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DEPOSITIONAL MODEL FOR LITHOFACIES OF THE UPPER JURASSIC SMACKOVER FORMATION IN THE CONECUH EMBAYMENT, NORTHEASTERN GULF OF MEXICO: IMPLICATIONS FOR PETROLEUM EXPLORATION

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ABSTRACT

An integrated well log and core study of the Upper Jurassic Smackover Formation and associated Jurassic lithofacies in the Conecuh Embayment, onshore northeastern Gulf of Mexico, has shown that the depositional environments for these updip lithofacies differ from the setting for other updip Upper Jurassic lithofacies in the onshore northeastern Gulf of Mexico. In the Conecuh Embayment, Jurassic Louann Salt is absent, Smackover beds directly overlie Upper Jurassic Norphlet deposits, and there is no overlying thick section of Buckner anhydrites as observed in other areas. The transgression of the Smackover sea was over a surface of Norphlet alluvial and fluvial deposits of variable thickness rather than a surface controlled by Norphlet eolian and Louann salt deposition and post-depositional salt movement. Lithofacies in this area consist of progradational subtidal peloidal and ooid grainstone and packstone sand bars deposited in a nearshore moderate-energy carbonate setting as compared to the typical inner ramp lithofacies of high-energy grainstone and packstone shoal and shoreface deposits. Subtidal microbial (thrombolite) buildups discovered in this embayment did not develop on pre-Jurassic high-relief basement structural features and are not overlain by high-energy shoal and shoreface grainstone and packstone lithofacies like the microbial buildups to the west and south of the Conecuh Embayment. These subtidal microbial buildups extended landward beyond the depositional limit of the carbonate sand bar complex and are postulated to have developed in a protected, low-energy bay or lagoonal environment within an embayed shoreline. The critical factor for microbial growth was the presence of a hard substrate, and microbial development was mainly controlled by available accommodation space created primarily by a rise in sea level. Black shale beds containing terrestrial-derived herbaceous organic material, including ferns, mosses and conifers, characteristic of a warm humid climate occur in the Conecuh Embayment. The presence of a more humid climate relative to areas to the west resulted in an influx of freshwater into the embayment. The introduction of freshwater affected depositional and post-depositional conditions, such that porosity in the reservoir facies is dominated by depositional, primary solution-enlarged, and secondary vuggy pores in the embayment rather than diagenetic intercrystalline dolomite and moldic pores characteristic of reservoirs in the Mississippi Interior Salt Basin. A revised Smackover depositional model that incorporates the implications of these findings on potential petroleum reservoir, source, and seal facies in the Conecuh Embayment provides additional petroleum exploration targets for the onshore northeastern Gulf of Mexico.

INTRODUCTION

The carbonate ramp depositional model of Ahr (1973), which was later modified by Burchette and Wright (1992) and by Ahr (2008, his figures 4.1 and 4.2), has been used by academics and petroleum exploration geoscientists to interpret Upper Jurassic Smackover carbonate sediment accumulation and distribution patterns in the onshore northern Gulf of Mexico area. Ahr (1973) defined a ramp as a sloping surface connecting two levels with-

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out a break in slope. The ramp represents an inclined carbonate platform that has a gentle low gradient slope from the shoreline to the basin and is characterized by higher-energy lithofacies near the shoreline that grade to lower-energy lithofacies toward the basin (Ahr, 1973; Burchette and Wright, 1992). In this depositional model, the inclined ramp surface can be interrupted by the presence of local topographic highs (Ahr, 1973).

According to Ahr (2008), a carbonate platform is the term for depositional surfaces on which carbonate lithofacies are deposited, and he referred to platforms that slope continuously from beach to basin without a pronounced break in slope as homoclinal ramps. The slope on ramps varies depending on antecedent topography, and the interaction of the oceanic hydrological regime with platform topography determines the characteristics and distribution of the depositional lithofacies (Ahr, 2008).

Burchette and Wright (1992) described a homoclinal (slope of less than 1 degree) carbonate ramp as consisting of three zones: inner ramp, mid-ramp, and outer ramp. Lithofacies of the outer ramp accumulated below normal storm wave base, and lithofacies of the mid-ramp are affected by storm waves but not fair weather waves in their model. They stated that the inner ramp lithofacies are deposited above the fair weather wave base and include sand shoals or organic barriers, shoreface deposits, and back-barrier peritidal areas. Tucker et al. (1993) divided the carbonate ramp into a deep ramp, including thin bedded limestones and storm deposits; a shallow ramp consisting of beach-barrier, strandplain, sand shoal, and patch reef lithofacies; and a back ramp, including lagoonal, tidal flat, supratidal carbonates, and evaporite lithofacies. Read (1985) proposed an alternate to the homoclinal ramp referred to as a distally steepened ramp. Ahr (2008) reported that a distally steepened ramp is characterized as having a slope change on its distal margin. He stated that there are no lithofacies variations associated with this change in slope because the distal steepening is at water depths below those at which waves and currents influence bottom sedimentation.

SMACKOVER CARBONATE RAMP DEPOSITIONAL MODEL

Early works by Ahr (1973) for Upper Jurassic Smackover carbonates in the onshore northern Gulf of Mexico, by Budd and Loucks (1981) for Smackover and lower Buckner deposits in south Texas of the northwestern Gulf of Mexico, by Mancini and Benson (1980) for Smackover sediments in southwestern Alabama of the northeastern Gulf of Mexico, and by Tew et al. (1993) for Smackover deposits in the coastal waters area off Mobile and Baldwin counties, Alabama, provide studies that used a carbonate ramp model in determining Smackover depositional setting. Schemper et al. (2018) also reported that Smackover deposits in the East Texas Basin accumulated in a seaward-deepening ramp setting with higher-energy peloidal and ooid packstones and grainstones in the inner ramp, packstones in the middle ramp, and low-energy organic-rich laminated mudstones in the outer ramp. Ahr (1973) described the Smackover ramp physiographic model as consisting of concentric lithofacies belts comprised of grainstones updip transitioning to pelagic mudstones downdip. He reported that this wedge-shaped package of deposits thickens seaward, except where local topography modifies the depositional trend, and that patch reefs may develop on topographic highs. He concluded that the Jurassic Louann Salt provided the primary underlying ramp surface.

On the basis of the work of Mancini and Benson (1980) and Benson and Mancini (1984), Smackover carbonate sediment accumulation in southwestern Alabama can be characterized by using a homoclinal carbonate ramp model. That is, overall Smackover deposition occurred on a gently dipping inclined plane interrupted by pre-Smackover topographic highs (Paleozoic basement structures, Louann salt features, and Norphlet dunes) and generally was characterized by higher-energy lithofacies in nearshore areas and lower-energy lithofacies in offshore areas (Mancini and Benson, 1980; Benson and Mancini, 1984). However, information from oil and gas drilling, along with the publications of Ottmann et al. (1973), Benson and Mancini (1982, 1984), Wade et al. (1987), and Kopaska-Merkel (2002), has shown that although a carbonate ramp can be used as a framework to interpret Smackover sedimentation in southwestern Alabama, variations to the typical Smackover model are evident in the depositional characteristics and patterns of Smackover lithofacies. Benson and Mancini (1984) pointed out that these variations from the typical model are mainly a result of Jurassic paleogeography.

Factors affecting Smackover deposition are more complicated in southwestern Alabama principally due to the influence of the Appalachian structural trend and associated ridges (Choctaw, Marengo, and Conecuh ridges), the Pensacola Arch, the Wiggins Arch and related Baldwin High, the Saint Stephens Ridge, numerous pre-Smackover topographic highs, and halokinesis during the Late Jurassic (Fig. 1). Depocenters in the eastern part of the Mississippi Interior Salt Basin, Manila Subbasin, and Conecuh Subbasin include some 400 to 550 ft (122 to 168 m) of Smackover deposits (Mancini and Benson, 1980). These elements have resulted in a diverse sequence of lithofacies in the Upper Jurassic stratigraphic section for the onshore northeastern Gulf of Mexico (Fig. 2).

The presence of the Wiggins Arch in the southern part of the eastern Mississippi Interior Salt Basin resulted in the deposition of high-energy shoreface grainstone lithofacies along the flanks of this structure (Benson and Mancini, 1982, 1984; Tew et al., 1993; Rhodes and Maxwell, 1993). Louann salt movement contributed to the deposition of these higher-energy lithofacies in this area by providing an elevated surface above the seafloor for Smackover sediment accumulation (Benson and Mancini, 1982). As predicted by the ramp model, Smackover higher-energy grainstones and packstones characterized deposition in the updip nearshore areas in the eastern part of the Mississippi Interior Salt Basin; however, high- to moderate-energy fine-grained and well-sorted sandstones (Fig. 3) are associated with these carbonates in the Manila Subbasin and Manila (Wilcox) Embayment area (Wade et al., 1987). Erosion of the Appalachian Highlands probably was the source for these siliciclastic deposits.

SMACKOVER DEPOSITIONAL SETTING IN THE CONECUH SUBBASIN AND EMBAYMENT

Information from oil and gas drilling in the Conecuh Subbasin and Embayment, southwestern Alabama, presents another example of a variation to the typical Smackover carbonate ramp model for the northeastern Gulf of Mexico. The Conecuh Embayment is defined as that area in Conecuh, Escambia, and Covington counties, Alabama, and Okaloosa County, Florida, north of the Pollard-Foshee Fault System, where Louann Salt is absent and pre-Jurassic high-relief basement structural features, such as the paleohigh at Appleton Field, have not been observed (Figs. 1 and 3). However, Paleozoic basement topography and/or relict Norphlet depositional features had the potential to impact microbial buildup development and distribution in the embayment. For example, analysis of three-dimensional (3D) seismic data indicates that the growth of the microbial buildups in the northwestern section of Brooklyn Field was affected by basement topography. In the Little Cedar Creek Field area of the embayment, the Smackover Formation attains a thickness of 117 ft (36 m) compared to a thickness of 400 ft (122 m) in parts of the Conecuh Subbasin (Mancini et al., 2008). The updip terminus of the Conecuh Embayment is the extent of Smackover deposition in the area.

