GCAGS JOURNAL A Publication of the Gulf Coast Association of Geological Societies www.gcags.org

Integrated Carbonate Reservoir Analysis and Modeling, Upper Jurassic Smackover Formation, Fishpond Field, Southwestern Alabama, Northeastern Gulf Coastal Plain

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ABSTRACT

An integrated field study focusing on the Upper Jurassic Smackover microbial buildup and associated carbonate facies at Fishpond Field in Escambia County, Alabama, northeastern Gulf Coastal Plain of North America, provides an opportunity to analyze the development and preservation of a microbial buildup reservoir, including the effects of structural control during deposition of the buildup and associated facies. This study incorporates cores, well logs, and 3D seismic data to characterize the petrophysical and productivity characteristics of the buildup facies, to develop a 3D reservoir model, and to evaluate the influence of differential structural control in buildup development. In the Conecuh Embayment area, Smackover microbial buildups commonly occur on Paleozoic basement paleohighs that generally occur within an inner carbonate ramp setting. The vertical trend in facies indicates repetitive variations in depositional conditions in the area as a result of changes in water depth, energy conditions, and/or water chemistry due to climate variations or changes in relative sea level. Accommodation for sediment accumulation was produced by a rise in relative sea level and a change in base level due to differential movement of Paleozoic basement rocks as a result of extensional faulting and subsidence associated with sediment compaction or thermal processes. At Fishpond Field, these changes in base level contributed to the development of a microbial buildup that ranges from 130-165 ft in thickness. The Fishpond Field carbonate reservoir includes microbial boundstone and grainstone/packstone facies. This field has sedimentary and petroleum system characteristics similar to the neighboring Appleton and Little Cedar Creek fields, but it also exhibits distinct differences when compared to these Smackover fields. The characteristics of the petroleum trap and reservoir at Fishpond Field require modification of the exploration strategy presently in use to identify potential Smackover hydrocarbon reservoirs in the Conecuh Embayment area.

INTRODUCTION

Oil from the Smackover Formation has been the most sought-after hydrocarbon in southern Alabama since the discovery of Toxey Field in 1967. This find, along with the discovery of other fields associated with Paleozoic basement highs, resulted in an exploration strategy that targeted paleohighs by using 2D seismic reflection data and, later, 3D data. Shoal and shoreface grainstone facies were found to have accumulated on the crest and flanks of these paleotopographic features (Markland, 1992; Mancini et al., 2000, 2004, 2008). The discovery of Melvin (1976) and Uriah (1970) fields indicated that microbial reservoirs were present in southern Alabama and could be exploration targets (Mancini et al., 2004, 2008). The discovery of Vocation Field in 1971 showed that thick microbial buildups developed in association with Paleozoic structure and that isolated paleohighs can support reservoirs with significant areal extent and with the potential to produce more than 1 million bbls of oil (Mancini et al., 2004).

Manuscript received April 6, 2020; revised manuscript received July 25, 2020; manuscript accepted July 22, 2020.

GCAGS Journal, v. 9 (2020), p. 28–40.

In southwestern Alabama, the Conecuh Embayment and updip limit of the Smackover Formation have been areas of particular interest for the state's oil and gas industry over the last two decades (Fig. 1). With the discovery of Little Cedar Creek (2004) and Brooklyn (2010) fields, the search for stratigraphic traps became the most popular exploration strategy. This was due to the large accumulations of oil in these petroleum traps, as well as the fact that, during this period, the basement ridge play yielded few major discoveries. As Little Cedar Creek Field developed, a large 3D seismic survey was acquired that assisted in the discovery of neighboring Brooklyn Field. Little Cedar Creek and Brooklyn fields both consist of a combination of a lower microbial boundstone facies and an upper grainstone/packstone facies. Development of the microbial buildup deposits in Brooklyn Field was impacted by pre-Smackover paleotopography (Mancini et al. 2019). These features have low relief compared to structures such as those associated with Appleton (1983) or Vocation fields.

The discovery of Brooklyn Field to the south of Little Cedar Creek Field and its subsequent development brought continued exploration focus to the area, leading to the discovery of Fishpond Field in Escambia County, Alabama, by Sklar Exploration Company in 2014. As of March 2020, according to the records of the State Oil and Gas Board of Alabama (SOGBA), Fishpond Field has produced 1,852,367 barrels of crude oil (BO). The field has a productive reservoir interval of up to 140 ft in net thickness and is characterized by high porosity and permeability as documented by core analyses and well logs from the wells in the field.

In 2007, Midroc Operating Company drilled the Cedar Creek Land and Timber 10–9 well (SOGBA permit 15383) south of the Little Cedar Creek Field, which turned out to be a dry hole. In March 2014, Sklar Exploration Company drilled a wildcat well, the Cedar Creek Land and Timber 10–5 #1 (SOGBA permit 16990) in the area. It was the first well to produce from the newly discovered Fishpond Field reservoir. The original flow rate for the well was 414 barrels of oil per day (BOPD). Two months later, Sklar drilled the Cedar Creek Land and Timber 9–8 #1 well (SOGBA permit 17021), which tested at 560 BOPD. By December 2014, these wells reached their highest combined production of 2213 BOPD. Finally, Sklar stepped out and drilled the Cedar Creek Land and Timber 9–3 #1 (SOGBA permit 17033), which was found to have very little productive pay. This well was subsequently plugged and abandoned. Using the information obtained from the drilling of well permits 15383 and 17033, the extent of Fishpond Field can be

