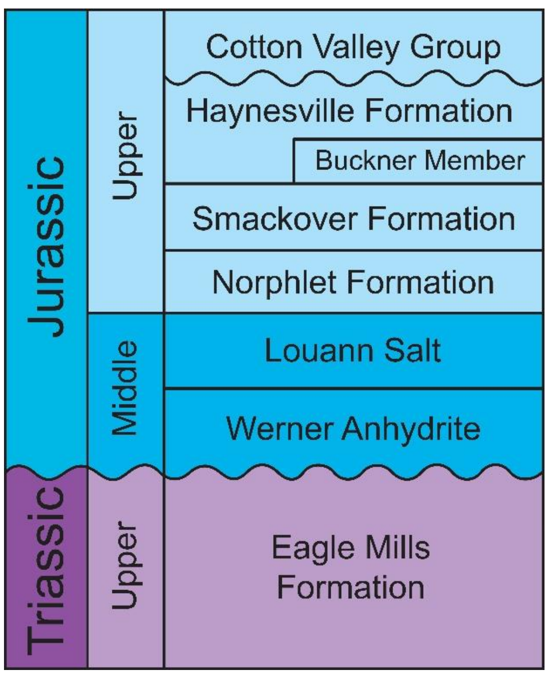

Figure 2. Triassic-Jurassic stratigraphic column of southern Arkansas.

METHODOLOGY

Grant funding from the United States Geological Survey (USGS) was provided in 2015 for a research project examining the reservoir characteristics of the upper Smackover Formation. Although funding was terminated in 2017 for budgetary reasons, this report was produced to present information gathered for the project that may be useful for predicting reservoir quality in this unit.

Core chips were collected from four wells at various intervals in the upper Smackover Formation and mailed to Weatherford Laboratories (Table 1). Thin sections were created and scientists at the laboratory produced general description reports (Appendix 2). Samples in three additional wells were collected and sent to National Petrographic Service to obtain more thin sections which were used to expand and enhance the existing data (Table 1). Both laboratories impregnated all samples with blue stained epoxy for porosity analysis, and all sections were stained for calcite.

Samples from all seven wells were examined under a petrographic microscope and analyzed for trends in primary and secondary porosity type as well as diagenetic features, including cementation, dissolution, replacement, and compaction.

RESULTS

Thin section images taken by the author are grouped by field and presented as part of Appendix 1. These are referenced in the text by field abbreviation (see Table 1) followed by a number rather than order of appearance. Additional thin section images and descriptions of samples were done by Weatherford Laboratories and are included in Appendix 2. These figures will be referenced in the text by "WF" for Weatherford Laboratories, field name, and depth. See Figure 3 for varieties of cementation identified in this study.

Porosity

Secondary intraparticle porosity from partial dissolution and moldic porosity created by selective dissolution of ooids was the dominant porosity type present in the Midway well and was common in the Paup Spur and McNeil East wells (WF Paup Spur 6222', P.S.1, P.S.2, M.W.2, M.W.3, M.E.1). Additionally, minor secondary vugs occurred in a few intervals in the Paup Spur, Mt. Vernon, and Atlanta wells. Primary interparticle porosity was the most common porosity type overall, appearing in at least one interval in every well and representing the dominant porosity type in the Mt. Vernon, Kress City SE, Atlanta, and Walker Creek wells.

Intercrystalline porosity was uncommon and only occurred as the dominant porosity type at 6238 feet in the Paup Spur well and 6379.5 feet in the Midway well. These rocks were recrystallized with very fine to fine calcite, destroying original fabrics and altering allochems (WF Paup Spur 6238').

Intervals with little to no porosity were observed at 6265 feet in the Paup Spur well, 10,744 and 10,842 feet in the Walker Creek well, 8442 feet in the Kress City SE well, and 7957 feet in the Mt. Vernon well (WF Paup Spur 6265', W.C.1, WF Kress City SE 8442', M.V. 4, WF Mt. Vernon 7957').