The embayment is bordered on the northwest by the Conecuh Ridge and on the southeast by the Pensacola Arch (Fig. 1).

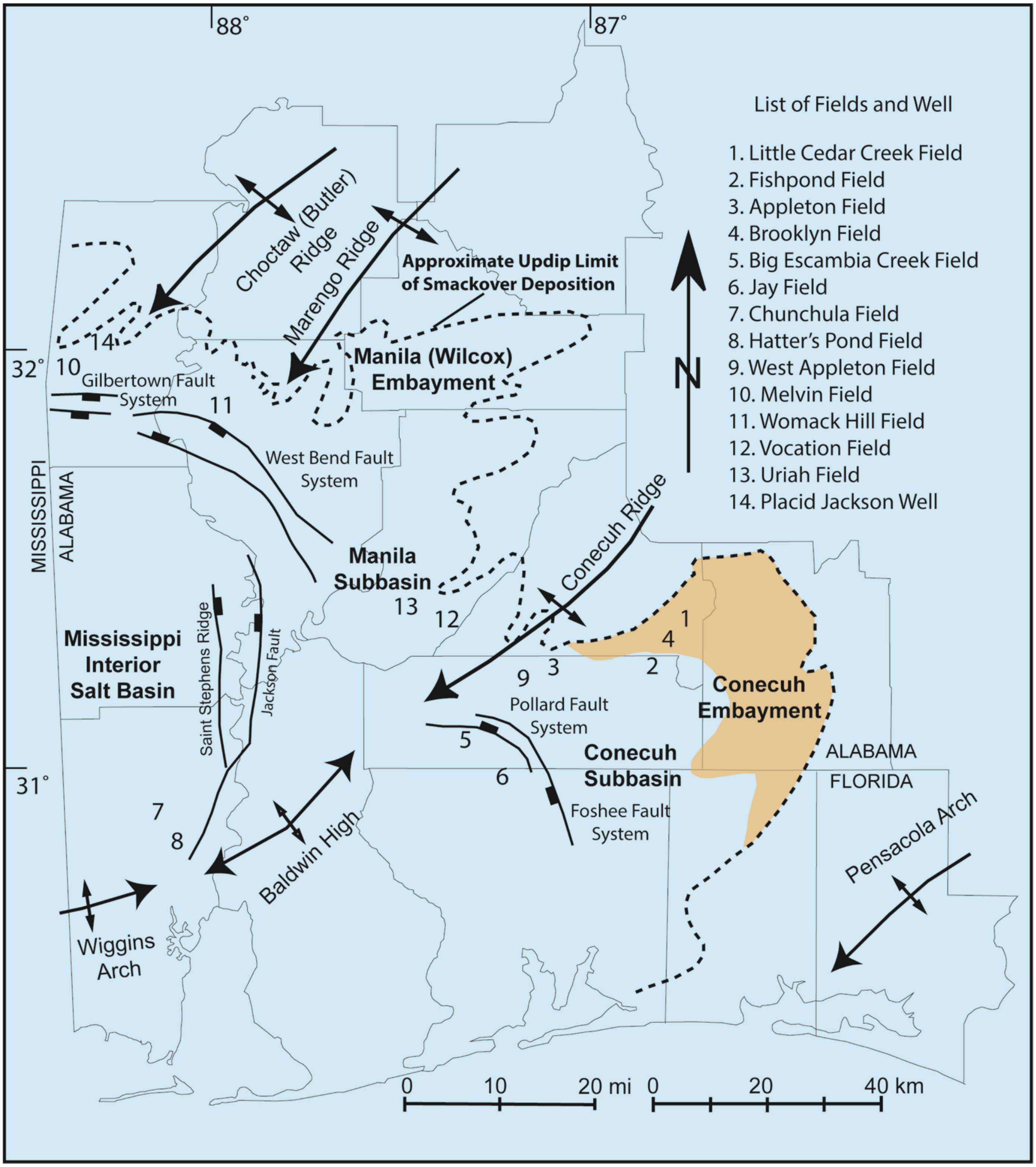
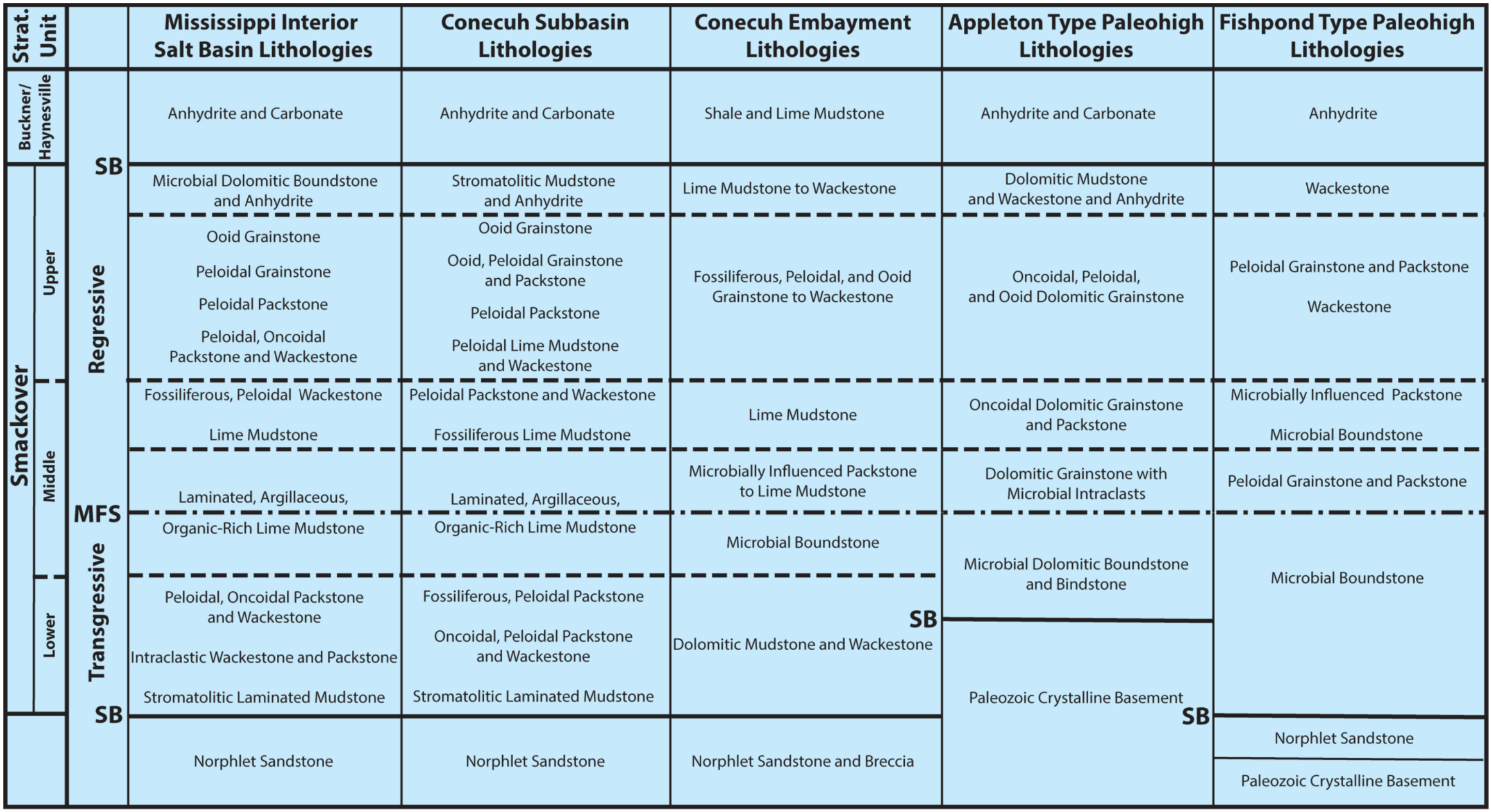


Figure 1. Major Jurassic structural features and basin and subbasins in southwestern Alabama constructed using data and information from this study, Wilson (1975), Mancini and Benson (1980), Benson (1988), Tew et al. (1991), and Kopaska-Merkel (2002). Area of the Conecuh Embayment is defined in text.