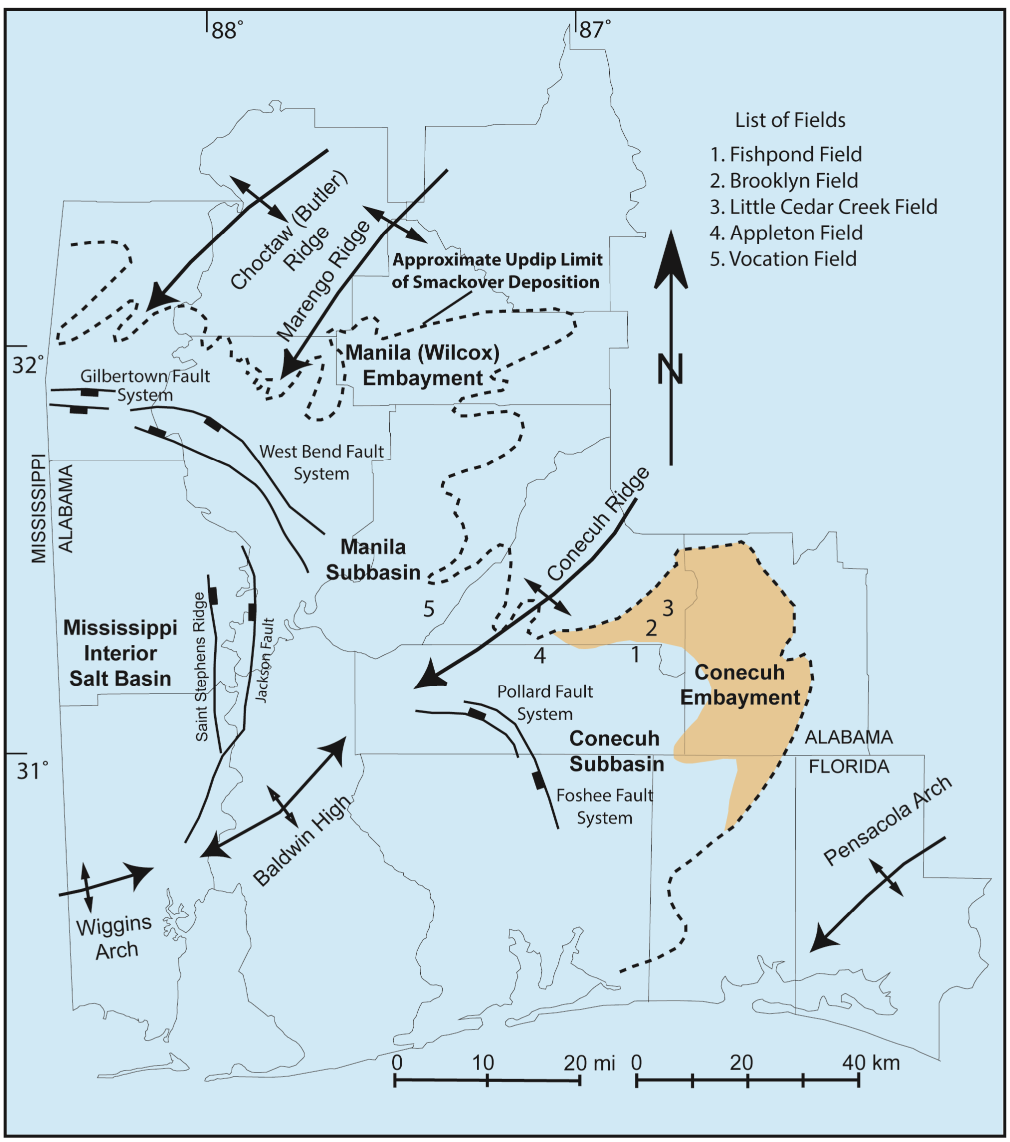

Figure 1. Location of Fishpond Field and the major Jurassic structural features and basins and subbasins in southwestern Alabama constructed using data and information from Wilson (1975), Mancini and Benson (1980), Benson (1988), Tew et al. (1991), Kopaska-Merkel (2002), and Mancini et al. (2019).

delineated. On the basis of data from the two producing wells, along with 3D seismic data, Sklar Exploration petitioned the SOGBA to establish Fishpond Field as a separate reservoir from the neighboring Brooklyn Field to the immediate north and the SOGBA granted Sklar's petition in March 2015. After one year of production from both wells, the field was unitized and well permit 16990 was converted into a gas injection well to optimize production from well permit 17021. Well permit 17021 is now the only producing well and, as of March 2020, was still producing over 360 BOPD.

PETROLEUM TRAP

The carbonate ramp depositional model, which was proposed by Ahr (1973) and subsequently modified by Burchette and Wright (1992), Ahr (2008) and Mancini et al. (2019), has been used to interpret the Upper Jurassic Smackover carbonate sediment accumulation and distribution patterns in the onshore Gulf of Mexico by exploration companies and academicians alike (Mancini et al., 2019). Structure maps on the top of the Norphlet and Smackover formations show that the carbonate ramp in the Conecuh Embayment area can be tracked from the northeast, where the most updip Smackover deposits in the embayment occur, to downdip areas in the southwest, with progressively increasing depths to these units (Fig. 1). Ahr (1973) indicated that variations in topography on a ramp are related to salt tectonics or paleostructure. In the Conecuh Embayment area, paleotopographic highs consist of faulted Paleozoic basement features (Mancini et al., 2004). These structures can potentially facilitate the development of microbial buildups under certain conditions, as microbial buildups generally occur on structural highs and are interpreted to be associated with changes in water conditions at the time of deposition. The lateral extent of microbial buildups is limited by the size and shape of paleohighs.

In the Fishpond Field area, deposition of the Norphlet Formation was impacted by a large structural feature in close proximity that created a source of abundant eroded siliciclastic materials. In the Conecuh Embayment, Norphlet siliciclastics generally have not been found to be deposited on the crests of topographic highs, but rather they are typically found pinching out or terminating on the flanks of these features (Llinas, 2004). However, in Fishpond Field, Norphlet deposits are present on the crest of the paleohigh as observed in well logs and cores.

The Smackover Formation in the Fishpond Field area was deposited on the crest and flanks of an elevated feature on the seafloor, but the Smackover reservoir in the field is restricted to the crest of the paleohigh (Fig. 2). The quality of the reservoir facies in the field indicates that Smackover depositional and post-depositional conditions over the crest were favorable for the origination, enhancement, and preservation of porous and permeable carbonates. Therefore, the petroleum trap at Fishpond Field is a combination structural and stratigraphic trap. The stratigraphic component consists of a facies change from porous grainstones/packstones and boundstones, isolated on the crest of the structural high, that transition to nonporous packstones and wackestones rimming the feature. Numerous stylolites filled with oil, found throughout the cores of the Smackover Formation in Fishpond Field, suggest that oil migration was facilitated as a result of pressure solution and compaction. Stained Norphlet sandstone below the Smackover at Fishpond indicates that oil may have migrated through the base of the formation. This would explain why the oil column at Fishpond Field spans almost the entire thickness of the Smackover Formation with no evident oil/water contact.

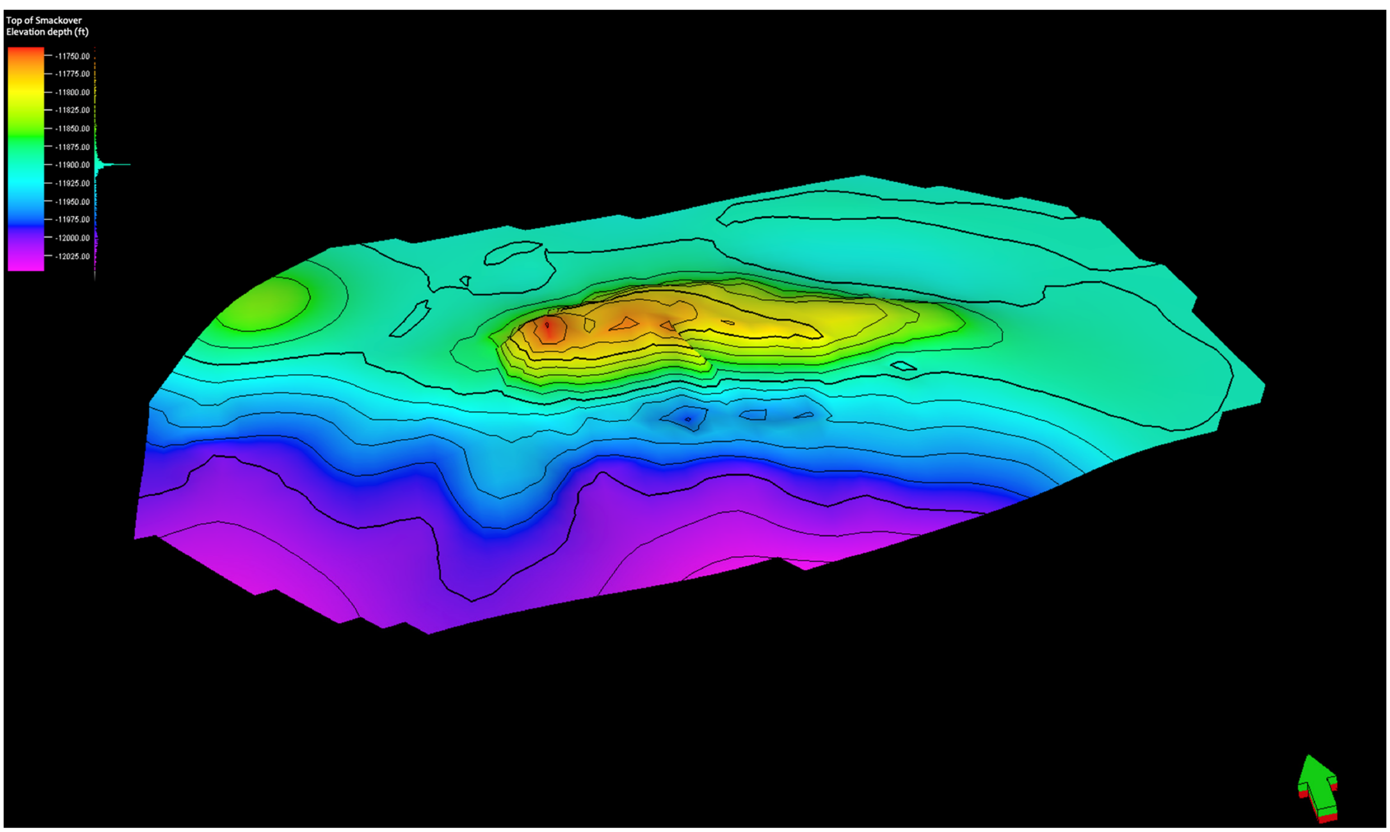

Figure 2. Structure map on top of the Smackover Formation, Fishpond Field. The structure map is derived from Exhibit 5 of Docket No. 3–24–15–19, State Oil and Gas Board of Alabama (SOGBA) (2015).