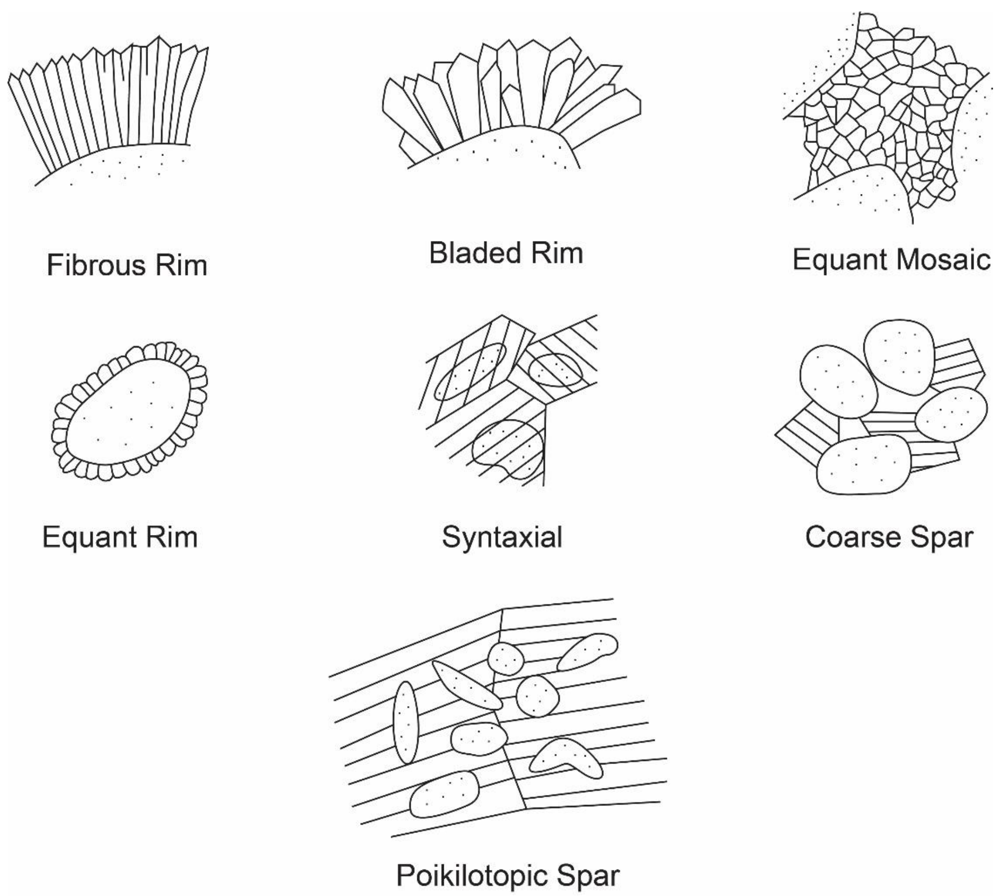

Figure 3. Types of cement most often encountered in this study. Modified in part after Flugel, 2004.

Table 1. Wells sampled for this study.

Permit	API	Well Name	County	Location (S-T-R)	Sampled Interval (ft); Number of Samples	Field
24445	03-091-10180-0000	Bolin Stricklin #1	Miller	5-15S-27W	6222-6265; 4	Paup Spur (P.S.)
18344	03-073-00273-0000	Midway Smackover Unit #11-5	Lafayette	11-15S-24W	6314.5-6386; 10	Midway (M.W.)
34944	03-073-11096-0000	Purser #2	Lafayette	2-17S-24W	8417-8451; 5	Kress City SE (K.C.)
24227	03-027-10486-0000	L. L. Est Nix #1	Columbia	26-16S-22W	7940-7957; 4	Mt. Vernon (M.V.)
21833	03-027-10068-0000	Walker Creek Smackover Unit #16-1	Columbia	19-19S-22W	10,744-10,850; 6	Walker Creek (W.C.)
31312	03-027-11258-0000	Doss #1	Columbia	8-16S-19W	6517-6522.5; 3	McNeil East (M.E.)
26629	03-027-10848-0000	Reeves Land & Timber "A" #1-8	Columbia	8-18S-19W	8294-8351; 6	Atlanta (A.)

