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GEOLOGICAL SURVEY OF ALABAMA REPRINT SERIES 89

GEOLOGICAL SURVEY OF ALABAMA

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REPRINT SERIES 89

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Reprinted from
Gulf Coast Association of Geological Societies Transactions,
v. 42, 1992, p. 237-244

Tuscaloosa, Alabama
1992

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ABSTRACT

The Upper Jurassic Smackover Formation is a prolific oil and gas reservoir in the eastern Gulf Coastal Plain. To date, over 838 million barrels of oil and condensate and 2.4 trillion cubic feet of natural gas have been produced from 157 Smackover fields located in the area. The tectonic setting and depositional and postdepositional history of the Smackover carbonates and associated strata have been conducive to the formation of numerous petroleum traps, the accumulation and preservation of substantial organic matter, the thermogenic generation and preservation of large quantities of hydrocarbons, the formation of extensive porous and permeable reservoirs, the subsequent enhancement of reservoir quality, and the formation of a regional impervious seal rock. In addition, the timing of trap formation and hydrocarbon generation and migration have been important to oil and gas entrapment and preservation. An understanding of the factors that contribute to the hydrocarbon productivity of the Smackover will assist with improving the recovery of oil and gas from these limestones and dolostones.

INTRODUCTION

The Upper Jurassic (Oxfordian) Smackover Formation has served as one of the primary oil and gas exploration targets in the eastern Gulf Coastal Plain area since the discovery of hydrocarbons from Tinsley field in Mississippi in 1951. To date over 838 million barrels of oil and condensate and 2.4 trillion cubic feet of natural gas have been produced from 157 Smackover fields located in the area. The purpose of this paper is to provide an overview of the hydrocarbon characteristics of the Upper Jurassic Smackover Formation of the eastern Gulf Coastal Plain. In particular, the principal factors that contribute to the hydrocarbon productivity of these carbonates are discussed. An understanding of these factors will assist in improving the recovery of oil and gas from these limestones and dolostones.

GEOLOGIC SETTING

The Smackover Formation of the eastern Gulf Coastal Plain was deposited on a differentially subsiding carbonate ramp developed on the passive southern margin of the North American continent. Pre-Smackover paleotopography and syndepositional deformation associated with salt movement affected the distribution of Smackover lithofacies. Structural elements that either alone or combined have altered the general ramp trend of carbonate deposition include basement features associated with continental suturing or rifting, features formed due to Jurassic salt movement, and Jurassic eolian dune paleotopographic highs. The major positive basement structures that influenced the distribution and nature of Smackover deposits in the study area are the Wiggins arch complex, which includes the Wiggins arch, Hancock ridge, Baldwin high, and related paleohighs; the Choctaw ridge complex; the Conecuh ridge complex; and the Pensacola-Decatur ridge complex (Fig. 1). The northeast-trending structural elements form salients and are, in part, associated with the Appalachian fold and thrust trend that was formed by Late Paleozoic tectonic events resulting from the convergence of the North American and Afro-South American continental plates. A rift-related system of horst and graben features resulted in response to tensional stresses associated with continental rifting. Movement of Louann Salt is believed to be related, in part, to reactivation along this system. In addition to the impact on the distribution of carbonate deposits, positive areas within basins and along basin margins provided sources for siliciclastic sediments which are associated with Smackover carbonates.

The Mississippi interior salt basin was a large, actively subsiding depocenter during Jurassic time. The Mobile graben is considered to be the eastern limit of the Mississippi interior salt basin. On the periphery of the Mississippi interior salt basin, Jurassic strata, including Smackover carbonates, thin dramatically or terminate on the Wiggins arch complex to the south and on the Choctaw ridge complex to the north and northwest. Salt pillows characterize the updip areas of the basin, whereas salt diapirs are common in the central part. The Conecuh and Manila embayments and the area south of the Wiggins arch were also Smackover depocenters. The western boundary of the Manila embayment is the Choctaw ridge complex, and the eastern boundary is the Conecuh ridge complex. The Conecuh embayment is bordered by the Conecuh ridge complex and Baldwin high to the north and west and the Pensacola-Decatur ridge complex to the east and south. The Smackover thins dramatically or terminates on the Conecuh and Pensacola-Decatur ridge complexes and Baldwin high.