RESERVOIR

Fishpond Field consists of a variety of reservoir-grade facies that form a unique build-up, interpreted to have accumulated with increasing accommodation space. Multiple studies conducted at Appleton and Little Cedar Creek fields have described the lithofacies present and have provided a general expectation for regional facies patterns. However, these studies do not represent depositional facies and their sequence at Fishpond Field, probably due to the field's updip location and the environmental changes that affected depositional patterns in the inner ramp area of the Conecuh Embayment. Through the integration of well log signatures, core information, and thin-section analysis from well permits 16990 and 17021, seven distinct lithofacies are identified in the Smackover at Fishpond Field (Fig. 3). These lithofacies include: (F–1) Peloidal Wackestone (Fig. 3A), (F–2) Peloidal Packstone (Fig. 3B), (F–3) Peloidal Grainstone (Fig. 3C), (F–4) Peloidal Grainstone/Packstone (Fig. 3D), (F–5) Microbially-Influenced Packstone (Fig. 3E), (F–6) Microbially-Influenced Wackestone (Fig. 3F), and (F–7) Microbial Boundstone (Figs. 3G–3I). Three additional facies—the (F–8) Ooid Packstone, (F–9) Shale, and (F–10) Dolomitized Wackestone/Packstone—were identified outside of the field in the two adjacent wells (well permits 17033 and 15383).

The peloidal grainstone, peloidal packstone, peloidal grainstone/packstone and the microbial boundstone facies comprise the best reservoir beds in the field and are characterized by very high porosities (averaging 11–20%) and permeabilities ranging from approximately 0.5 md to 7010 md. The reservoir quality of these rocks is directly affected by the amount and type of diagenesis that alters their original textures. Dissolution and cementation can drastically modify permeability associated with these rocks in either a positive or negative manner, respectively (Fig. 4).

The lithofacies in the studied wells occur in a characteristic vertical succession. The Upper Jurassic Smackover Formation unconformably overlies the Norphlet Formation at Fishpond Field. The Norphlet consists of fluvial-alluvial and coastal eolian and shoreline conglomerates, sandstones, and shales. The upper Norphlet facies appear to have been reworked with the initiation of marine transgression. The Smackover microbial buildup sequence begins with microbially-influenced wackestone or microbially-influenced packstone and then grades into microbial boundstone. This boundstone is capped with peloidal packstone, peloidal grainstone/packstone or peloidal grainstone. In well permit 16990, four such sequences were observed and in well permit 17021, eight sequences were observed. Peloidal wackestone completes the Smackover succession and the Buckner Member of the Haynesville Formation overlies the Smackover Formation. This formational contact is observed to be gradational or sharp depending on the location of the well in the Conecuh Embayment. The upper Haynesville Formation overlies the Buckner and includes carbonate, sand, and shale.

The majority of rocks analyzed for this study are peloidal. *Parafavreina* pellets (Rindsberg and Kopaska-Merkel, 2013) are found throughout, but are most common in facies associated with a lower energy environment. For example, the peloidal wackestone facies (Fig. 4A) is found to have a low number of grains that include peloids, foraminifera, and gastropods, thus indicating lower energy conditions. Some siliciclastics are present in the form of quartz silt. The argillaceous silt influx into the carbonate system is interpreted to be due to local rivers and streams flowing into this part of the embayment from updip highland areas associated with the Appalachian structural front. In some places, micrite in the peloidal wackestone appears to be recrystallized. However, this recrystallization did not alter the rock enough to create significant porosity or permeability.

The peloidal packstone facies (Fig. 4B) consists largely of peloids, with bivalves, echinoids, and *Tubiphytes* making up a small percentage of the rock. This facies is heavily compacted in some areas while exhibiting significant amounts of leaching in others. It appears that large clusters of peloids were leached early, while early-stage cement was leached later.

The peloidal grainstone facies (Fig. 4C) is very similar to the packstone facies, but it does not have any original mud matrix among the allochems. The majority of allochems are peloids and bioclasts (which may be reworked microbialite fragments). Some grains are covered with early-stage fibrous marine cement with late-stage, blocky cement (in the larger pore spaces).

The peloidal grainstone/packstone facies (Fig. 4D) resembles the grainstone and packstone facies, but cannot be placed into a single category. The fabric is not homogeneous on the scale of a thin section. The microbially-influenced packstone facies (Fig. 4E) is found to have had large numbers of calcimicrobes which produced its current well-preserved fabric. This facies was probably porous at one time but much of its porosity has been occluded by cementation. The microbially-influenced wackestone facies (Fig. 4F) is similar to the microbially-influenced packstone facies but had less microbial activity and fewer grains. This is likely due to a lower-energy environment with water chemistry negatively affecting microbial activity.

The microbial boundstone facies (Figs. 4G and 4H) is by far the most distinctive facies in the succession and therefore the easiest to identify. This facies is characterized by pervasive dissolution of the depositional growth (intraframe) fabric (Al Haddad, 2012). The pore network is characterized by vuggy, interconnected pores that have vertical and lateral continuity. Patches of cyanobacteria formed in large clusters throughout the buildup (Owen, 2017). Clotted fabrics are common in intervals exhibiting high primary porosity, as well as those with secondary porosity caused by dissolution. Other porosity types are formed from fractures and nonselective dissolution that created the vuggy pores. The boundstone of this facies was susceptible to extensive alteration, including high amounts of neomorphism, due to its composition and fabric. In some parts of the reservoir, it appears that the rock has been completely recrystallized as evidenced by a change in color and fabric.

Although the principal control on reservoir architecture and geographic distribution in Smackover carbonates is the depositional facies, diagenesis (chiefly dissolution and dolomitization) is a significant factor that can preserve and enhance reservoir quality (Benson, 1988; Kopaska-Merkel et al., 1992; Mancini et al., 2004). At Fishpond Field, dissolution has served to increase porosity and permeability in the microbial carbonate and associated facies. Dolomitization is minimal in the field. Some fracturing is evident in these carbonates. Compaction, pressure solution, cementation, and recrystallization have acted to occlude porosity in Fishpond Field. These facies experienced both early-stage, selective and late-stage, non-selective dissolution. Allochems have been partially leached or totally dissolved and some are no longer identifiable.

Fishpond Field's reservoir facies are interpreted to have developed as a microbial buildup on a paleohigh in an inner ramp setting. The buildup is characterized by multiple sequences of alternating facies. Off the paleohigh, the rocks consist of nonreservoir grade packstone/wackestone and shale in well permits 17033 and 15383. These facies have little to no porosity and permeability, which limits lateral petroleum migration. The initial microbial boundstone facies is found in the base of both productive wells (well permits 17021 and 16990). During development of the buildup, lower Smackover depositional conditions varied as evidenced by the multiple stages of vertical microbial growth in the field. On the eastern side of the field, a zone consisting of interbedded peloidal packstone and grainstone within the buildup is observed, whereas on the western side, a uniform buildup of thrombolite boundstone is evident. In well permit 16990, the buildup consists of interbedded dendritic and reticulate thrombolite. In the field area, the middle part of the Smacko-