These structural features acted as barriers to strong wave activity and intense storm events, and thus, created a protected, lower-energy setting for Smackover carbonate deposition in the Conecuh Embayment. In addition, Sigsby (1976) concluded that Smackover sedimentation in the Jay Field area of the Conecuh Subbasin was influenced by relict Norphlet sandstone relief and Louann Salt mobility and occurred within an embayed shoreline that restricted marine circulation producing low-energy depositional conditions. Bradford (1984) observed that a moderate-energy setting existed in parts of the Conecuh Subbasin probably



Strat. Unit		Mississippi Interior Salt Basin Lithologies	Conecuh Subbasin Lithologies	Conecuh Embayment Lithologies	Appleton Type Paleohigh Lithologies	Fishpond Type Paleohigh Lithologies
Buckner/ Haynesville		Anhydrite and Carbonate	Anhydrite and Carbonate	Shale and Lime Mudstone	Anhydrite and Carbonate	Anhydrite
Smackover Upper	SB Regressive	Microbial Dolomitic Boundstone and Anhydrite	Stromatolitic Mudstone and Anhydrite	Lime Mudstone to Wackestone	Dolomitic Mudstone and Wackestone and Anhydrite	Wackestone
		Ooid Grainstone Peloidal Grainstone Peloidal Packstone Peloidal, Oncoidal Packstone and Wackestone	Ooid Grainstone Ooid, Peloidal Grainstone and Packstone Peloidal Packstone Peloidal Lime Mudstone and Wackestone	Fossiliferous, Peloidal, and Ooid Grainstone to Wackestone	Oncoidal, Peloidal, and Ooid Dolomitic Grainstone	Peloidal Grainstone and Packstone Wackestone
Smackover Middle		Fossiliferous, Peloidal Wackestone Lime Mudstone	Peloidal Packstone and Wackestone Fossiliferous Lime Mudstone	Lime Mudstone	Oncoidal Dolomitic Grainstone and Packstone	Microbially Influenced Packstone Microbial Boundstone
		Laminated, Argillaceous,	Laminated, Argillaceous,	Microbially Influenced Packstone to Lime Mudstone	Dolomitic Grainstone with Microbial Intraclasts	Peloidal Grainstone and Packstone
	MFS Transgressive	Organic-Rich Lime Mudstone	Organic-Rich Lime Mudstone	Microbial Boundstone	Microbial Dolomitic Boundstone and Bindstone	Microbial Boundstone
Smackover Lower		Peloidal, Oncoidal Packstone and Wackestone Intraclastic Wackestone and Packstone Stromatolitic Laminated Mudstone	Fossiliferous, Peloidal Packstone Oncoidal, Peloidal Packstone and Wackestone Stromatolitic Laminated Mudstone	SB Dolomitic Mudstone and Wackestone	SB Paleozoic Crystalline Basement	
	SB	Norphlet Sandstone	Norphlet Sandstone	Norphlet Sandstone and Breccia		SB Norphlet Sandstone Paleozoic Crystalline Basement

MISB = Mississippi Interior Salt Basin, SB = Sequence Boundary, MFS = Maximum Flooding Surface

Figure 2. Upper Jurassic Smackover lithostratigraphic correlation, southwestern Alabama, constructed using data and information from this study, Bradford (1984), Benson (1988), McKee (1990), Markland (1992), Mancini et al. (2008), and Owen (2017).

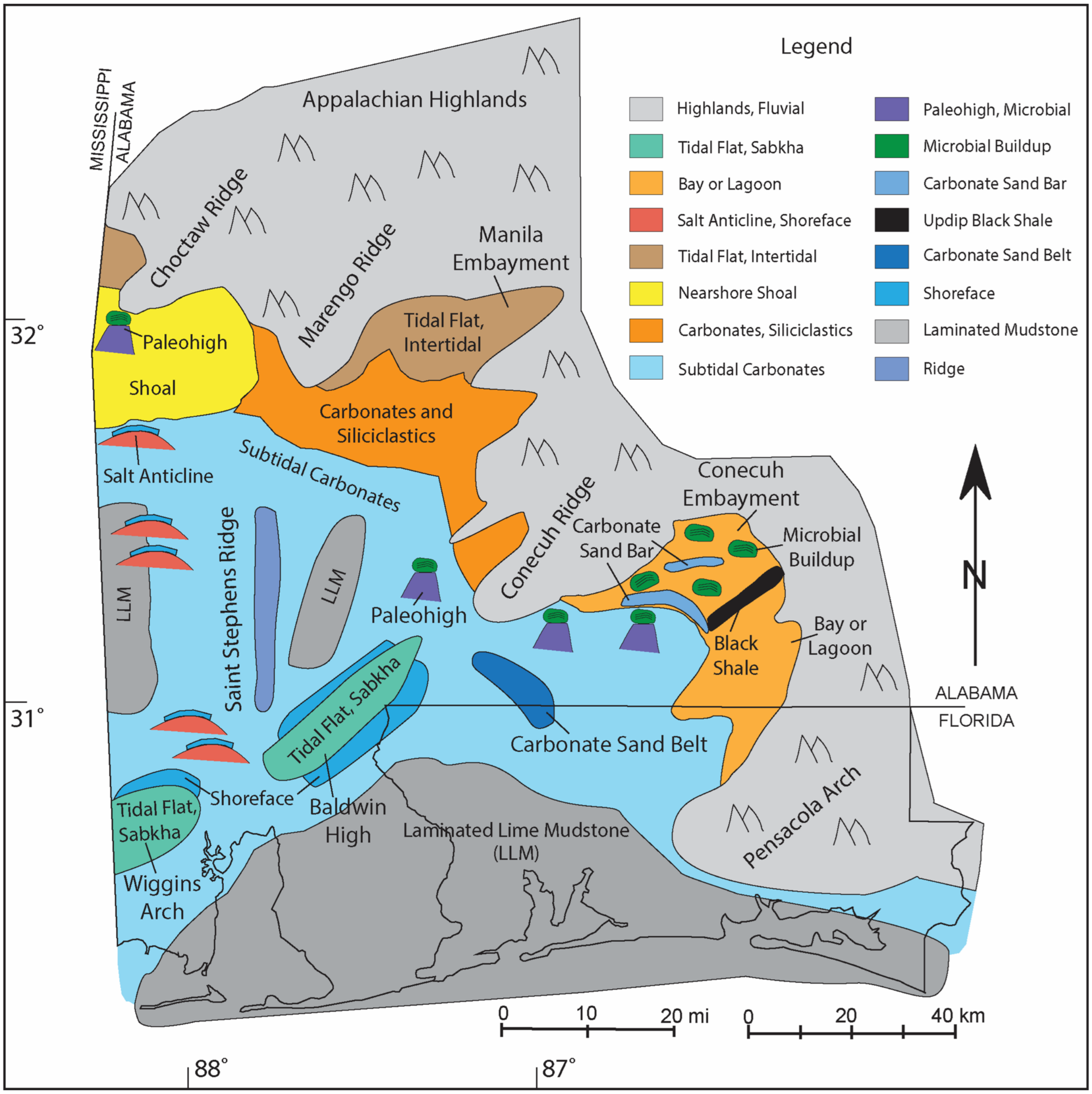


Figure 3. Late Jurassic paleogeography for the Smackover Formation, southwestern Alabama, constructed using data and information from this study, Ottmann et al. (1973), Bradford (1984), Benson and Mancini (1984), Wade et al. (1987), Rhodes and Maxwell (1993), Prather (1992), Kopaska-Merkel (2002), Mancini et al. (2004a), and Baria et al. (2008).

due to Louann Salt movement at the time of Smackover deposition.

The distribution of Smackover carbonate lithofacies from the shoreline to the basin on a low-angle surface of deposition, in combination with varying paleogeography, antecedent topography, halokinesis, and depositional conditions, resulted in a complex homoclinal carbonate ramp depositional setting for the Conecuh Subbasin and Embayment (Fig. 4). In this Smackover ramp model, the back ramp was characterized by protected bay or lagoonal lithofacies associated with tidal flat and microbial buildup deposits; the inner ramp consisted of shallow subtidal carbonate sand bars and paleohighs with microbial and shoreface carbonates; the middle ramp included salt features with subtidal carbonate sand belts; and the outer ramp was dominated by subtidal low-energy microbial laminates.

In the Conecuh Embayment, underlying Louann Salt is absent, and there is no thick overlying section of Buckner anhydrites. Smackover beds directly overlie a diversity of lithologies of variable thickness representing alluvial and fluvial deposits of the Upper Jurassic Norphlet Formation (Fig. 2). In the eastern part of the Mississippi Interior Salt Basin, Smackover strata usually rest on less heterogeneous Norphlet eolian and marine sandstone deposits, which are relatively continuous but may exhibit variable dune thickness. Updip of the regional peripheral fault system, the Smackover can overlie Paleozoic basement rocks associated with pre-Jurassic paleohighs in the Mississippi Interior Salt Basin and Manila and Conecuh subbasins (Baria et al., 1982; Benson et al., 1996; Mancini et al., 2000; Llinas, 2004).

In addition, wells drilled in the Conecuh Embayment area encountered black shale within the Smackover section (Baria et al., 2008; Niemeyer, 2011; Owen, 2017). These shale beds contain terrestrial-derived herbaceous organic material, including ferns, mosses, and conifers, characteristic of a warm humid climate (Niemeyer, 2011). Niemeyer (2011) also reported that these deposits were associated with freshwater runoff from highlands to the north and east of the embayment. This runoff may be a product of a humid climate and seasonal precipitation in the Appalachian Highlands that lead to periods of adequate rainfall

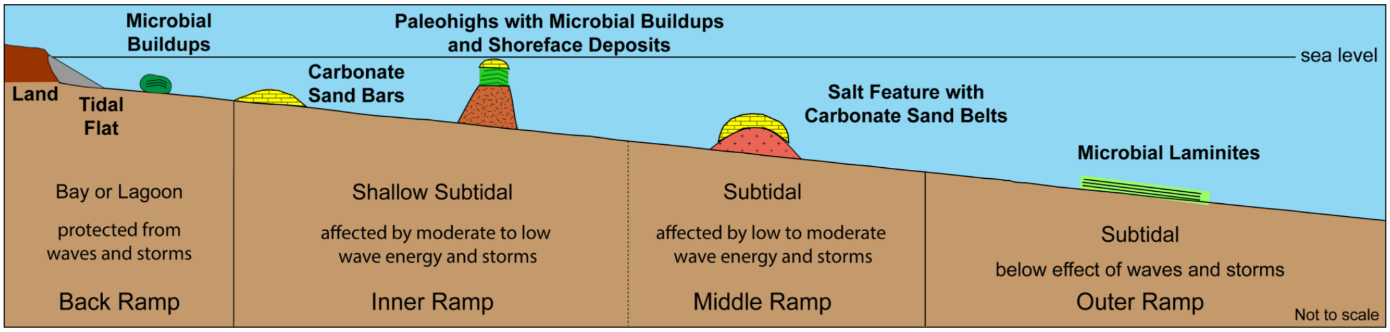


Figure 4. Smackover homoclinal carbonate ramp depositional model for the Conecuh Subbasin and Embayment illustrating structural features and sedimentary lithofacies constructed using data and information from this study, Bradford (1984), Mancini et al. (2004a), and Al Haddad and Mancini (2013) and integrated with the carbonate ramp models of Tucker et al. (1993) and Ahr (2008).

to support the floral assemblage reported by Niemeyer (2011). The shale may represent deposits from terrestrial environments rimming a bay or lagoon setting and accumulating in a more humid climate than that represented by sabkha deposition in the Mississippi Interior Salt Basin.