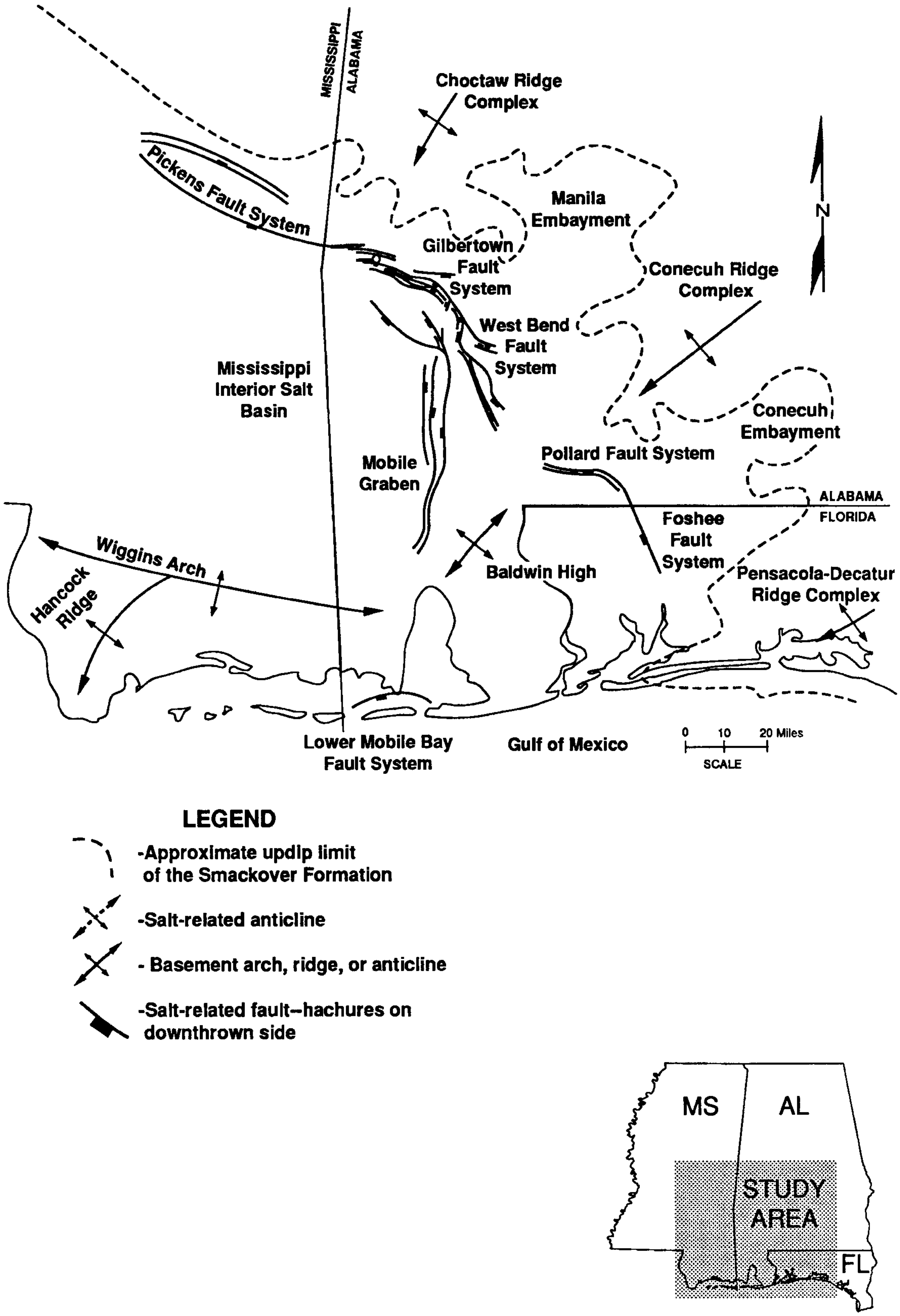

Figure 1. Location map illustrating major structural features in the eastern Gulf Coastal Plain.