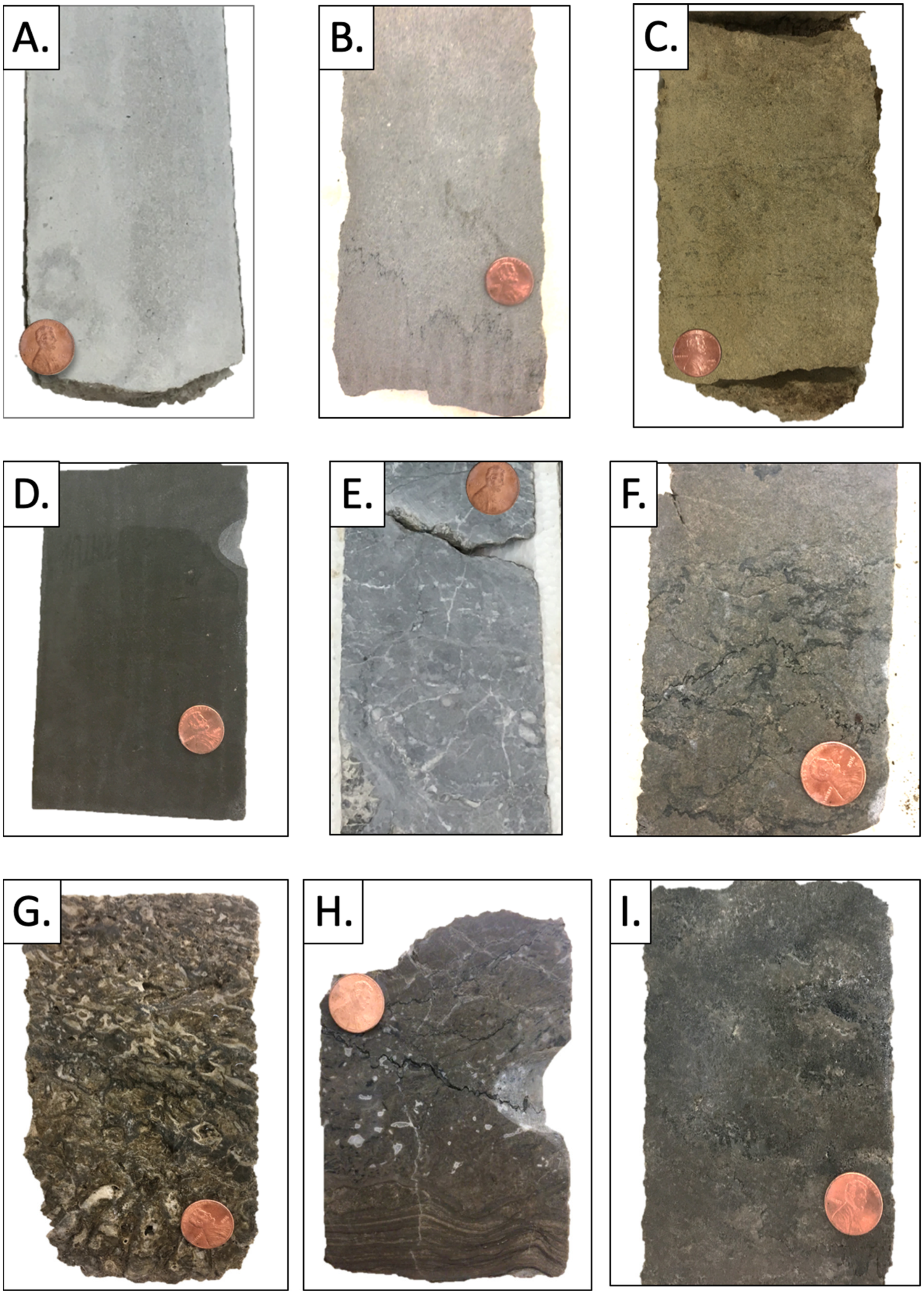

Figure 3. Core photographs of Smackover lithofacies: (A) Peloidal Wackestone, well permit 16990, 12124 ft (3695 m); (B) Peloidal Packstone, well permit 17021, 12265 ft (3738 m); (C) Peloidal Grainstone, well permit 17021, 12258 ft (3736 m); (D) Peloidal Grainstone/Packstone, well permit 17021, 12311 ft (3752 m); (E) Microbially-Influenced Packstone, well permit 17021, 12108 ft (3690 m); (F) Microbially-Influenced Wackestone, well permit 16990, 12240 ft (3730 m); (G) Reticulate Microbial Boundstone, well permit 16990, 12139 ft (3699 m); (H) Laminated Microbial Boundstone, well permit 17021, 12141 ft (3700 m); and (I) Dendritic Microbial Boundstone, well permit 16990, 12269 ft (3739 m).

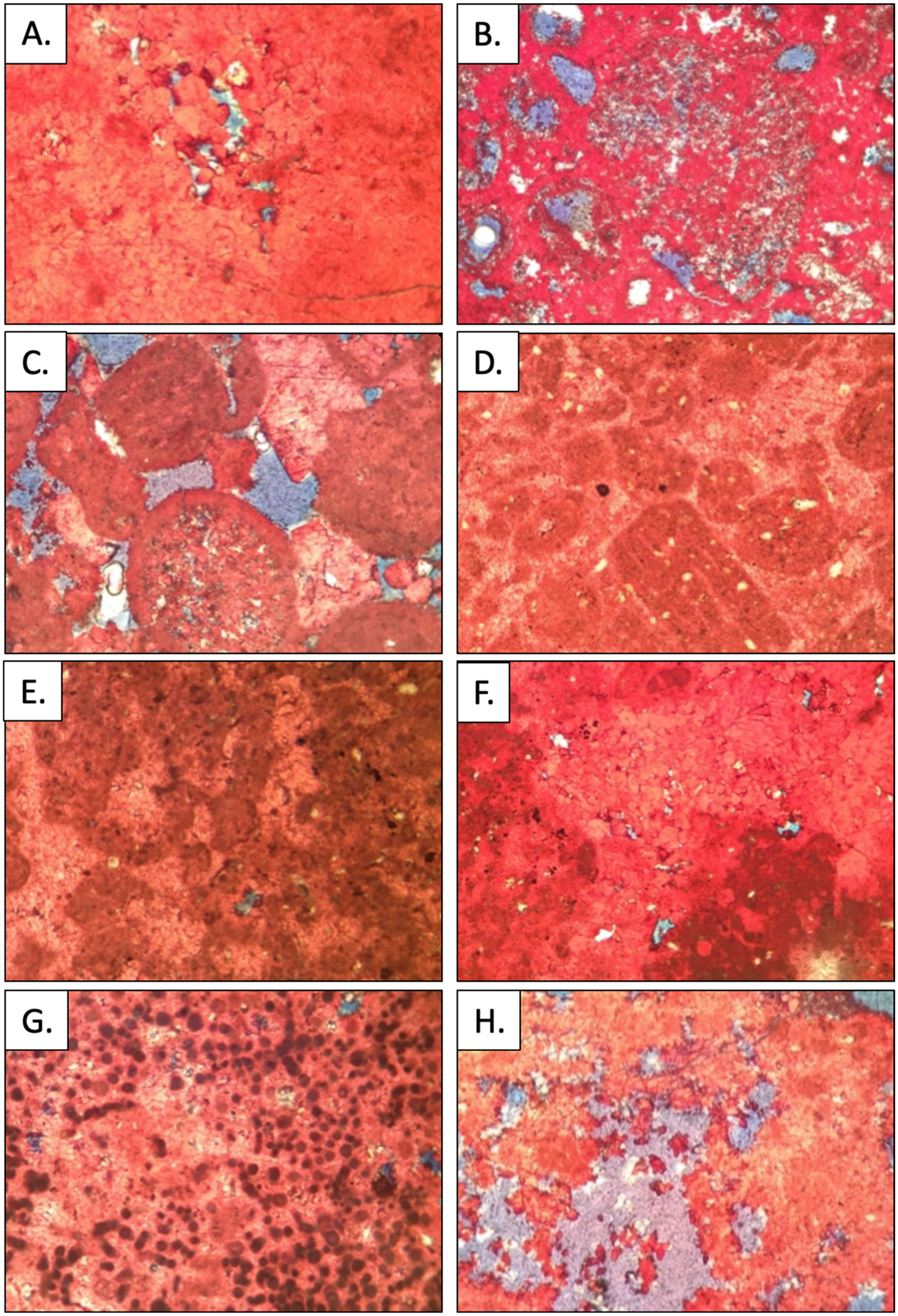

Figure 4. Photomicrographs of Fishpond Field Smackover facies types: (A) low energy micrite, peloidal wackestone, well permit 17021, 12186 ft (3714 m); (B) solution-enlarged primary pores and diagenetic moldic pores, peloidal packstone, well permit 17021, 12197 ft (3717 m); (C) solution enlarged primary pores, peloidal grainstone, well permit 17021, 12218 ft (3724 m); (D) heavily compacted and calcite cemented pores, peloidal grainstone/packstone, well permit 16990, 12227 ft (3726 m); (E) microbially-influenced packstone, well permit 16990, 12124 ft (3695 m); (F) microbially-influenced wackestone, well permit 17021, 12141 ft (3700 m); (G) microbial boundstone fabric, well permit 16990, 12139 ft (3699 m); and (H) depositional intraframe, solution-enlarged primary and diagenetic vuggy pores, microbial boundstone, well permit 17021, 12284 ft (3744 m).

ver was characterized by more uniform deposition of microbially influenced wackestone that separates the main boundstone intervals. Microbial colonies then renewed their growth and continued to develop across the buildup until grading into a microbial-influenced packstone. A high-energy subtidal shoal of grainstone/packstone was deposited in the upper part of the Smackover and serves as a thin reservoir that is separate from the underlying microbial reservoirs. In the field area, Smackover deposition concluded with the accumulation of peloidal wackestone, which caps the succession and grades upwards into anhydrite of the Buckner Member of the Haynesville Formation.