Further, the development of the Little Cedar Creek Field in the Conecuh Embayment resulted in the availability of substantial core data on the reservoir facies in the updip area of Smackover deposition. In studying these cores, it was found that progradational subtidal peloidal and ooid grainstone and packstone sand bars were deposited in the Conecuh Embayment (Fig. 3). These nearshore carbonate sand bar deposits, which had relief above the seafloor, accumulated in a moderate-energy environment, rather than a high-energy system like the shoal and shoreface deposits characteristic of the Mississippi Interior Salt Basin (Fig. 3). In addition, the microbial (thrombolite) buildups present in the Little Cedar Creek Field are unlike those generally observed in other areas. These microbes did not nucleate and grow on high-relief structural features overlain by high-energy shoal and shoreface lithofacies like the microbial buildups to the west and south of the embayment (Mancini et al., 2004a, 2008). These buildups extended further landward than the subtidal carbonate sand bar accumulations (Fig. 3), and they thrived in a protected low-energy environment, such as a bay or lagoon. Isotopic data from these microbial facies in this study are inconclusive as to whether the Smackover waters in which these microbes lived were normal marine or hyposaline.

A major key in determining depositional conditions in the Conecuh Embayment is the determination of the factors controlling microbial buildup origin, development, and demise. The abundance of thrombolites worldwide in the Mesozoic is attributed to a rise in global sea level (Leinfelder and Schmid, 2000). Leinfelder et al. (1993) further concluded that microbes are not restricted by water depth, salinity, temperature, light penetration, oxygen content, or nutrient supply. These organisms are dependent on a hard substrate for nucleation, a zero to low background sedimentation rate for initial growth, and a low to moderate background sedimentation rate for continued growth (Leinfelder et al., 1993).

Baria et al. (1982), in their study of Smackover buildups in the Gulf Coastal Plain (Arkansas to Florida), reported that in the western part of the trend (Arkansas and Louisiana), buildups occur in the upper Smackover interval, and nearly all the buildups in the eastern part of the trend (Alabama and Florida) are found at the base of the upper Smackover interval. The lack of corals in the eastern Gulf buildups is probably caused by adverse paleoenvironmental conditions (Baria et al., 1982).

Kopaska-Merkel (2003) published that Smackover microbial and biodetrital mounds developed on the Saint Stephens Ridge in southwestern Alabama (Fig. 1) and that microbial mound facies occurred in association with the Chunchula Field salt feature in the southeastern part of the Mississippi Interior Salt Basin. Also, biodetrital mound facies or organosedimentary deposits were recognized in a core from the Uriah Field basement paleohigh in the southern part of the Manila Subbasin (Kopaska-Merkel, 2003).

Mancini et al. (2004a) found that Smackover microbes nucleated on Paleozoic crystalline rocks associated with paleohighs or on a firm to hard substrate, such as a hardground or encrusted surface associated with shells and cementation. The initial growth of microbe colonies corresponded with a rise in sea level and a low to zero background sedimentation rate. Microbial growth prospered with a continued rise in sea level, low water energy level, and low background sedimentation rate. The demise of the microbes was attributed to a reduction in accommodation space caused by the slowing of the rate of relative sea-level rise in combination with an increase in background sedimentation rate and an increase in the water energy level (Mancini et al., 2004a). Higher-energy shoal and shoreface ooid and peloidal grainstone and packstone deposits typically overlie the microbial buildups (Mancini et al., 2004a). At Vocation Field, southwestern Alabama, Llinas (2004) found that Smackover thrombolite facies developed only on the leeward flank of this emergent paleohigh because higher-energy conditions characterized the windward side of this feature resulting in the deposition of shoreface ooid grainstone.

Parcell (2003) simulated the development of Upper Jurassic microbial buildups in the Conecuh and Manila subbasins using a 3D numerical stratigraphic model. The work of Parcell (2003) showed that background sedimentation rate, water energy, substrate, relative sea-level change, and climate influenced the development of these buildups. Climate and the amplitude of sea-level change were global factors that determined whether or not buildups developed. Substrate, water energy and background sedimentation rate were found to influence the lateral distribution of the buildups. The model indicated a strong correlation between buildup development and the rate of sea-level rise and that the initial buildup development corresponds to the greatest rate of sea-level rise with peak growth occurring prior to attaining the deepest water (Parcell, 2003).

Thus, Smackover deposition in the Conecuh Subbasin and Conecuh Embayment can be described as occurring in an Upper Jurassic transgressive-regressive sedimentary system (Fig. 2) (Mancini et al., 1990). Smackover carbonate deposition was initiated as part of a transgressive event in southwestern Alabama. With the onset of sea-level rise, erosion of the upper part of the Norphlet Formation commenced, and the eolian and alluvial sediments were reworked and deposited in a marine shoreface environment. The initiation of Smackover sediment accumulation resulted in the deposition of intertidal and subtidal stromatolitic laminated lime mudstone and oncoidal, peloidal wackestone and packstone followed by the accumulation of subtidal fossiliferous, peloidal packstone. With continued rise in sea level a thick section of subtidal laminated and organic-rich lime mudstone was deposited. During this time of transition from maximum transgression to regression, ocean circulation was somewhat restricted facilitating the accumulation of these organic-rich deposits in basinal areas (Benson, 1988). Also, during this time of transition, microbe colonies thrived in the Smackover seas as the waters inundated elevated seafloor features, including Paleozoic basement paleohighs, Louann Salt structures, and antecedent Norphlet depositional and erosional features, which resulted in the growth of significant microbial buildups. Development of these thrombolite facies was not limited to paleohighs; microbial buildups also developed in the Conecuh Embayment area in low-energy bays or lagoons where they nucleated on hard surfaces on the water bottom (Fig. 3). Off of these paleohighs, subtidal fossiliferous lime mudstone and peloidal packstone and wackestone accumulated during this period of high carbonate productivity.

With a reduction in the rate of sea-level rise accompanied by high carbonate productivity, there was a loss in available accommodation space resulting in reduced water depths over these structures. This period of relative stability and depositional aggradation, produced higher-energy conditions, and ooid and peloidal grainstone and packstone shoals formed on paleohighs. Typically, at this point in the development of a Smackover carbonate transgressive-regressive system, shoals would characterize updip areas. However, in this case, the Conecuh Embayment was protected from high wave activity due to the presence of the Conecuh Ridge to its northwest and Pensacola Arch to the southeast. Thus, subtidal carbonate sand bars developed in this moderate-energy nearshore setting. With continued high rates of carbonate production that were greater than the rate of subsidence, the loss of accommodation space continued and marine regression was initiated. Across most of the onshore northeastern Gulf of Mexico, this marine regression in the Smackover carbonate system is characterized by progradation of ooid, peloidal grainstone and packstone shoal deposits capped by coastal sabkha deposits, as seen in the Mississippi Interior Salt Basin. However, in the Conecuh Embayment area, Smackover carbonate peloidal, ooid grainstone and packstone sand bars migrated seaward. In an arid climate setting, the regression ends with coastal sabkha progradation; however, in the more humid climate of the Conecuh Embayment the regression culminated with siliciclastics being transported into this area rather than the development of coastal sabkha deposits.

In summary, these findings show that Smackover sediment accumulation in the onshore northeastern Gulf of Mexico area was not uniform mainly due to varying paleogeography, antecedent topography, salt movement, and depositional conditions in the region. For example, in the eastern part of the Mississippi Interior Salt Basin, Smackover higher-energy shoal and shoreface carbonate lithofacies characterize inner ramp deposition, whereas in the Conecuh Embayment Smackover moderate-energy subtidal carbonate sand bar and low-energy thrombolite facies are the predominant Smackover deposits. The thrombolite facies extend updip northeast of the nearshore sand bar complex and are postulated to represent bay or lagoonal deposits in this embayment. In this area, the updip limit of Smackover deposition is defined as an embayed shoreline rather than a high-energy shoreline. Therefore, modifications to the typical carbonate ramp model for southwestern Alabama are required to describe adequately the depositional characteristics and patterns of Smackover lithofacies observed in the Conecuh Embayment (Figs. 3 and 4).

A revised carbonate depositional model provides potential Smackover targets for petroleum exploration in the onshore northeastern Gulf of Mexico area. In the Conecuh Embayment area, these include: (1) progradational nearshore, subtidal peloidal and ooid grainstone and packstone sand bar lithofacies (Figs. 5A and 6A), (2) bay or lagoonal microbial boundstone lithofacies (Figs. 5B and 6C), and (3) subtidal thrombolite boundstone buildup lithofacies not associated with high-relief basement structural features (Figs. 5C, 5D, and 6B).