Cement and Occurrence of Dolomite

Fine equant calcite mosaic cement fully or partially occluded primary interparticle pore space in samples from the Paup Spur, McNeil East, Kress City SE, and Midway wells (P.S.2, K.C.2, M.E.4, M.W.2, M.W.3, M.W.4). Fibrous to bladed calcite rim cement on the surfaces of allochems was observed at 8294 feet in the Atlanta well, 6519.5 feet in the McNeil East well, and 6386 feet in the Midway well (A.1, M.E.3, M.W.6). Equant calcite rims on allochems were common and occurred in at least one interval in every field. At certain intervals in the Atlanta, Walker Creek, and Mt. Vernon wells, rim cement was absent or formed as very fine, incomplete crusts on allochems (A.2, WF Atlanta 8303’, 8326’, 8334’, W.C.4, M.V.1, WF Mt. Vernon 7940’). Medium to coarse interparticle sparry calcite cement occurred in the Walker Creek, Atlanta, Kress City SE, and Mt. Vernon wells (W.C.1, W.C.2, A.4, K.C.1, M.V.2). Syntaxial calcite overgrowths of echinoderm fragments appeared in minor amounts in the Atlanta, Mt. Vernon, and Walker Creek wells (A.2, M.V.1, W.C.4).

Coarse poikilotopic dolomite spar was uncommon but observed in the Paup Spur, Walker Creek, and McNeil East wells. Medium to coarse dolomite spar was present in the Atlanta and Walker Creek wells and often appeared altering from calcite spar. Subhedral to euhedral fine to medium dolomite crystals were observed rimming allochems and occluding interparticle pore space in the Kress City SE well (WF Kress City SE 8417-8424’). Abundant dolomite cement also infilled interparticle pore space at 7957 feet in the Mt. Vernon well (M.V.4). Complete dolomitization of ooid grainstones occurred in the Midway and McNeil East wells (M.W.1, M.E.1). Fine subhedral and euhedral dolomite also infilled moldic pores at multiple intervals in the Midway well (M.W.4). Medium to coarse undulose dolomite spar (baroque dolomite) was uncommon but observed in notable amounts in the Walker Creek well.

Coarse anhydrite was rare but observed in all wells except the Atlanta well.

Ooids

Significant recrystallization of ooids to fine-grained calcite or dolomite was prevalent in the Paup Spur, Midway, and McNeil East wells (P.S.1, M.W.2, M.W.6, M.E.3). Micritization was the most common post-depositional process affecting ooids and was observed in Mt. Vernon, Kress City SE, Walker Creek, Atlanta, and one interval in the McNeil East well. Micritized ooids were often partially replaced with very fine calcite.

Both tangential and radial internal structures of ooids were observed in most wells, although in many instances these features were poorly preserved due to micritization or recrystallization.

Compaction

Physical compaction features such as fractures, collapsed molds (post-dissolution collapsed allochems), and broken allochems and cement rims were observed in at least one interval in every well to varying degrees. Samples from the Paup Spur, Midway, and McNeil East wells exhibited mild to moderate amounts of physical compaction with rare to mild occurrences of chemical compaction features.

Pressure solution surfaces between allochems and stylolites indicative of chemical compaction occurred in the Atlanta, Kress City SE, Mt. Vernon, Midway, and Walker Creek wells, and were most prevalent in the Atlanta and Walker Creek wells (WF Atlanta 8307', M.V.3, M.W.5, W.C.1, W.C.5).