Fishpond Field's depositional sequences can be divided into three major reservoir zones: a lowermost microbial boundstone, an uppermost microbial boundstone and a grainstone/packstone interval that separates the boundstone intervals. The grainstone/packstone zone is thickest on the western side of the field, but the microbial boundstone is thick throughout the field. Each of these zones has different petrophysical properties and an understanding of these can be helpful in optimizing production from the overall reservoir. Well permit 17021 has 140 ft of net pay, whereas well permit 16990 has 113 ft. These net pay zones are thick despite the fact that the reservoir underwent differential compaction and pressure solution resulting in the formation of numerous stylolites. These microbial buildups might have been much thicker before compaction.

DEPOSITIONAL MODEL

The Conecuh Embayment area underwent a series of extensional faulting episodes due to the rifting of the North and South American plates during the Mesozoic fragmentation of Pangea. The pre-Jurassic Fishpond Field area is interpreted here to have formed in an active normal fault-bounded graben with an adjacent horst structure (Fig. 5). Norphlet deposition in the Conecuh Embayment began in Middle to Late Jurassic times. Alluvial and fluvial red shale and eolian and coastal sandstone were deposited on low-lying basement in the Fishpond Field area. After an increase in extension, the Fishpond Field structure was formed as the area was uplifted in association with a horst structure. In the model proposed by Mancini et al. (2019), Norphlet deposits were preserved on the crest of the horst. These sandstones were reworked at the initiation of a rapid Smackover transgression. The first Smackover facies that accumulated was peloidal wackestone followed by microbially-influenced packstone and microbialite with a continued rise in relative sea level. Depositional conditions in the area varied with differential basement fault movement across the field area. Higher energy characterized some areas of the field due to localized environmental conditions or due to variation in the depositional surface relief and availability of accommodation space. Movement along basement extensional faults resulted in different structural elevations in the field. These differences produced a higher energy environment in the western part of the field, while microbialites continued to grow in the eastern part of the field. With continued rise in relative sea level, more uniform environmental conditions returned with deposition of wackestone and microbial carbonates across much of the area. As accommodation space increased due to a continued rise in relative sea level and probably due to subsidence as a result of continued sedimentation and compaction of Norphlet shale, microbial carbonate aggradation continued in parts of the field and the deposition of subtidal wackestone and packstone characterized other parts. Development of microbial buildups is interpreted to have ceased because of changes in environmental conditions, including an influx of freshwater and mud containing terrestrial-derived plant material (Niemeyer, 2011). Shale deposition was abundant on the flanks of the Fishpond structure. With continued subsidence and relative sea level rise, subtidal wackestone accumulated throughout the field area. Migration of thermal fluids associated with faulting is assumed to have dolomitized the lower beds of the Smackover Formation on the flanks of the field's structure. Availability of accommodation space then decreased due to a reduction in the rise of relative sea level and subsidence and an increase in sedimentation rate. These changes resulted in higher energy shoreface, shoal, and carbonate bank grainstone/packstone and lagoonal deposits prograding over the field area. Deposition of these facies marked the shift from marine transgression to progradation. Smackover deposition ended with the accumulation of lagoonal/bay wackestone. Accumulation of marginal marine and nonmarine Haynesville shale and anhydrite followed.

PETROPHYSICAL PROPERTIES

The Fishpond Field reservoir is characterized by multiple microbial growth phases, which can be divided into distinct porous and permeable zones that have varying petrophysical properties (Fig. 6). These reservoir zones consist of microbial boundstone in the lower to middle part of the Smackover section, a grainstone and packstone zone that overlies it, and an upper microbial boundstone zone that grades into microbially influenced packstone with a thin grainstone/packstone interval at the top of the Smackover section. This uppermost grainstone/packstone unit correlates to a reservoir zone in the upper part of the Smackover section in neighboring Brooklyn Field. In well permit 17021, the reservoir is composed of the microbial boundstone and grainstone-packstone facies. Figure 6 shows that the lower to middle boundstone zone has an average porosity of 11% and an average permeability of approximately 305 md, due to its inherent pore system of depositional growth (intraframe), plus diagenetic solution-enhanced and vuggy pores. The grainstone and packstone zone is much thicker in well permit 17021 than in other parts of the field. This zone has a higher average porosity than the underlying boundstone, due to its primary and solution enhanced pores. This grainstone/packstone zone has an average porosity of approximately 20%. The average permeability in this zone is over 45 md, which is an indicator of connectivity in the reservoir resulting in observed high hydrocarbon productivity. The upper boundstone zone has less production potential in well permit 17021 than in well permit 16990. In well permit 17021, the upper boundstone has an average porosity around 10% due to greater compaction and cementation (visible in thin section). Permeability ranges from 0.5 to 7000 md in the microbial boundstone and grainstone/packstone zones in this part of the field. The variability in porosity and permeability is attributed mainly to diagenetic effects. The lower to middle boundstone and grainstone/packstone zones are inferred to have the highest productivity in well permit 17021 due to higher average porosities and permeabilities than those found in the upper boundstone zone. The microbially influenced packstone and grainstone/packstone facies found in the upper Smackover section lack sufficient porosity or permeability to contribute to production.

In well permit 16990, the lower to middle boundstone, the middle grainstone/packstone, and upper boundstone zones were evaluated for the same petrophysical properties as in well permit 17021. All of the zones were characterized by high average porosities and permeabilities. The lower to middle boundstone zone has an average porosity of 19% and an average permeability of approximately 246 md due to its depositional texture and inherent pore system. The grainstone/packstone occurring between the lower to middle and upper boundstone zones in well permit 16990 has a lower average porosity than is found in the equivalent zone in well permit 17021, but has a similar permeability. The decrease in porosity in this zone is attributed to the cementation and compaction of the carbonate texture of the microbially-influenced packstone and wackestone. These facies are not as susceptible to dissolution as a packstone or grainstone. The upper boundstone zone in well permit 16990 has an average porosity of around 14%, which is higher than in the upper boundstone