In addition to advancing knowledge regarding depositional systems of the reservoirs and their architecture, an understanding of the origin and development of pre-Smackover paleohighs in southwestern Alabama would serve to facilitate petroleum exploration in the onshore northeastern Gulf of Mexico. Through the drilling of wells in the 2000s, geoscientists found that the development of the microbial buildups on pre-Jurassic paleohighs was more complicated than originally assumed principally due to Mesozoic block faulting in Paleozoic crystalline rocks; thermal subsidence; differential sediment accumulation, burial, and compaction rates; and/or late fault movement related to Paleozoic structural features. Knowledge of the geohistory of the paleohighs is important in designing a successful exploration strategy for these structures and associated microbial buildups.

APPLICATION OF DEPOSITIONAL MODEL FOR PETROLEUM EXPLORATION IN THE CONECUH EMBAYMENT AREA

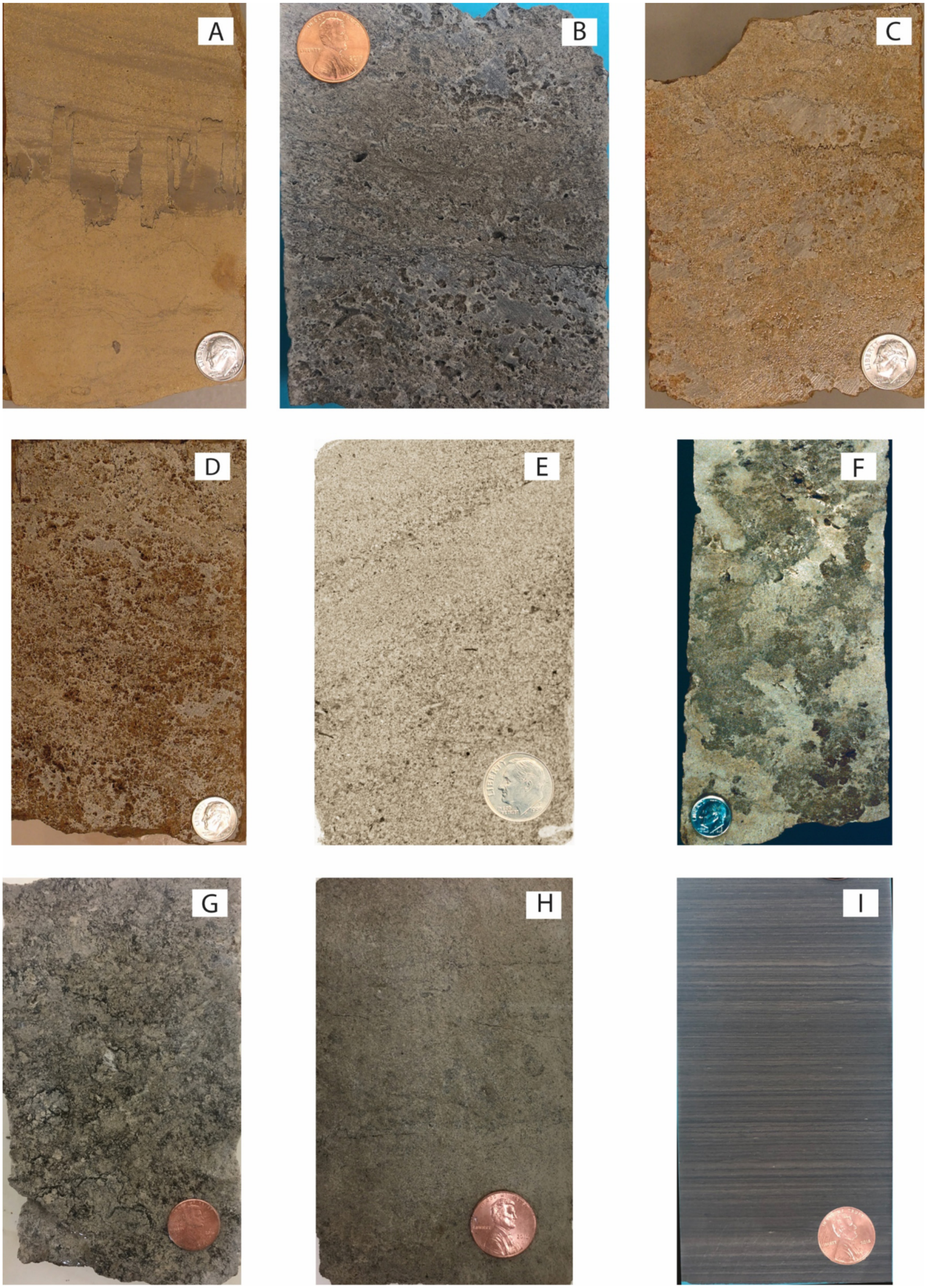
Petroleum Reservoir, Source, and Seal Lithofacies

In his paper describing a carbonate ramp, Ahr (1973) contrasted potential reservoir facies in a ramp setting to potential reservoir facies in a carbonate shelf setting. He concluded that the main reservoir facies in the ramp model were nearshore lenticular barrier bar grainstones that were commonly dolomitized through reflux processes under arid climatic conditions. Ahr (1973) also stated that patch reef boundstones developed on local topographic highs have potential as reservoir facies in this setting. Mancini and Benson (1980) used Ahr's (1973) carbonate ramp model in their regional stratigraphic and depositional study of Upper Jurassic Smackover carbonates. They found that in the eastern part of the Mississippi Interior Salt Basin in southwestern Alabama (Fig. 1) the principal petroleum reservoir facies were grainstone; dolomitized and leached grainstone, packstone and wackestone; and dolostone of the upper part of the Smackover Formation (Figs. 5E and 6D–6F). They also reported that the petroleum source rock for these potential reservoirs was algal (microbial) subtidal laminated lime mudstone of the Smackover Formation. Baria et al. (1982) and Mancini et al. (2004a) recognized the petroleum reservoir potential of Smackover algal (microbial) buildup facies (Figs. 5F, 5G and 6H) and shoal and shoreface deposits overlying the microbial facies (Figs. 5H and 6G) associated with pre-Jurassic paleohigh settings in the Manila and Conecuh subbasins and related embayment areas.

In the Smackover petroleum system, seal rocks in the Mississippi Interior Salt Basin are uppermost Smackover peritidal carbonates and anhydritic beds and the overlying Buckner subaerial (sabkha) and subaqueous anhydrites (Mancini et al., 2003). In the Conecuh Embayment, upper Smackover peritidal carbonates and lower Haynesville argillaceous beds constitute the petroleum seal rocks (Heydari and Baria, 2006; Mancini et al., 2008).

Reservoir Petrophysics

According to Ahr (1973), grainstones associated with a ramp depositional setting that included a sabkha coastline commonly experienced diagenetic alterations, such as reflux dolomitization. He concluded that an updip dolomitization process increased porosity in the grainstone reservoirs. He also reported that subaerial leaching was a possible diagenetic agent on local topographic highs. In southwestern Alabama, although the primary control on reservoir architecture in Smackover carbonates is the depositional fabric, diagenesis is a significant factor in modifying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(FACING PAGE) Figure 5. Core photographs of Smackover lithofacies: (A) nearshore sand bar grainstone, well permit 14181, 11237 ft (3425 m); (B) back ramp bay or lagoonal microbial buildup boundstone, well permit 17045, 10154 ft (3095 m); (C) subtidal microbial buildup boundstone, well permit 13439, 11605 ft (3537 m); (D) subtidal microbial buildup porous boundstone, well permit 12872, 11868 ft (3617 m); (E) inner ramp shoal grainstone, well permit 1330, 10350 ft (3155 m); (F) inner ramp microbial buildup dolomitic boundstone showing dendroidal growth form, well permit 3986, 12972 ft (3954 m); (G) inner ramp microbial buildup boundstone associated with paleohigh, well permit 17021, 12149 ft (3703 m); (H) inner ramp upper shoreface grainstone associated with paleohigh, well permit 17021, 12115 ft (3693 m); and (I) outer ramp laminated lime mudstone, well permit 1766, 15535 ft (4735 m).

reservoir quality (Benson, 1985). Of the diagenetic events, dissolution and dolomitization probably had the greatest influence in Smackover reservoir development (Benson and Mancini, 1984, 1999). Meteoric vadose dissolution is the principal process, resulting from the exposure of Smackover beds through the depositional process or through emergence of Smackover deposits as a result of a fall in relative sea level (Benson, 1985). Brine reflux, which results in dolomitization, also occurs in association with marine regression and has the potential to enhance reservoir quality (Benson, 1985); however, this mechanism for dolomitization of Smackover lithofacies has been reported to be restricted to the uppermost Smackover strata (Vinet, 1984; McKee, 1990).

Porosity in inner ramp reservoirs in the eastern part of the Mississippi Interior Salt Basin and reservoirs in the Conecuh Subbasin is both depositional and diagenetic (Benson and Mancini, 1984; Bradford, 1984; Benson, 1985). The main pore types in upper Smackover shoal and shoreface grainstone reservoirs in the Mississippi Interior Salt Basin are depositional interparticle and diagenetic solution-enlarged interparticle, grain moldic, intercrystalline dolomite, and vuggy pores (Fig. 6D–6F) (Benson and Mancini, 1982, 1984; Benson, 1985; McKee, 1990). Smackover porosity in the grainstone, packstone-wackestone, and stromatolite reservoirs in the Conecuh Subbasin consists of diagenetic grain moldic, intercrystalline dolomite, and leached matrix (vuggy) (Ottmann et al., 1973). Dissolution resulting from early leaching in the vadose zone served to enlarge primary interparticle pores, to produce new secondary grain moldic and intraparticle pores, and to enlarge early secondary moldic and intercrystalline dolomite pores (Benson, 1985; McKee, 1990). Moldic porosity was also produced by early fabric-selective dissolution of carbonate grains and is associated with areas that experienced subaerial exposure (Benson, 1985). In southwestern Alabama, dolomitization is fabric destructive and results from seepage reflux involving the downward movement of evaporitically concentrated brines into limestone, or from the mixing of seawater and near-surface meteoric waters at the base of a meteoric lens after deposition and short-tem exposure (McKee, 1990). Vuggy porosity is nonfabric-selective and is produced from solution enlargement of earlier formed interparticle, moldic, or intercrystalline dolomite pores (Benson, 1985).