DISCUSSION

The seven fields were grouped into zones based on observed diagenetic trends (Fig. 4, Table 2). The boundaries that Moore and Druckman (1981) originally established matched the observations in this study, though a minor adjustment of the contact between the northern and transitional zones is necessary (Fig. 4). In the northern zone, samples often exhibited fine equant calcite mosaic cement that occluded interparticle pore space. This cement is likely an early cement precipitated prior to significant burial because the allochems and molds exhibit a relatively open framework without tight grain packing (P.S.2, M.W.3, M.W.4, M.E.4). This early cementation may have increased the competency of the rocks since compaction features were not severe in this area. Ooids were recrystallized with very fine to fine calcite, partially dissolved, or completely dissolved from apparent fabric-selective dissolution, making secondary moldic and intraparticle porosity more common in this zone than any others. There was one instance of micritic ooids in the McNeil East well at 6522.5 feet, but even these ooids appeared partially dissolved as they had "shrunken" away from their cement rims (M.E.4). Primary interparticle porosity occurred in at least one interval in each well in the northern zone, though it was much more prevalent in the southern zone.

Table 2. Diagenetic characteristics of fields in this study.

Zone	Field	Porosity Type	Pre-Compaction/Early Cement	Post-Compaction/Late Cement and Mineralization	Compaction Features	Ooids
Northern Zone	**Paup Spur**	Fabric selective secondary moldic, secondary intraparticle, primary interparticle, minor vugs, secondary intercrystalline	Equant calcite rim cement, fine equant calcite mosaic	Fine calcite recrystallization of preexisting matrix and allochems (6238 ft), coarse poikilotopic dolomite spar (6222 ft), minor anhydrite	Mild to moderate physical compaction	Recrystallized with very fine to fine calcite, fabric selective dissolution
Northern Zone	**Midway**	Fabric selective secondary moldic, secondary intraparticle, primary interparticle, secondary intercrystalline	Fine equant calcite mosaic, bladed calcite rim cement	Fully dolomitized ooid grainstone with dolomite replacing allochems and precursor rims (6314.5 ft), subhedral to euhedral dolomite filling oomoldic pores, fine calcite recrystallization of preexisting matrix and allochems, minor anhydrite	Mild to moderate physical compaction, mild chemical compaction (stylolites)	Fabric selective dissolution, recrystallization with very fine to fine calcite or dolomite
Northern Zone	**McNeil East**	Secondary intraparticle, fabric selective secondary moldic, primary interparticle	Bladed calcite rim cement, fine to medium calcite mosaic	Fully dolomitized ooid grainstone with dolomite replacing allochems and precursor rims (6517 ft), poikilotopic dolomite spar, fine to medium calcite spar	Mild physical compaction	Micritization, partial replacement of micritic ooids with very fine to fine calcite, full to partial fabric selective dissolution, recrystallization with very fine to fine calcite or dolomite
Transitional Zone	**Kress City SE**	Primary interparticle, secondary intraparticle, minor moldic	Equant calcite rim cement, fine equant calcite mosaic (8451 ft)	Fine to medium euhedral and subhedral dolomite likely replacing precursor rims or interparticle cement, fine to coarse calcite spar cement, minor anhydrite	Mild to moderate chemical compaction (pressure solution), mild to moderate physical compaction	Micritization, partial replacement of micritic ooids with very fine to fine calcite, minor to moderate dissolution
Transitional Zone	**Mt. Vernon**	Primary interparticle, minor to moderate vugs	Very fine incomplete calcite crusts on allochems, equant calcite rim cement, minor syntaxial cement	Fine to medium euhedral and subhedral dolomite (7957 ft), medium to coarse calcite spar, minor anhydrite	Mild to moderate physical compaction, mild to moderate chemical compaction (pressure solution)	Micritization, partial replacement of micritic ooids with very fine to fine calcite
Southern Zone	**Atlanta**	Primary interparticle, minor secondary intraparticle, minor vugs	Bladed calcite rim cement, very fine incomplete calcite crusts on allochems, equant calcite rim cement, minor syntaxial cement	Medium to coarse calcite spar, minor coarse dolomite spar	Mild to moderate physical compaction, moderate to severe chemical compaction (pressure solution, stylolites)	Micritization, partial replacement of micritic ooids with very fine calcite
Southern Zone	**Walker Creek**	Primary interparticle	Equant calcite rim cement, minor syntaxial cement	Medium to coarse calcite and dolomite spar, minor poikilotopic dolomite spar, minor baroque dolomite, minor anhydrite	Mild to severe chemical compaction (pressure solution, stylolites), mild physical compaction	Micritization, partial replacement of micritic ooids with very fine to fine calcite