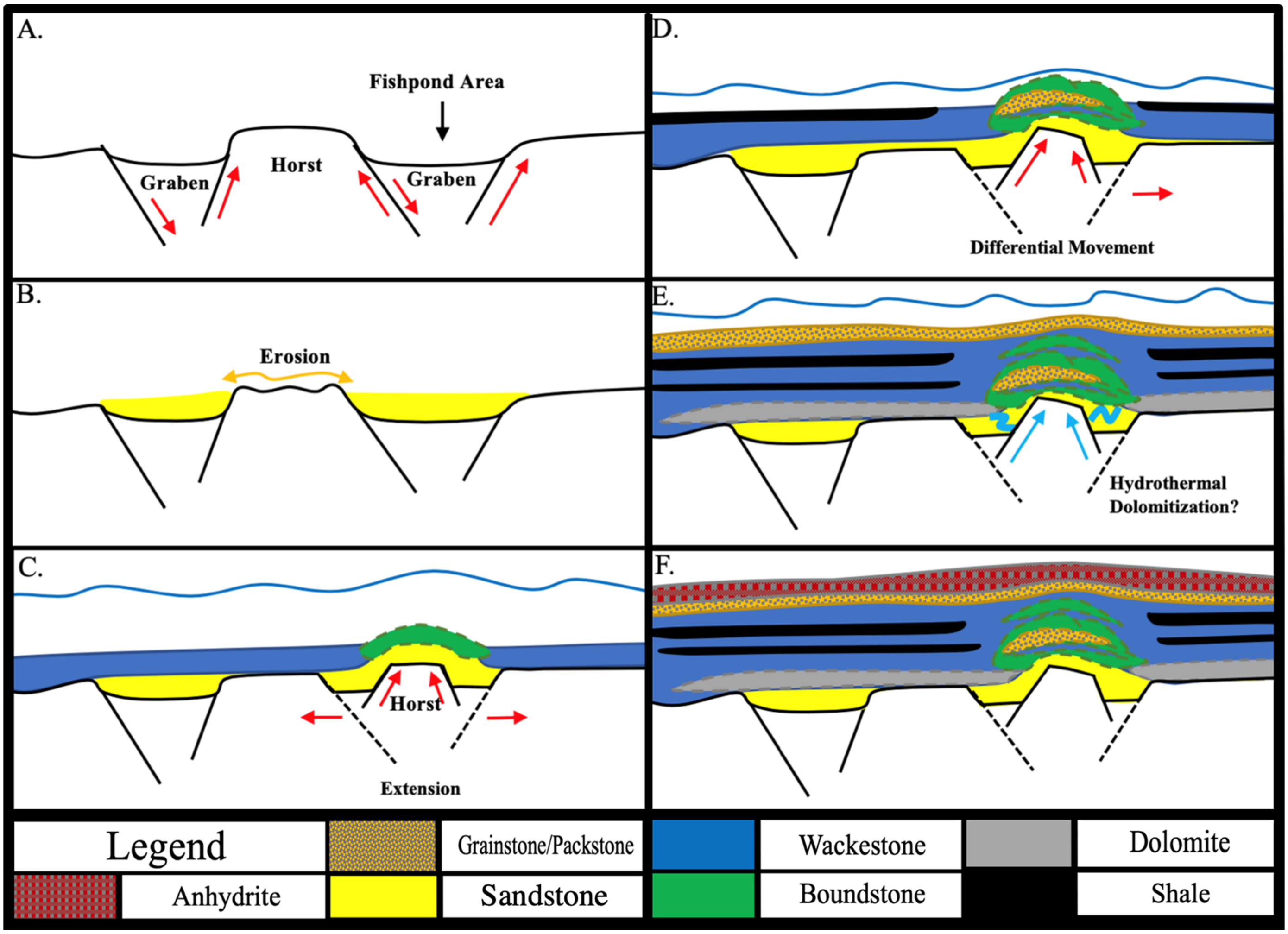

Figure 5. Depositional history of facies in the Fishpond Field area: (A) Pre-Jurassic Fishpond Field area undergoing extensional faulting; (B) horst feature erosion creating Norphlet deposition in the Fishpond Field area; (C) Smackover Formation aggradation with microbial buildup development; (D) horst feature movement resulting in Smackover Formation depositional changes. Siliciclastic deposition begins resulting in microbial buildup growth ceasing and Smackover grainstone/packstone facies being deposited; (E) Smackover Formation deposition ends with regressive grainstone/packstone facies being deposited regionally and hydrothermal dolomitization begins altering lower Smackover facies in the offset areas to Fishpond Field; and (F) Buckner Anhydrite Member of the Haynesville Formation is deposited and serves as a petroleum seal rock for the underlying Smackover Formation.

zone in well permit 17021. The average permeability of the upper boundstone zone is approximately 100 md. Dissolution is considered to be the main contributor to the high permeabilities in the microbial boundstone zones in well permit 16990, resulting in a pore system characterized by solution-enhanced and vuggy pores. Based on the porosity and permeability values, the microbial boundstone zones in well permit 16990 have the potential to be the most productive intervals in the western side of the field. The grainstone/packstone zone in the upper part of the Smackover was not cored in well permit 16990, but on the basis of well-log information, it is interpreted to have the same minimal productivity profile as in well permit 17021, and probably does not contribute to production.

FACIES EVALUATION

The seven facies found within Fishpond Field were analyzed in the two producing wells for permeability/porosity relationships. The cross-plots serve to illustrate the differences in the quality of the reservoir rock due to variations in petrophysical properties as a result of different Smackover carbonate facies, textures and pore systems (Figure 7). In well permit 17021, the microbial boundstone facies has the highest potential for hydrocarbon productivity because its pore system produces high average permeability of approximately 300 md. The microbial boundstone facies and peloidal packstone facies have parallel trend lines for porosity values, while the peloidal packstone facies has a slightly lower average permeability due to its pore system. This indicates that these two facies both have a high potential to be reservoir rock of good quality, but the microbial boundstone facies texture and pore system results in higher permeability and connectivity. The one facies that was found in well permit 17021 and not in well permit 16990 was the peloidal grainstone facies. This facies has a relatively high average permeability, but its average porosity was less than that of the peloidal grainstone/packstone and microbial boundstone facies due to oolitic framework with very little particle leeching; partial dissolution of interparticle calcite cement; and the intrusion of late stage blocky cement negatively impacting pore space. The peloidal wackestone facies and microbially-influenced packstone faci-