Porosity in the higher-energy shoreface and shoal facies, associated with pre-Jurassic paleohighs in the Manila and Conecuh subbasins, was developed through a combination of depositional and diagenetic processes, mainly dolomitization and dissolution (Benson and Mancini, 1999; Llinas, 2004). The primary control on the reservoir quality is the depositional setting; however, dolomitization and dissolution were important to reservoir development in these subbasins (Benson and Mancini, 1999). The reservoirs include grainstone and packstone and dolomitic grainstone and packstone. Porosity in these carbonates includes moldic, intercrystalline dolomite, and vuggy pores (Fig. 6G). Porosity in the microbial buildup facies associated with paleohighs includes depositional shelter and intraframe pores and secondary intercrystalline dolomite and vuggy pores (Fig. 6H) (Benson and Mancini, 1999; Llinas, 2004). These reservoirs include boundstone and dolomitic boundstone.

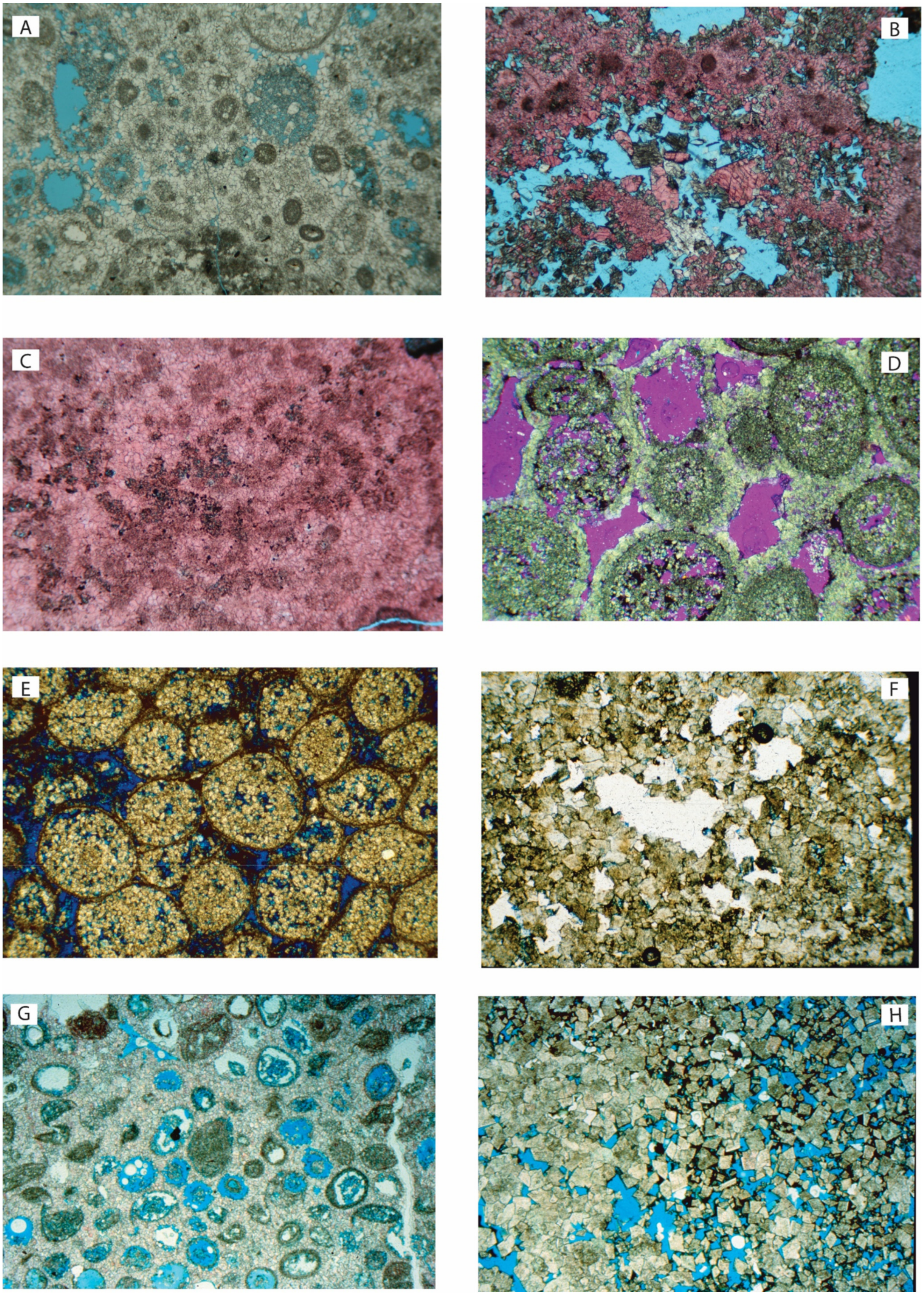
In the Conecuh Embayment, depositional and post-depositional conditions have produced reservoirs with petrophysical properties that differ from the eastern part of the Mississippi Interior Salt Basin. Much of the porosity in the Conecuh Embayment is depositional and enhanced primary resulting from post-depositional meteoric vadose dissolution. The post-depositional setting for this embayment is not conducive for seepage reflux dolomitization, but depositional and post-depositional conditions are favorable for dissolution of carbonates through freshwater leaching. The Smackover nearshore carbonate sand bar complex in this area developed in a subtidal moderate-energy environment that experienced times of freshwater runoff probably associated with humid climatic conditions. The depositional and post-depositional conditions resulted in peloidal and ooid grainstone and packstone reservoirs characterized by depositional interparticle pores and diagenetic solution-enhanced interparticle, grain moldic, and vuggy pore types (Fig. 6A) (Breeden, 2013; Al Haddad and Mancini, 2013).

The depositional and post-depositional conditions in the Conecuh Embayment resulted in microbial boundstone reservoirs characterized by depositional intraframe pores and diagenetic solution-enhanced primary and vuggy pore types (Fig. 6B) (Al Haddad and Mancini, 2013). Al Haddad and Mancini (2013) reported that the microbial boundstone reservoirs are significantly more oil productive than the carbonate sand bar grainstone and packstone reservoirs in Little Cedar Creek Field. They attributed the higher productivity of the microbial boundstone reservoir to its pore system. This boundstone pore system is characterized by more abundant large-sized pores that are interconnected by larger and more uniform pore throats (Fig. 6B) resulting in higher effective porosity, permeability, and connectivity than found in the grainstone and packstone reservoirs (Fig. 6A) according to Al Haddad and Mancini (2013). The microbial boundstone reservoir in Brooklyn Field also is highly productive of hydrocarbons according to Alabama state oil and gas production records from this field.

Petroleum Source Rock Characterization and Petroleum System Modeling

The laminated lime mudstone of the Smackover Formation is a petroleum source rock in southwestern Alabama (Figs. 2 and 7) (Mancini and Benson, 1980). Several studies have contributed to characterizing these beds as the source rocks for the oil and gas discovered in the onshore northeastern Gulf of Mexico. Oehler (1984), Sassen et al. (1987), and Claypool and Mancini (1989) concluded that the Smackover laminated lime mudstone (Fig. 5I) is the main source of petroleum for Smackover reservoirs and other Jurassic and Cretaceous reservoirs in the onshore northeastern Gulf of Mexico. These organic-rich beds, which are located in the lower part of the middle Smackover of Benson (1988) (Fig. 2), attain a thickness of 330 ft (101 m) in the eastern part of the Mississippi Interior Salt Basin (McKee, 1990) and 50 ft (15 m) in the Conecuh Subbasin (Bradford, 1984).

In southwestern Alabama, Smackover total organic carbon contents vary on the basis of a variety of factors, such as paleogeographic setting, stratigraphic variations, and depositional and post-depositional conditions. Samples from Smackover beds have a mean total organic carbon of 0.60% for the Mississippi Interior Salt Basin (Mancini et al., 2003) and 0.65% mean total organic carbon for the Conecuh Subbasin (Mancini et al., 2005). Total organic carbon content of up to 4.55% has been measured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(FACING PAGE) Figure 6. Photomicrographs of Smackover porosity types: (A) depositional interparticle and solution-enlarged primary pores and diagenetic moldic pores, nearshore sand bar grainstone, well permit 13472, 11496 ft (3504 m), 10x; (B) depositional intraframe, solution-enlarged primary and diagenetic vuggy pores, subtidal microbial boundstone, well permit 13472, 11553 ft (3521 m), 10x; (C) bay or lagoonal microbial boundstone fabric, well permit 17045, 10154 ft (3095 m), 10x; (D) solution-enlarged primary pores and diagenetic moldic pores, inner ramp shoal grainstone, well permit 1330, 10313 ft (3143 m), 10x; (E) diagenetic moldic and intercrystalline dolomite pores, inner ramp shoal dolomitic grainstone, well permit 3085, 11182 ft (3408 m), 4x; (F) diagenetic intercrystalline dolomite and vuggy pores, upper shoreface dolomitic grainstone on flank of Wiggins Arch, well permit 1978, 18106 ft (5519 m), 40x; (G) diagenetic moldic and intercrystalline dolomite pores, shoreface-shoal dolomitic grainstone associated with paleohigh, well permit 4997, 13068 ft (3983 m), 1x; and (H) diagenetic intercrystalline dolomite and vuggy pores, microbial dolomitic boundstone associated with paleohigh, well permit 3986, 12971 ft (3954 m), 4x.

in the Smackover lime mudstone beds in the Mississippi Interior Salt Basin (Mancini, et al., 2003). Mancini et al. (1993) reported that high total organic carbon content is found in Smackover condensed section deposits of the Smackover stratigraphic sequence. Also, high total organic carbon is associated with stylolitic surfaces (Sassen et al., 1987). Total organic carbon contents in Smackover lime mudstones in the Conecuh Embayment are generally low, ranging from 0.12 to 0.17% (Mancini et al., 2008).