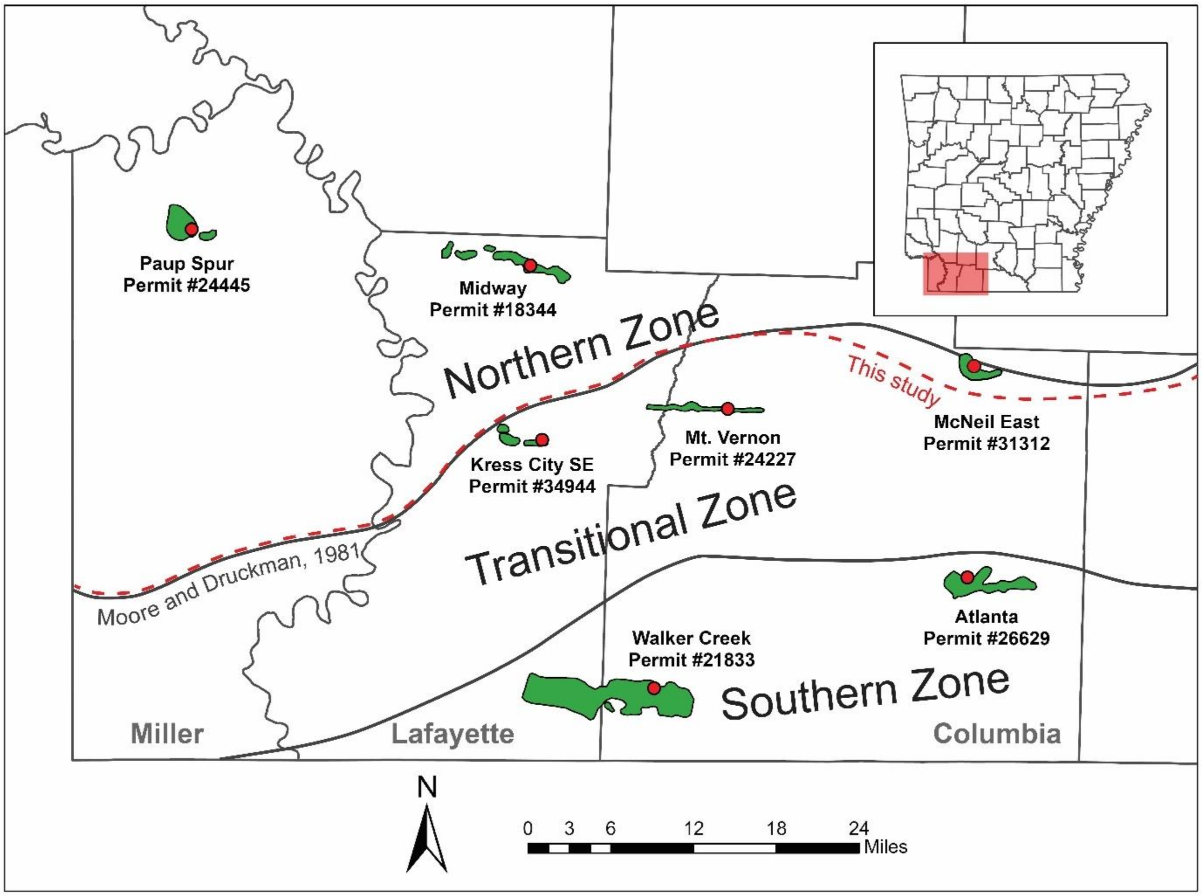

Figure 4. Diagenetic zones identified in this study (Modified after Moore and Druckman, 1981). Oil fields in green and wells in red.