Halokinesis of the Jurassic Louann Salt has produced a complex array of salt-related structural elements in the area, including the Hatchetigbee anticline. Salt-related structures include diapirs, pillows, anticlines, and extensional fault and graben systems. The regional peripheral fault trend consists of a group of genetically related, generally *en echelon* extensional faults which are associated with salt movement. In the eastern Gulf Coastal Plain, this trend is composed of the Pickens, Gilbertown, West Bend, Pollard, and Foshee fault systems. The faults of the regional peripheral trend are generally parallel or subparallel to regional strike, and the trend approximates the updip limit of thick Jurassic salt. Most of the faults in the trend are normal, down-to-the-basin or antithetic faults that form grabens which are generally 5 to 8 miles across (Murray, 1961). These faults are listric, and the dips of fault surfaces range from 35° to 70° (Murray, 1961). Displacements on major faults in the trend range from 200 feet to more than 2,000 feet in the Jurassic section (Mancini et al., 1985). An extensive group of east-west trending Jurassic faults, including the Lower Mobile Bay fault system, occur in coastal and offshore Alabama (Bearden, 1987). The Lower Mobile Bay fault, which is one of the larger faults affecting Jurassic strata in this system, exhibits displacement of approximately 600 feet in the Jurassic section. This normal fault is listric and pull-apart, extending upward into Cretaceous strata (Bearden, 1987).

Many of the salt-related faults in the area terminate upward into or just above the Haynesville Formation and sole downward into the Louann Salt (Mink et al., 1990). Faults that cut the Jurassic section and extend upward into the Haynesville typically display growth during deposition of the upper Smackover and the Haynesville. The development of salt structures has resulted in numerous petroleum traps, including salt anticlines, faulted salt anticlines, and extensional fault traps, in the study area.

STRATIGRAPHY

The Smackover Formation overlies the Norphlet Formation (Fig. 2), and in the area of study, the formational contact is usually sharp but can be gradational over an interval of a few feet or less. Although the carbonate rocks of the Smackover are regionally extensive, paleotopography associated with Norphlet dunes and interdune areas had a significant impact on the distribution and thickness patterns of these rocks in some areas. Smackover thicknesses range up to 550 feet. Deposition of the Smackover occurred on a modified carbonate ramp in a variety of paleoenvironments ranging from supratidal to below wave base.

Three stratigraphically successive Smackover lithofacies associations have been recognized in the eastern Gulf Coastal Plain. These units have been informally termed the lower, middle, and upper members of the Smackover (Moore, 1984; Benson, 1988). A thin sequence of intertidal to subtidal, stromatolitic mudstone and intraclastic and peloidal-oncoidal wackestone and packstone comprises the lower Smackover member (Benson, 1988). A thick interval of dominantly subtidal, laminated mudstone interbedded with peloidal and skeletal wackestone and packstone composes the middle member (Mancini and Benson, 1980; Benson, 1985). The interbedded laminated mudstone is typically dark-gray to black, nonfossiliferous, and exhibits minor bioturbation (Sassen and Moore, 1988). The upper member of the Smackover consists of a thick sequence of subtidal to intertidal, oolitic, oncolitic, and peloidal grainstone and packstone that is interbedded with intertidal to supratidal laminated or fenestral mudstone and local anhydritic sabkha and salina deposits (Mancini and Benson, 1980; Benson, 1988; Mann, 1988). Siliciclastics commonly are found in the upper member, particularly along the eastern updip margin of Smackover deposition. Algal (microbial) boundstone is an important constituent of the Smackover in parts of the study area, especially around paleohighs, such as the Wiggins arch and the Choctaw and Conecuh ridge complexes (Baria et al., 1982). The boundstone lithofacies generally occurs in the lower or upper members of the Smackover. The Haynesville Formation conformably overlies the Smackover Formation throughout much of the study area.