The dominant kerogen types in the Smackover carbonates are microbial and microbial-derived amorphous in the Mississippi Interior Salt Basin and Conecuh Subbasin. In the Conecuh Embayment, herbaceous kerogen type occurs in the Smackover lime mudstones (Mancini et al., 2008). In southwestern Alabama, thermal maturation levels as determined by vitrinite reflectance range from below 0.45% in updip areas to 4.00% in downdip areas (Mancini et al., 2003, 2005).

Petroleum system modeling by Mancini et al. (2005, 2006) shows that oil generation and expulsion were initiated during the Early Cretaceous and continued into the Cenozoic in the Mississippi Interior Salt Basin, and oil generation and expulsion were initiated during the Late Cretaceous and continued into the Cenozoic in the Conecuh Subbasin (Fig. 7) (Mancini et al., 2005, 2006). Oil generation commenced at a vitrinite reflectance (R_o) level of 0.55% (Sassen and Moore, 1988; Mancini et al., 2006). The thermal maturation profiles for wells located updip or along the margins of the Mississippi Interior Salt Basin and Conecuh Subbasin indicate that the Smackover lime mudstones in these areas are thermally immature and did not generate and/or expel an abundance of crude oil (Mancini et al., 2003, 2006). The presence of herbaceous kerogen in the lime mudstones in the Conecuh Embayment also presents an issue for oil generation, because this type of kerogen is not as oil prone as microbial and amorphous kerogen types. Petroleum system modeling indicates that Smackover hydrocarbons experienced intermediate range migration (Mancini et al., 2003, 2005). Oil migration was initiated in the Early Cretaceous and continued into the Cenozoic in the Mississippi Interior Salt Basin (Mancini et al., 2003) and began in the Late Cretaceous and continued into the Cenozoic in the Conecuh Subbasin (Fig. 7) (Mancini et al., 2006). Migrated and entrapped oils were subjected to thermal cracking with increasing depth of sediment burial and time (Claypool and Mancini, 1989).

The timing of hydrocarbon migration in southwestern Alabama was ideal to insure that the generated, expelled, and migrated oils were trapped in porous and permeable reservoirs capped by impervious seal rocks. Petroleum traps in southwestern Alabama are typically structural traps associated with favorable stratigraphy. However, the petroleum trap at Little Cedar Creek Field in southwestern Alabama is a stratigraphic trap consisting of porous and permeable microbial boundstone and carbonate sand bar grainstone and packstone lithofacies (Mancini et al., 2008). These reservoirs are underlain and overlain by nonporous lime mudstone to wackestone, and they grade into impervious lime mudstone and argillaceous beds near the updip limit of Smackover deposition in the Conecuh Embayment according to Mancini et al. (2008).

The quality of a petroleum source rock is dependent upon the accumulation and preservation of ample organic carbon, the thickness and areal distribution of the organic-rich beds in the basin, the kerogen type, and thermal maturity. These factors along with the timing of hydrocarbon generation, expulsion, migration, and entrapment are important in petroleum system modeling and resource assessment. Based on petroleum source rock characterization and petroleum system modeling, the Mississippi Interior Salt Basin and Conecuh Subbasin in southwestern Alabama would be expected to have high hydrocarbon productivity.

According to production records of the Mississippi, Alabama, and Florida state oil and gas boards through 2018, fields that produce from Jurassic reservoirs in the Mississippi Interior Salt Basin have a high cumulative production total of more than 570 million barrels of oil and 6.0 trillion cubic ft of natural gas, and the Jurassic fields in the Conecuh Subbasin and Embayment also have a high cumulative production of more than 716 million barrels of oil and 2.4 trillion cubic ft of natural gas. Jay Field has produced the highest total of oil (more than 433 million barrels of oil), and Big Escambia Creek Field (Fig. 1) has produced the most gas (more than 1.1 trillion cubic ft of natural gas) in the Conecuh Subbasin according to Alabama and Florida state oil and gas production records.

Petroleum Traps

Although the petroleum trap at Little Cedar Creek Field is stratigraphic, hydrocarbons are typically trapped by a combination of structure and stratigraphy in the Mississippi Interior Salt Basin and Conecuh Subbasin. The structural component for a Smackover combination petroleum trap generally is a Jurassic Louann Salt-related feature or a Paleozoic basement-related structure. The stratigraphic element associated with the salt-related petroleum trap includes grainstone-packstone shoreface-shoal or carbonate sand belt grainstone-packstone lithofacies, and the stratigraphic component associated with the basement-related paleohigh petroleum trap is microbial boundstone and grainstone-packstone shoreface-shoal lithofacies.

In southwestern Alabama, Jurassic Louann Salt movement commenced in the Late Jurassic, and salt trap formation and faulting continued into the Cenozoic (Mancini et al., 2003). Salt-related petroleum traps in the area include Hatter's Pond Field, a faulted salt anticline (Benson and Mancini, 1982); Chunchula Field, a salt anticline (Mancini and Benson, 1980); and Womack Hill Field, an extensional fault related to salt movement (Fig. 1) (Mancini et al., 2004b).

The horst and half-graben features evident in the Paleozoic basement rocks in southwestern Alabama were produced by extensional block faulting associated with the break up of Pangea. Block faulting was initiated in the Late Triassic to Early Jurassic and was related to tensional stresses associated with the opening of the Atlantic Ocean (Prather, 1992). The extensional block faulting continued into the Late Jurassic in this region. The structural features resulting from the block faulting in the Paleozoic basement rocks produced the structural component for the Smackover combination basement-related paleohigh petroleum traps. These topographic highs also provided an elevated surface above the seafloor to support microbial and shoreface lithofacies development.

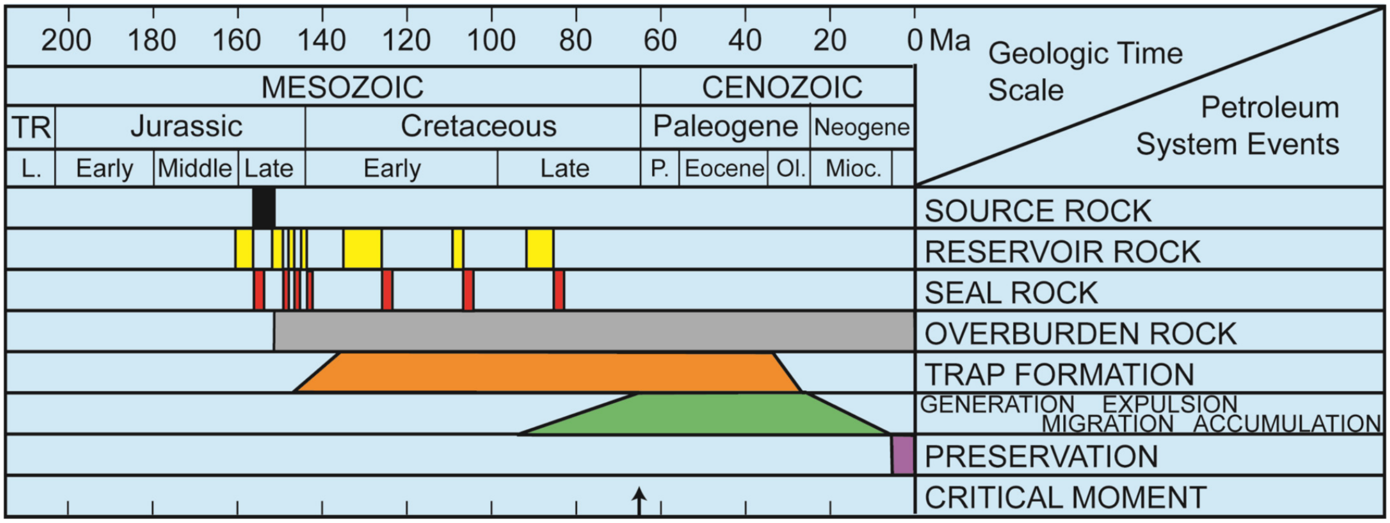

Figure 7. Petroleum system event chart for Smackover source beds and associated reservoir, seal, and overburden rocks in the Conecuh Subbasin showing the timing of hydrocarbon generation, expulsion, migration, and entrapment constructed using information from Mancini et al. (2005, 2006).

Analysis of the well log and seismic data available for basement-related paleohigh petroleum traps in southwestern Alabama indicates that extensional block faulting formed horst, graben, and half-graben features. Figure 8A shows a conceptual model of how a paleohigh petroleum trap could form in association with a horst feature and that topographic high could serve as an elevated surface above the seafloor that microbes could colonize and develop into a microbial buildup. Figure 8C illustrates the petroleum trap at Appleton Field, Conecuh Subbasin (Fig. 1), as interpreted by Mancini et al. (2000, 2004a), which represents an example of the horst structure model (Fig. 8A), where the paleohigh remained below sea level during microbial and shoreface lithofacies development. Paleohigh petroleum traps could also form in association with half-graben features as a result of a series of normal faults (Fig. 8B). Figure 8D shows the petroleum trap at Melvin Field (Fig. 1), Mississippi Interior Salt Basin, as interpreted by Baria et al. (1982) and Mink and Mancini (1995), which is an example of the half-graben structure model (Fig. 8B).