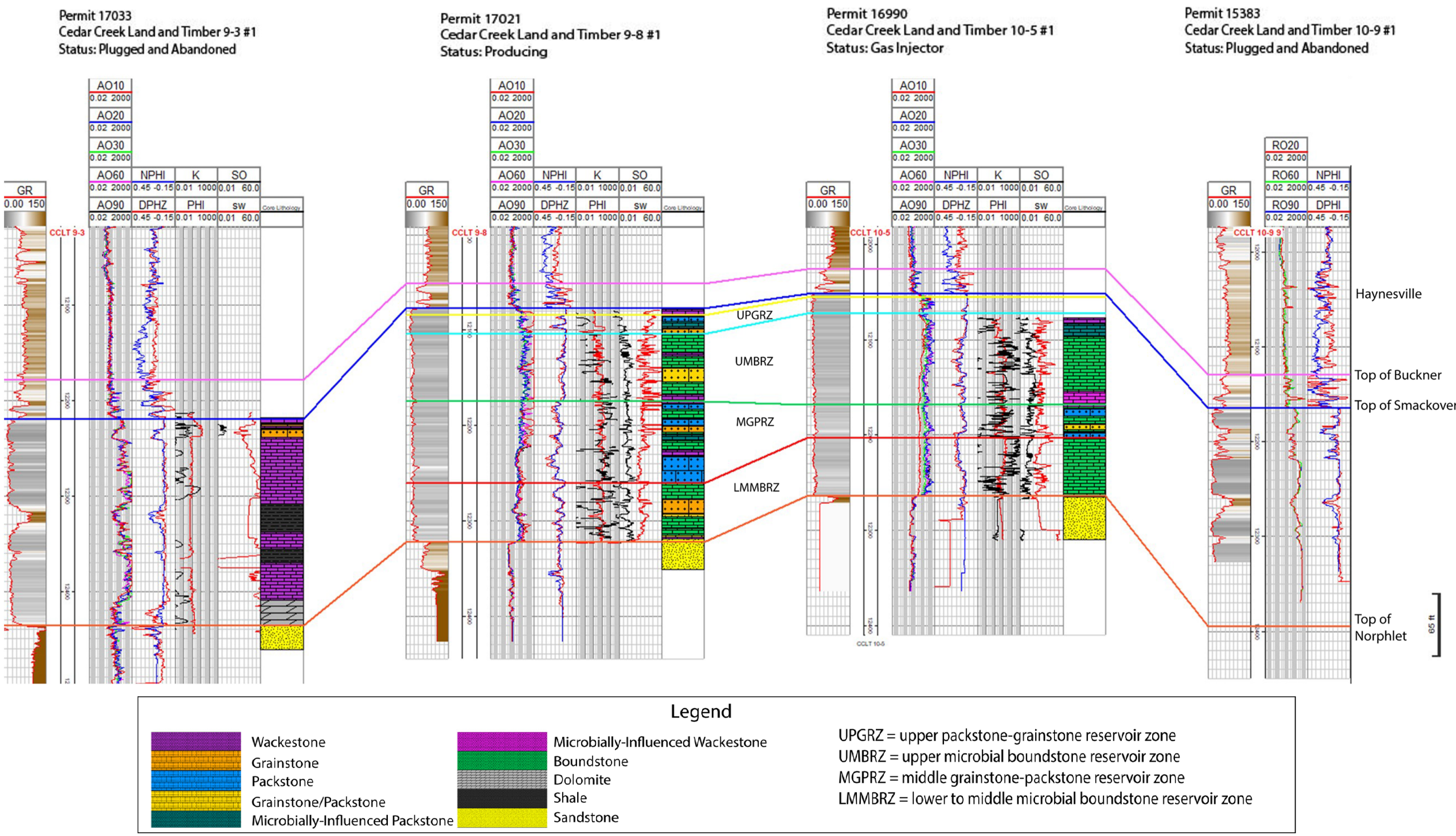

Figure 6. Petrophysical log suite cross section of strata in Fishpond Field from west to east: Well permits 17033, 17021, 16990, and 15383. Logs include: gamma ray (GR), array induction resistivity (AO), neutron porosity (NPHI), density porosity (DPHZ), core porosity (PHI), core permeability (K), core water saturation (SW), oil saturation (SO), and core lithology.

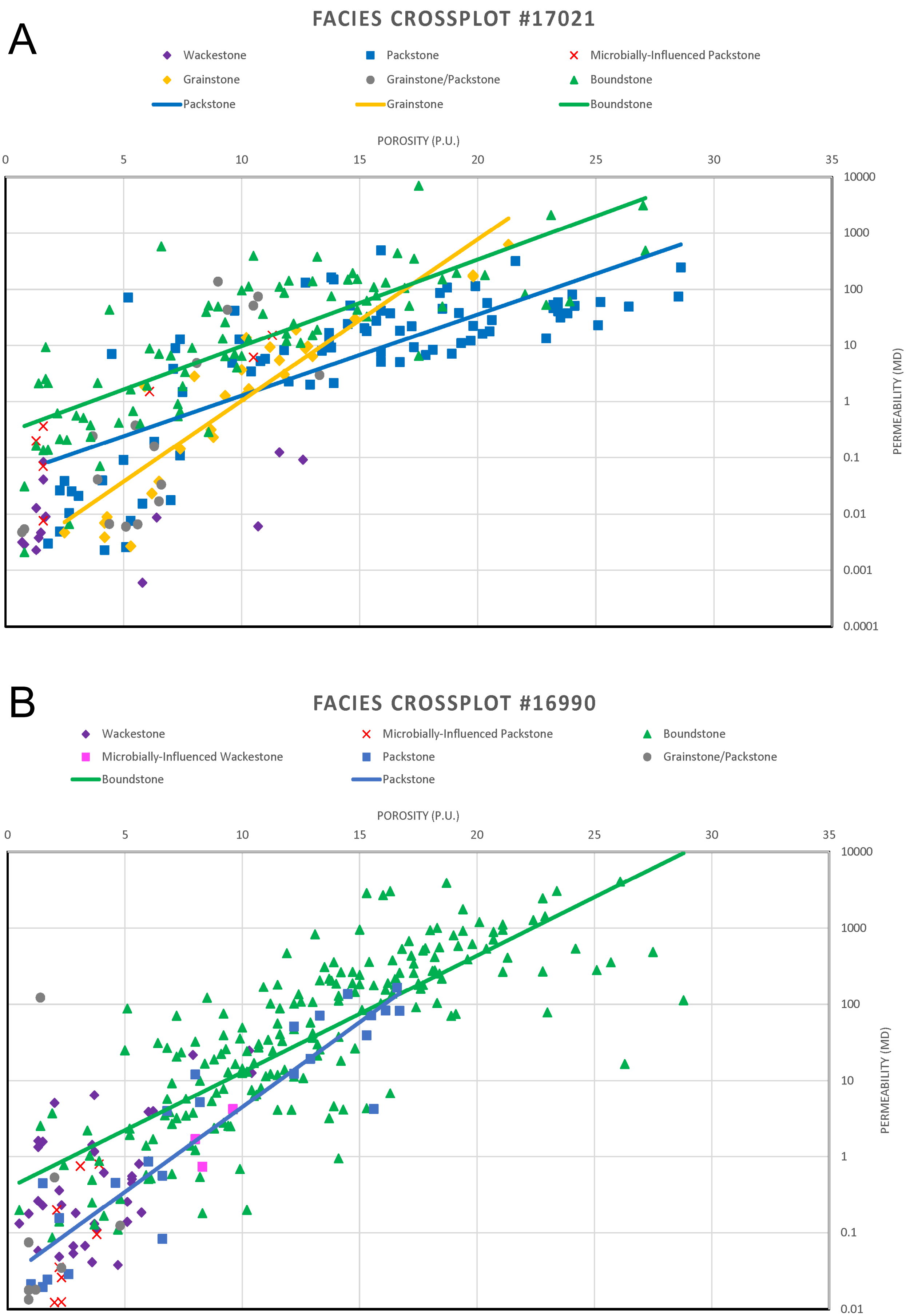

Figure 7. Porosity-permeability cross plots for Smackover facies observed in (A) well permit 17021 and (B) well permit 16990 in Fishpond Field. Data from core analysis.

es have low porosity and permeability due to their depositional textures and pore systems, and therefore, these facies have low reservoir potential.

In well permit 16990, the microbial boundstone facies is the most productive reservoir. It has an average trend line that matches that of well permit 17021. However, well permit 16990's peloidal packstone facies has a slightly lower average porosity and does not have a trend line parallel to that of well permit 17021. This change in trend line suggests a probable facies change from peloidal packstone in well permit 17021 to microbial boundstone in well permit 16990. This is proven by there being very little peloidal packstone found in well permit 16990. Thus, the composite porosity data for the peloidal packstone facies that is found in well permit 16990 indicates this facies has low potential to be of high reservoir quality.

FIELD COMPARISON

To assist with interpreting the geological history and evaluating the significance of Fishpond Field, the petroleum trap and associated reservoir at this field are compared to the petroleum traps and associated reservoirs at Appleton and Little Cedar Creek fields (Fig. 1). Fishpond Field's petroleum trap is similar to the combination structural and stratigraphic trap at Appleton Field (Mancini et al., 2004) rather than the stratigraphic trap at Little Cedar Creek Field (Mancini et al., 2008). Buckner anhydrite beds serve as a seal rock at Appleton (Mancini et al., 2004) and Fishpond fields, as observed in cores and well log signatures. However, during Smackover time, the basement paleohigh at Fishpond Field was not continuously submerged (below sea level) (as at Appleton Field) or continuously exposed (above sea level) (as at Vocation Field). The depositional history of the paleohigh at Fishpond Field is more complex, as evidenced by the vertical changes in Smackover lithofacies observed in cores and well log patterns. This paleotopographic high was flooded and possibly exposed during Smackover time. Although changes in relative sea level played a major role in Smackover accumulation and sediment reworking in the Fishpond Field area, subsidence resulting from differential movement of basement rocks related to the activation of basement faults and sediment burial compaction were also critical elements that impacted Smackover deposition.

The principal reservoir in Fishpond Field consists of microbialites associated with buildups similar to the main reservoirs in Appleton and Little Cedar Creek fields. The microbial boundstone at Fishpond Field is not pervasively dolomitized like the doloboundstone in Appleton Field (Mancini et al., 2004), rather it is similar to the highly leached boundstone at Little Cedar Creek Field (Mancini et al., 2008). The boundstone reservoir pore system at Fishpond and Little Cedar Creek (Al Haddad and Mancini, 2013) fields consists of depositional growth (intraframe), solution-enhanced intraframe and/or vuggy pores that are interconnected. However, the vertical thickness of the reservoir at Fishpond Field (140 ft) is similar to the thickness of the reservoir at Appleton Field (190 ft) (Mancini et al., 2004) because in both these fields, the microbialites are associated with basement paleohighs, and the development of the buildups are not only affected by rises in relative sea level but also changes in base level as a result of faulting and subsidence.