DEPOSITIONAL SEQUENCES AND ENVIRONMENTS

Four regional Jurassic unconformities have been identified by Todd and Mitchum (1977) in the Gulf of Mexico area. These unconformities have been used to divide the Jurassic strata, including the Smackover Formation, into three depositional sequences associated with transgression and regression resulting from sea level fluctuations (Todd and Mitchum, 1977; Vail et al., 1984; Mancini et al., 1990). The LZAGC-4.1 (lower Zuni A Gulf Coast) sequence (Mancini et al., 1990) is composed of the marine reworked sandstone of the upper part of the Norphlet Formation, the Smackover Formation, and the Buckner Anhydrite Member and middle part of the Haynesville Formation (Fig. 2). The LZAGC-4.1 sequence represents a composite of four depositional cycles recognized globally by Haq et al. (1988). The LZAGC-4.1 cycle includes a basal type 2 sequence boundary, shelf margin systems tract deposits, transgressive systems tract deposits, and regressive highstand systems tract deposits.

Deposition of this type 2 sequence was initiated with transgression which resulted in the reworking of eolian sandstone of the Norphlet Formation by marine processes. These marine sandstones accumulated as shelf margin systems tract deposits in shoreface environments. The initiation of Smackover carbonate deposition occurred during a major Jurassic transgressive event in the Gulf of Mexico basin. This event is indicated by the widespread distribution of this marine unit throughout the Gulf of Mexico region.

Depositional Sequences	Lithostratigraphy	Deposits	Stages
LZAGC-4.2	upper Haynesville clastics & anhydrites	Highstand	Kimmeridgian
	upper Haynesville carbonates & shales	Condensed	
	upper Haynesville sandstones	Transgressive	
LZAGC-4.1	middle Haynesville clastics, evaporites & carbonates; Buckner anhydrites; Smackover mudstones to grainstones	Highstand	
	Smackover carbonate mudstones	Condensed	
	Smackover carbonate mudstones, wackestones & packstones	Transgressive	Oxfordian
	Norphlet marine sandstones	Shelf Margin	
LZAGC-3.1	Norphlet continental clastics	Highstand	
	Pine Hill anhydrites & shales	Condensed	
	Louann salt; Werner evaporites & clastics	Transgressive	Callovian

Figure 2. Jurassic lithostratigraphy and depositional sequences in the eastern Gulf Coastal Plain.

Rocks deposited during the transgressive phase of the LZAGC-4.1 cycle exhibit the characteristics of a catch-up transgressive carbonate sedimentation system which lags behind relative sea level rise as a result of rapid rise and/or a relatively low rate of carbonate productivity (Sarg, 1988). Mud-rich lithologies dominate catch-up systems. The lower Smackover, which generally includes a sequence of intraclastic wackestone and packstone, peloidal and oncoidal wackestone and packstone, and stromatolitic carbonate mudstone, characterizes the lower part of this transgressive systems tract. The intertidal to subtidal stromatolitic carbonate mudstone represents initial carbonate sediment accumulation in low areas, whereas deposition of the intertidal to subtidal wackestone and packstone occurred on basement paleohighs, on salt highs, or on eolian dunes.

The middle Smackover laminated carbonate mudstone constitutes the preponderance of the deposits of the transgressive systems tract. These subtidal mud-rich and organic-rich strata dominate this systems tract and can attain thicknesses in excess of 250 feet. Peloidal and skeletal wackestone and packstone are found near the top of the middle Smackover section. The upward increase in particle abundance in these rocks signals a shift from the catch-up carbonate system of the lower and middle Smackover to the keep-up system that characterizes the upper Smackover. Usually, wackestone and packstone of the middle Smackover grade up into stacked, shallowing-upward parasequences of subtidal to intertidal oolitic, oncolitic, peloidal grainstone and packstone interbedded with intertidal to supratidal laminated or fenestral carbonate mudstone which commonly exhibit mudcracks, fenestral fabric and exposure surfaces. Some cycles are capped by supratidal sabkha or salina deposits. These successions exhibit characteristics of a keep-up carbonate sedimentation system. Keep-up systems are characterized by rapid rates of sediment accumulation, are dominated by grain-rich, mud-poor parasequences, and commonly contain small amounts of early marine cement (Sarg, 1988), which is the case in the Smackover of southwest Alabama.