In the southern zone, primary interparticle porosity was the dominant porosity type and secondary porosity (intraparticle, moldic) was uncommon or absent. Ooids were micritized or partially replaced with very fine calcite. Fine equant cement rims sometimes occurred on allochems and were often broken, suggesting that they formed early in the diagenetic history (WF Atlanta 8307’, W.C.3). Multiple intervals lacked cement rims or had very fine, incomplete crusts on allochems, indicating that early cementation was less prevalent than in the northern zone (A.2, W.C.2, W.C.4). Medium to coarse calcite spar was common in interparticle pores, and medium to coarse dolomite spar, poikilotopic dolomite, and baroque dolomite occurred in minor amounts. Samples frequently exhibited moderate to severe compaction features, including pressure solution contacts at grain boundaries, stylolites, and broken grains or rims (W.C.1, W.C.5, A.3).

The transitional zone had characteristics of both the northern and southern zones, though southern zone features were more common. Both physical and chemical compaction features, especially pressure solution contacts, were more widespread than in the northern zone, but weren't as severe as the southern zone. Late calcite spar cement became more common south of the northern zone, and many samples exhibited equant calcite rim cement (M.V.2, K.C.1). Cement in one sample appeared reminiscent of the fine equant calcite mosaic common in the northern zone (K.C.2). The dominant porosity type was primary interparticle, and ooids were micritized and sometimes partially replaced with very fine to fine calcite.

What controls these diagenetic patterns in south Arkansas has long been a topic of debate. There is a consensus that both aragonite and calcite ooids were deposited in the upper Smackover, with primary aragonite mineralogy updip and primary calcite mineralogy downdip (Moore et al., 1986; Swirydczuk, 1988; Heydari and Moore, 1994). Variations in carbonate mineralogy throughout geologic time have been attributed to global-scale changes in atmospheric partial pressure of CO_2 (PCO_2), global sea level, and tectonics (Mackenzie and Pigott, 1981; Sandberg, 1983; Wilkinson et al., 1985). This has led to the assumption that different geologic periods favor either aragonite precipitation (aragonite seas) or calcite precipitation (calcite seas) depending on global climate and tectonics. Scientists have suggested that the Jurassic Period was characterized by calcite seas and therefore calcite was the dominant mineral precipitated (Sandberg, 1983). However, this argument has been challenged by multiple examples throughout geologic history of precipitation of aragonite in a calcite sea or vice versa regardless of PCO_2 levels (Adabi, 2004). For example, in the Upper Jurassic Mozduran Limestone in the Kopet-Dagh Basin in Iran, variations in ooid mineralogy occurred in different parts of the basin, with aragonite ooids precipitating in the shallowest part of the basin and calcite ooids forming below wave base (Adabi and Rao, 1991). Other studies have also recognized this pattern of aragonite precipitation in warm, shallow waters, often in settings with increased evaporation and restricted circulation (Land et al., 1979; Heydari and Moore, 1994; Tedesco and Major, 2012; Lin et al., 2022). While we do not have a definitive answer for primary mineralogy of ooids since geochemical analyses were not conducted for this study, it is reasonable to assume that depositional environment (shallow lagoons and sabkhas closer to the paleoshore and relatively deeper water offshore) may have resulted in bimineralic ooid precipitation in the upper Smackover Formation. Further geochemical analysis is needed to confirm this assumption since inferring primary mineralogy from textures (ex: moldic porosity inferring original aragonite mineralogy, radial fabrics suggesting original calcite mineralogy, etc.) may be unreliable (Sandberg, 1983; Cantrell, 2006).