Although the structural component for many of the basement-related paleohigh petroleum traps in southwestern Alabama can be assigned to one of these two structure models, some of the traps are more complicated due to the geohistory of a particular feature. To understand the stratigraphic component of these traps, knowledge of the tectonic and depositional histories of individual paleohighs is important. The paleohigh petroleum trap at Vocation Field (Fig. 1) is an example of the horst structure model, but this paleohigh remained above sea level during Smackover deposition (Llinas, 2004). Thus, Smackover microbial and shoreface deposits only accumulated on the flanks of the structure (Fig. 8E). The paleohigh petroleum trap at Fishpond Field (Fig. 1) is an example of the horst structure model, but this microbial buildup experienced multiple microbial growth phases due to changes in relative sea level, rates of subsidence, rates of sediment compaction, and/or depositional conditions (Fig. 8F) (Owen, 2017). This is not unusual because at Appleton Field Markland (1992) observed during core study an alternation in Smackover microbial growth forms from layered bindstone (moderate-energy and low background sedimentation) to dendroidal bafflestone (low-energy and increased background sedimentation) (Fig. 5E). In addition, Kopaska-Merkel (1998) reported the presence of soil horizons, brecciated intervals, and tepee structures associated with Smackover microbial beds in a core from West Appleton Field (Fig. 1).

CONCLUSIONS

The homoclinal carbonate ramp depositional model has been used to interpret Upper Jurassic Smackover carbonate sedimentation in the onshore northern Gulf of Mexico, and the model has provided a strategy to explore for hydrocarbon productive reservoir facies in this region. However, an integrated well log and core study of the Smackover Formation and associated Jurassic lithofacies in the Conecuh Embayment in the onshore northeastern Gulf of Mexico has shown that modifications to this model are required to describe adequately the depositional characteristics and patterns of Smackover carbonate lithofacies observed in the Conecuh Embayment of southwestern Alabama.

The findings from this study show that Smackover carbonate deposition in the onshore northeastern Gulf of Mexico area was variable mainly due to tectonic history, regional paleogeography, antecedent topography, salt movement, and depositional conditions, particularly changes in relative sea level. In the eastern part of the Mississippi Interior Salt Basin, higher-energy carbonate shoal and shoreface lithofacies dominate inner ramp Smackover deposition, while in the Conecuh Embayment Smackover moderate-energy nearshore subtidal carbonate sand bar and low-energy microbial (thrombolite) lithofacies characterize Smackover deposition. The microbial deposits extend to the northeast and probably represent bay or lagoonal deposits in this embayment. The Conecuh Embayment is bordered and protected on the northwest by the Conecuh Ridge and on the southeast by the Pensacola Arch. In this area, the updip limit of Smackover deposition may be defined as an embayed shoreline rather than a high-energy shoreline.

The petroleum traps in the Conecuh Subbasin are typically combination traps. The structural component for a Smackover combination petroleum trap generally is a Jurassic Louann Salt-related feature or a Paleozoic basement-related structure. The basement structures are interpreted as horst and half-graben features produced by extensional block faulting. The stratigraphic element associated with the salt-related petroleum trap includes grainstone-packstone shoreface-shoal or carbonate sand belt grainstone-packstone lithofacies, and the stratigraphic component associated with the basement-related paleohigh petroleum trap is microbial boundstone and grainstone-packstone shoreface-shoal lithofacies.

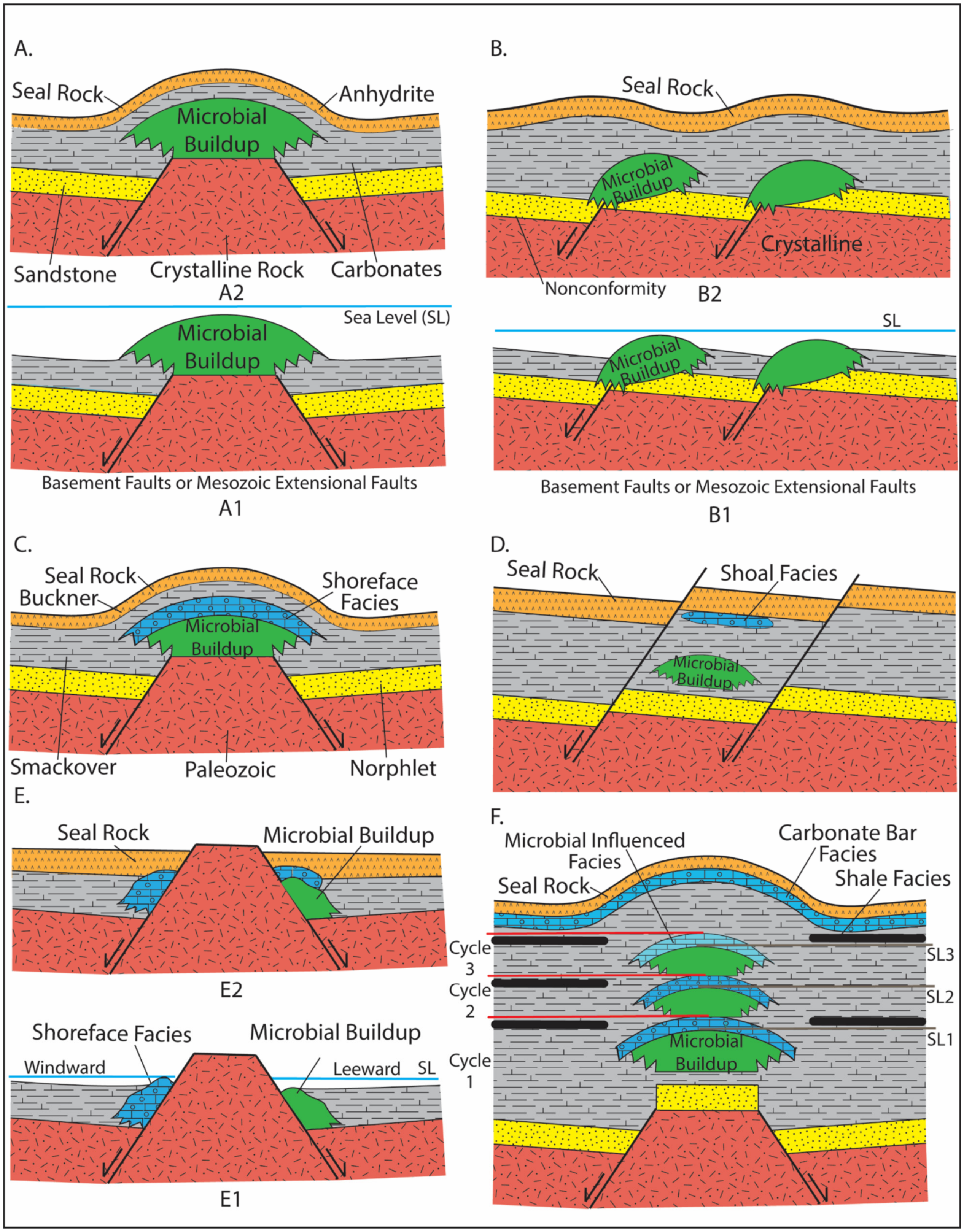

Figure 8. Conceptional structural trap development associated with pre-Jurassic paleohighs and interpretation of Smackover combination basement-related paleohigh petroleum traps in southwestern Alabama: (A) conceptional model for a horst feature and petroleum trap in two steps (A1 and A2); (B) conceptional model for a half-graben feature and petroleum trap in two steps (B1 and B2); (C) petroleum trap at Appleton Field (Mancini et al., 2000), example of the horst structure model, where the paleohigh remained below sea level during lithofacies development; (D) petroleum trap at Melvin Field (Mink and Mancini, 1995), example of the half-graben structure model; (E) petroleum trap at Vocation Field (Llinas, 2004), example of the horst structure model, where the crest of the paleohigh remained above sea level during lithofacies development resulting in the lithofacies only being deposited on the flanks of the feature in two steps (E1 and E2); and (F) petroleum trap at Fishpond Field (Owen, 2017), example of the horst structure model, exhibiting multiple stacked microbial lithofacies.

A revised carbonate depositional model provides potential Smackover targets for petroleum exploration in the onshore northeastern Gulf of Mexico. In the Conecuh Embayment, these include: (1) progradational subtidal carbonate sand bar lithofacies in nearshore settings, (2) bay or lagoonal microbial facies, and (3) subtidal thrombolite buildup facies not associated with high-relief basement structural features.

The quality of a petroleum source rock is dependent upon the accumulation and preservation of ample organic carbon, the thickness and areal distribution of the organic-rich beds in the basin, the kerogen type, and thermal maturity. These factors along with the timing of hydrocarbon generation, expulsion, migration and entrapment are important in petroleum system modeling and resource assessment. Based on petroleum source rock characterization and petroleum system modeling, the Mississippi Interior Salt Basin and Conecuh Subbasin in southwestern Alabama would be expected to have high hydrocarbon productivity. State production records as of 2018 show that fields that produced from Jurassic reservoirs in the Mississippi Interior Salt Basin have a high cumulative production total of more than 570 million barrels of oil and 6.0 trillion cubic ft of natural gas, and the Jurassic field reservoirs in the Conecuh Subbasin and mbayment also have a high cumulative production of more than 716 million barrels of oil and 2.4 trillion cubic ft of natural gas).

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