The upper Smackover constitutes the carbonate part of the progradational, regressive highstand phase of the LZAGC-4.1 cycle. The Buckner Anhydrite Member and middle part of the Haynesville Formation comprise the evaporitic and terrigenous clastic parts of this cycle. The Buckner accumulated as subaqueous to subaerial strata that were deposited in a series of upward shallowing parasequences (Mann, 1988). The sandstones and interbedded shales, carbonates and evaporites of the middle part of the Haynesville accumulated in subtidal to supratidal environments.

HYDROCARBON PRODUCTIVITY CHARACTERISTICS

Smackover petroleum traps in southwest Alabama are principally structural or combination structural and stratigraphic traps. Many of these traps result from halokinesis of the Jurassic Louann Salt. Movement of the Louann Salt was initiated in the Jurassic and continued into the Tertiary in parts of the study area. Halokinesis has produced anticlines, faulted anticlines, diapiric structures, pillows, and extensional faults that serve as petroleum traps. Basement-related structural traps are also common in southwest Alabama. These traps typically are anticlines associated with basement paleohighs. Combination traps involve pinch-outs of porosity and/or permeability as the stratigraphic component in association with salt anticlines, structural noses, or basement-related anticlines.

Smackover oils are enriched in aromatic hydrocarbons, have pristane/phytane ratios of less than one, are enriched in sulfur, and have saturated and aromatic hydrocarbon fractions with carbon isotope differences of almost zero. These characteristics support the contention that these oils have been derived from algal (microbial) kerogen associated with marine carbonates which accumulated in a reducing environment (Claypool and Mancini, 1989). Subtle differences in the molecular and isotopic compositions of the oils are attributed to variations in depositional conditions of the organic facies of the Smackover source beds and the degree of maturation of the oils. For example, organic facies in the Manila and Conecuh embayments contain more terrestrial organic matter than those facies in the Mississippi interior salt basin (Sassen, 1989). Also, updip oils closely approximate the original composition of the crude oil, while the makeup of the gas-condensates reflect continued maturation in the reservoir as a result of increased depth of burial (Claypool and Mancini, 1989).

The organic-rich, laminated, lower to middle Smackover carbonate mudstones are believed to be the petroleum source rocks for the Smackover oil and gas resources of southwest Alabama. These rocks, in fact, are the principal source rocks for much of the oil and gas discovered in the Mesozoic rocks found in the area (Erdman and Morris, 1974; Hughes, 1984; Oehler, 1984; Sassen et al., 1987; Sofer, 1988; Sassen, 1989; Claypool and Mancini, 1989). These carbonate mudstones accumulated in a catch-up system characterized by low-energy, hypersaline, anoxic intertidal to subtidal depositional conditions. Because of these paleoenvironmental conditions and due to a slow rate of sediment accumulation, substantial amounts of organic matter (as much as 2.19 percent of amorphous and algal kerogen with an average of 0.81 percent of total organic matter) were deposited, concentrated, and preserved in certain lithofacies of these carbonate sediments. The low energy conditions favored the accumulation of organic matter, in part, because the hypersaline and oxygen-poor conditions discouraged the establishment of large populations of algal (microbial) ingesting organisms in this environment.

The petroleum source rock capability of the Smackover laminated mudstones was enhanced by a number of factors. Pressure solution acted to concentrate organic matter along stylolites (Sassen et al., 1987). The Smackover was subjected to elevated temperatures early in its burial history due to initial rapid sediment accumulation and to tectonic processes associated with early rifting of the Gulf of Mexico basin, and these elevated temperatures resulted in the generation and migration of liquid hydrocarbons from the Smackover source rocks during the Cretaceous (Nunn and Sassen, 1986). Dissolution and fracturing associated with salt movement facilitated migration, and impermeable evaporites overlying Smackover reservoirs acted as effective roof rocks (Sassen, 1989).

Oolitic, oncolitic, peloidal grainstone, dolograinstone and crystalline dolostone are the principal petroleum reservoirs in the upper Smackover. These rocks accumulated as highstand deposits of the LZAGC-4.1 depositional sequence associated with a carbonate keep-up system. Characteristics of these reservoirs indicate high-energy, subtidal to intertidal depositional conditions, and these strata have undergone favorable diagenetic changes which have acted to increase porosity and permeability through dissolution and dolomitization. Porosity types in the Smackover include interparticulate, moldic, vuggy, and intercrystalline.