The dissolution of ooids updip has been attributed to preferential dissolution in an active meteoric water system (Moore and Druckman, 1981; Swirydczuk, 1988; Moore, 2001). However, studies have shown that fabrics once considered diagnostic of meteoric diagenesis (ex: moldic porosity, early calcite spar) can form in marine environments (Melim et al., 1995, 2002; Albader, 2019; Laya et al., 2021). Therefore, we cannot accurately describe a mechanism for dissolution in the northern zone without additional geochemical data.

The patterns of dolomite occurrence throughout the study area were also noteworthy. Moore and others' study (1988) of dolomitization in east Texas and west Arkansas suggested both meteoric water influence and an evaporative-reflux model closely tied to overlying Buckner evaporites. Additionally, other studies of Smackover dolomite across the northern Gulf of Mexico Basin have postulated that several dolomitization processes occurred throughout the burial history of the Smackover (Moore and Druckman, 1981; Prather, 1992; Prather et al., 2023). There is a consensus that some of the dolomitization in the upper Smackover is tied to the deposition of the overlying Buckner (Moore, 1984; Heydari and Keyes, 2003; Prather, 1992; Prather et al., 2023). When examining geophysical logs for the wells in this study, the Buckner Formation was present in all wells except the one in Atlanta Field. The Buckner in the Midway, Mt. Vernon, McNeil East, and Kress City SE wells is likely composed mostly of anhydrite at the base while the Walker Creek and Paup Spur wells had mostly shale at the contact (Plate 1). This may be significant given that the four fields with anhydrite at the base of the Buckner had the greatest overall occurrences of dolomite in thin section. Complete dolomitization of ooid grainstones was present only in the northern zone in the Midway and McNeil East wells immediately below the Buckner-Smackover contact (M.W.1, M.E.1). The Kress City SE well also had significant amounts of dolomite in the uppermost Smackover Formation (WF Kress City SE 8417', 8424'). However, the Mt. Vernon well, which had anhydrite at the Buckner-Smackover contact, only had significant dolomitization at 7957 feet, at least 20 feet below the contact (M.V.4). Further geochemical data is needed to determine the provenance of dolomite.

Only the general order of different periods of dolomitization can be estimated based on petrography. Fine euhedral dolomite is a common occurrence in moldic pores in multiple intervals in the Midway well, suggesting that this was likely a later precipitation event following early calcite cementation and selective ooid dissolution (M.W.4). Poikilotopic dolomite in the McNeil East, Walker Creek, and Paup Spur wells is likely later post-compaction cement because it encases compacted grains and rim cement (M.E.2). The subhedral and euhedral dolomite at 8417 feet and 8424 feet in the Kress City SE well is interpreted as post-compaction cementation or mineralization because some grains appear to crosscut pressure solution contacts. Additionally, the undulose dolomite spar (baroque dolomite) in the Walker Creek well likely formed post-burial since baroque dolomite is considered a late diagenetic cement commonly associated with hydrocarbons (Radke and Mathis, 1980). While there is no conclusion regarding the mechanisms behind dolomitization in this study, the presence of several types of dolomite suggests multiple episodes of dolomitization in the upper Smackover throughout its burial history.

CONCLUSION

In most instances, the locations of Moore and Druckman's (1981) original diagenetic zones remain valid. Selective dissolution of ooids, moldic and intraparticle porosity, and early cement dominate the upper Smackover in its northern extent, and primary interparticle porosity, micritized ooids, late spar cement, and moderate to severe compaction features characterize the southern subcrop. There is no definitive conclusion for primary mineralogy of ooids or the mechanisms behind the diagenetic patterns across the study area due to a lack of geochemical data. Future work to supplement this study should focus on isotopic and trace elemental data.

ACKNOWLEDGEMENTS

The thin sections and descriptions from Weatherford Laboratories were made possible through grant funding from the USGS (Award No. G15AC00294: Reservoir characterization and resource assessment of Upper Jurassic Smackover Formation, south Arkansas). The thin section description reports from Weatherford Laboratories (Appendix 2) are included to provide information for the public. The Office of the State Geologist does not endorse any company listed in this publication. Company logos are retained in the original thin section reports to disclose the name of the laboratory.

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