Grainstone and packstone are also reservoirs in these three fields. The grainstone and packstone at Fishpond Field are not highly dolomitized like the dolograinstone and dolopackstone in Appleton Field (Mancini et al., 2004); rather these carbonates are similar to the leached grainstone and packstone at Little Cedar Creek Field (Mancini et al., 2008). The grainstone/packstone pore system at Fishpond and Little Cedar Creek (Al Haddad and Mancini, 2013) fields consists of primary interparticle, solution-enhanced interparticle, grain moldic, and/or vuggy pores. The grainstone/packstone beds accumulated as carbonate bank deposits at Little Cedar Creek Field (Al Haddad and Mancini, 2013) and as shoreface/shoal deposits in Appleton (Mancini et al., 2004) and Fishpond fields.

The complexity of the geological history of the petroleum trap and reservoir development at Fishpond Field distinguishes this field from the Appleton paleohigh and related microbial buildups and the Little Cedar Creek Field stratigraphic trap and associated back ramp microbial buildups.

EXPLORATION STRATEGY

In the Fishpond Field area, seismic reflection data has been the key to detecting basement structures associated with microbial buildups. Before 3D seismic reflection was introduced, 2D seismic data were used to locate these highs. The use of 2D seismic data resulted in drilling a number of dry holes because structural closure was difficult to define using 2D seismic profiles. With the advent of 3D seismic techniques, the ability to map 4–way closure on a structure was significantly improved. However, problems remained in finding paleohighs associated with microbial buildups and hydrocarbon-bearing reservoirs. Thus, exploration issues remain in the search for oil and gas in the updip basement play area of the Conecuh Embayment, including locating paleohighs that are associated with microbial buildups, delineating paleohighs that have microbial buildups developed on the crest of the structure, and identifying paleohighs that are associated with hydrocarbon bearing microbial reservoirs that lie above the oil/water contact.

The discovery of Little Cedar Creek Field in the Conecuh Embayment added a stratigraphic play for the southern Alabama area. Little Cedar Creek Field was essentially discovered without the use of 3D seismic reflection data and is being developed based on an extensive drilling and coring program. The updip limit of shoreface and carbonate bank facies and nearshore microbial buildup facies became a preferred target due to the areal extent of these facies. The use of 3D seismic data is not beneficial in this play because of the limited thickness of the microbial and bank deposit intervals and of their depth of burial, which present seismic resolution problems. Interestingly, the prolific reservoirs at Little Cedar Creek and Brooklyn fields were not highly dolomitized, but rather the porosity was depositional microbial growth intraframe or interparticle, solution-enhanced, and/or vuggy. In the early days of petroleum exploration in southwestern Alabama, some geologists thought that in order to achieve success one had to find a reservoir that was dolomitized. This concept has turned out not to be the case at Little Cedar Creek and Brooklyn fields and now in Fishpond Field. Although dolomitization is a significant diagenetic process for preserving, enhancing and creating porosity in Smackover carbonate reservoirs in the updip basement ridge and structural salt plays in southwest Alabama, dolomitization is not critical for enhancing reservoir quality in the Conecuh Embayment area (Al Haddad and Mancini, 2013). The preservation of depositional porosity, the enhancement of primary porosity through dissolution, and the creation of secondary porosity as a result of dissolution are critical processes to produce high-quality reservoirs in the Conecuh Embayment area.

The discovery of Fishpond Field further extended the search area for paleohighs associated with vertically thick microbial buildups in the Conecuh Embayment area. The geologic history of the Fishpond Field basement structure and the microbial buildup and associated facies, along with an understanding of the petroleum trap and carbonate reservoir interval, should be integrated for a successful exploration strategy in the area.

For example, in southwestern Alabama, companies are aware that certain basement areas were emergent during specific geologic times, such as the Middle to Late Jurassic times, and this controlled the potential reservoir facies that accumulated on the crests of a particular paleohigh. The paleohigh at Fishpond

Field was flooded by the initial Smackover transgression and microbialite growth followed, but then development was interrupted. Microbial buildup growth began and ceased multiple times in the Fishpond Field area. The multi-stage development pattern of microbial buildup at Fishpond Field is probably a result of changes in accommodation space. There is an overall initial increase in accommodation space that results from Smackover transgression and a continued rise in relative sea level followed by an overall decrease in accommodation space due to a reduction or cessation in the rise of relative sea level with subsequent Smackover progradation. In addition, there could be seasonal changes, environmental physical or chemical changes, or changes in rates of sediment deposition that impacted microbial buildup growth. However, changes in base level produced by differential movement in the basement rocks underlying the field as a result of faulting or subsidence, mainly due to Norphlet sediment burial compaction, also appears to be a viable mechanism to explain the vertically thick microbial buildup at Fishpond Field. In this regard, it is important to be aware of the possible factors controlling microbial buildup development and to have knowledge of the geologic history of the area of interest for oil and gas exploration. The inclusion of 3D geologic modeling as part of the exploration strategy has the potential to improve the success rate in drilling wildcat wells.

Hydrocarbon migration in the Conecuh Embayment area is not well understood at this time. Understanding why a porous and permeable facies is water wet rather than hydrocarbon bearing continues to be a major problem for exploration geologists in southwest Alabama. Geologic modeling is also an important tool for interpreting the geologic history of a basin and in predicting the timing of hydrocarbon migration in regard to the timing of petroleum trap formation.

Fishpond Field has shown that exploration is more complicated than just drilling a basement high identified using seismic reflection data. Knowledge of the geologic history is vital and the data utilized to obtain this knowledge must be comprehensive. A combination of 3D seismic interpretation and geologic modeling can help increase exploration success. However, the discovery of Fishpond Field proves that the deposition of microbial buildups on structural highs is more complex than originally thought.

CONCLUSIONS

The discovery of Fishpond Field shows that vertically thick microbial buildups with limited areal extent occur in association with paleohighs in the Conecuh Embayment area. Integrated reservoir characterization and modeling in Fishpond Field demonstrates that the reservoir is composed of microbial and higher energy carbonate facies that were deposited under variable conditions. The principal factors most likely affecting depositional conditions based on an integration of well log, core and seismic analyses in this study include changes in relative sea level and in base level due to subsidence, variations in the energy level, and differing water chemistry in the sedimentary environment. Changes in base level due to differential movement in basement rocks may have occurred as a result of normal faulting caused by Mesozoic extension in the region, which affected the Paleozoic basement rocks. This extension impacted the availability of accommodation space controlling the vertical growth and development of the microbial buildups.

At Fishpond Field, the microbial boundstone reservoir zone of the lower to middle part of the Smackover section has the highest reservoir potential because it has high average porosity and permeability values. The productivity of the microbial boundstone reservoir zone of the upper part of the Smackover section is variable because it consists of a combination of porous and permeable boundstone and nonporous diagenetically altered packstone/wackestone. The porous grainstone/packstone reservoir zone that occurs stratigraphically between the two microbial reservoir zones is productive of hydrocarbons primarily on the western side of the field.

The petroleum trap at Fishpond Field is a combination trap. The structural component is a fault-bounded basement topographic high. The stratigraphic component consists of a lithologic and petrophysical change from porous boundstone and grainstone/packstone on the crest of the fault-bounded structure grading laterally off structure into nonporous packstone/wackestone facies.

Fishpond Field is currently producing oil at a rate of over 360 BOPD, and this reservoir should continue to be productive due to the thickness, connectivity, and quality of the reservoir; the continuous high flow rate of the wells; and the early initiation of gas injection for enhanced recovery in the field. With an areal extent of approximately 60 acres, there is little potential that any additional wells will be drilled in the field. However, the successful discovery, development, and production at Fishpond Field demonstrates that the Conecuh Embayment area is a place where an operator can achieve exploration success using a combination of 3D seismic reflection data and geologic modeling.

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