The two most commonly reported mechanisms for replacement dolomitization in the Smackover are reflux dolomitization, which is associated with hypersaline brines generated during deposition of the overlying Buckner Anhydrite Member of the Haynesville Formation, and mixing zone dolomitization, which is associated with the mixing of meteoric and marine waters (Vinet, 1984; Prather, 1992). Dolomitization in the Smackover probably was initiated with the reflux of hypersaline brines resulting from evaporation in coastal sabkha to shallow subaqueous environments during the time of deposition of Buckner evaporites (Fig. 3). With continued fall in sea level, the Buckner surface was buried by prograding shallow marine to marginal marine Haynesville rocks. A freshwater lens resulted, and this lens migrated from the exposed inner shelf basinward with progressive sea level fall. Mixing of meteoric waters with marine waters occurred along the front of the freshwater lens and resulted in dolomitization in parts of the upper Smackover (Fig. 3). In addition, Smackover grainstones subjected to meteoric water movement were particularly susceptible to leaching. Dissolution was especially common in the updip areas and around paleohighs.

The productivity of the Smackover Formation in the eastern Gulf Coastal Plain can be attributed directly to the hydrocarbon characteristics of these limestones and dolostones. The timing of the petroleum trap formation in relationship to the timing of hydrocarbon generation

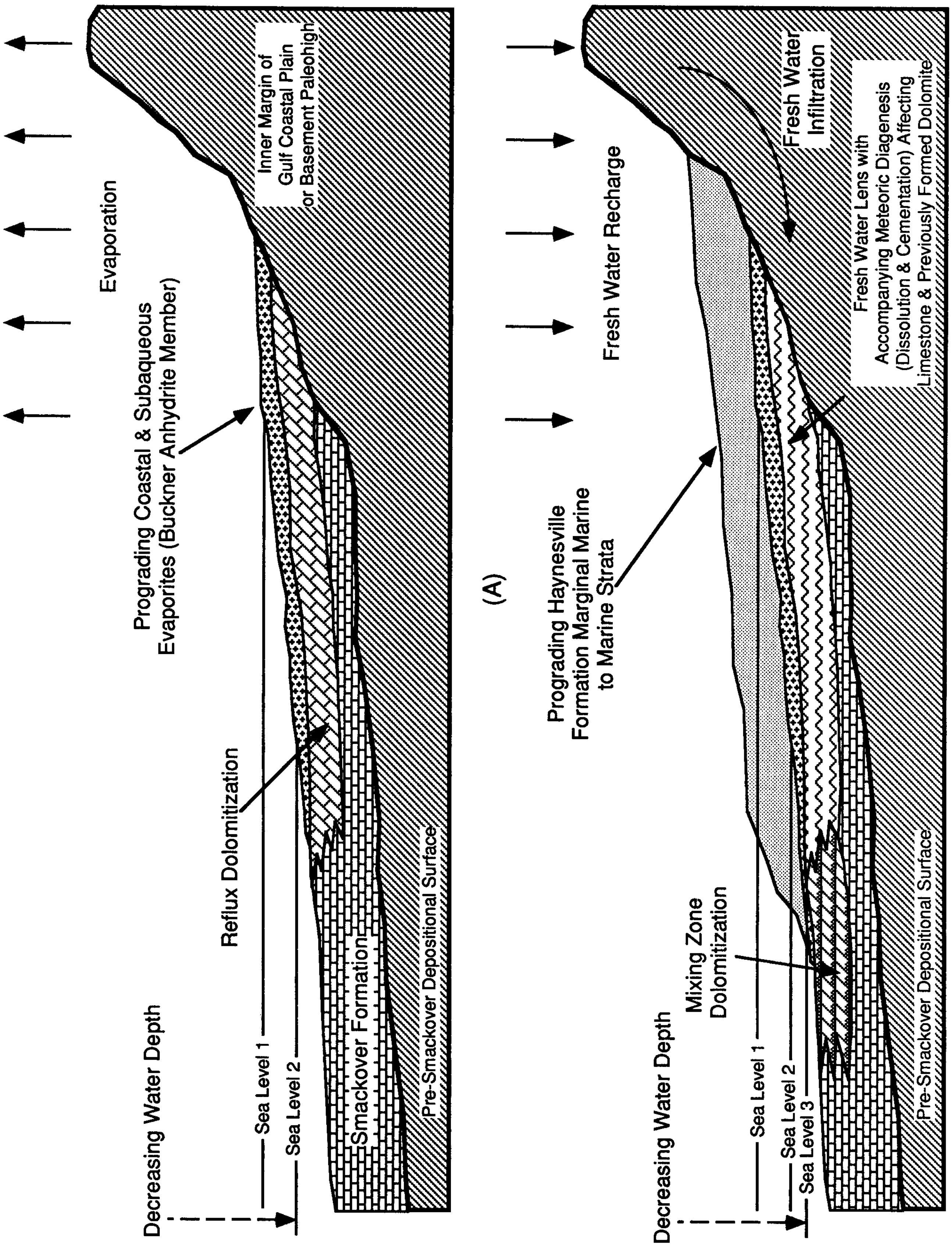

Figure 3. Models for replacement dolomitization in the Smackover Formation (a) reflux and (b) mixing zone.

and migration has been conducive to the entrapment and preservation of substantial quantities of Smackover oil and gas. The tectonic setting, especially the presence of a significant thickness of salt, and the timely movement of these evaporites has produced a host of potential petroleum traps. The depositional and postdepositional history of the Smackover carbonates have resulted in a thick section of porous and permeable reservoir rocks, prolific petroleum source beds, and an areally extensive impervious anhydrite seal rock. The stratigraphic relationships of the Smackover petroleum source beds directly underlying and/or interbedded with the upper Smackover reservoirs and the Buckner anhydrite seal rocks directly overlying these reservoirs have contributed greatly to the productivity of the Smackover Formation.

CONCLUSIONS

1. The Smackover Formation of the eastern Gulf Coastal Plain was deposited on a differentially subsiding carbonate ramp surface. The overall ramp morphology was modified by pre-Smackover paleotopography.

2. Evaporite accumulation prior to Smackover deposition was a crucial element of the geologic history of the area. Halokinesis produced an array of salt-related structural and combination petroleum traps.

3. Paleozoic basement and Norphlet paleotopographic highs also contributed to the formation of petroleum traps.

4. Lower to middle Smackover organic-rich, laminated carbonate mudstones that accumulated as transgressive to condensed section deposits associated with a carbonate catch-up system are the principal petroleum source rocks. The early thermal history of these rocks was conducive for hydrocarbon generation, migration, and preservation. Diagenetic processes such as dissolution and fracturing in association with salt movement provided enhanced migration pathways.

5. Upper Smackover grainstones, dolograinstones and dolostones that accumulated as highstand deposits associated with a carbonate keep-up system are the chief petroleum reservoir rocks. Grainstones have undergone favorable diagenetic changes which have acted to increase porosity and permeability through dissolution and dolomitization.

6. Initial dolomitization was associated with the reflux of hypersaline brines generated as a result of evaporation in coastal sabkha to shallow subaqueous environments. Later the establishment of a freshwater lens that migrated from the exposed inner shelf basinward resulted in mixing zone dolomitization and the dissolution of carbonate particles in the meteoric vadose zone.

7. Smackover porosity includes principally interparticulate, moldic, vuggy, and intercrystalline.

8. Highstand deposits of the Buckner Anhydrite Member of the Haynesville Formation that overlie the Smackover limestone and dolostone reservoirs are effective seal rocks.

9. Movement of the Jurassic Louann Salt was initiated in the Jurassic and continued into the Tertiary, and liquid hydrocarbon generation and migration began during the Cretaceous and continued into the Tertiary with peak oil generation occurring in the Cretaceous. Such structural and migration timing was ideal for hydrocarbon entrapment and preservation.

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