Petroleum Source Rocks of the Onshore Interior Salt Basins, North Central and Northeastern Gulf of Mexico

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Abstract

Understanding the burial and thermal maturation histories of the strata in the onshore interior salt basins of the north central and northeastern Gulf of Mexico area is critical in petroleum source rock identification and characterization. The burial and thermal maturation histories of the strata in these basins and subbasins are consistent with the rift-related geohistory of these features. Source rock analysis and thermal maturity modeling indicate that lime mudstone of the Upper Jurassic Smackover Formation served as an effective regional petroleum source rock in the North Louisiana Salt Basin, Mississippi Interior Salt Basin, Manila Subbasin and Conecuh Subbasin. The Upper Cretaceous marine shale was an effective local petroleum source rock in the Mississippi Interior Salt Basin and a possible local source bed in the North Louisiana Salt Basin given the proper organic facies. Lower Cretaceous lime mudstone was an effective local petroleum source rock in the South Florida Basin, and these rocks were possible local source beds in the North Louisiana Salt Basin and Mississippi Interior Salt Basin given the proper organic facies. Uppermost Jurassic strata were effective source rocks in Mexico, and therefore, were possible source beds in the North Louisiana Salt Basin given the proper organic facies. Lower Tertiary shale and lignite have been reported to have been source beds in south Louisiana and southwestern Mississippi, but these beds have not been subjected to favorable burial and thermal maturation histories required

for petroleum generation in the North Louisiana Salt Basin, Mississippi Interior Salt Basin, Manila Subbasin, and Conecuh Subbasin.

Introduction

Petroleum reservoirs in the interior salt basins and subbasins of the onshore northern Gulf of Mexico have produced 4 billion barrels of oil and 21 trillion cubic feet of natural gas. The lime mudstone beds of the Upper Jurassic Smackover Formation are the main petroleum source rocks from which this oil and gas have been generated. The Smackover Formation has been documented to be an effective regional source rock in the northern Gulf of Mexico (Oehler, 1984; Sassen et al., 1987; Claypool and Mancini, 1989).

The purpose of this paper is to provide data and information regarding the organic and thermal maturation characteristics of potential petroleum source rocks and in particular the Smackover lime mudstone beds from the onshore interior salt basins and subbasins in the north central and northeastern Gulf of Mexico. These data are a combination of new information and data compiled from previous studies, especially those of Sassen et al. (1987), Sassen and Moore (1988), Claypool and Mancini (1989), and Mancini et al. (2003).

Geologic Setting

The geologic history of the North Louisiana Salt Basin, Mississippi Interior Salt Basin, Manila Subbasin and Conecuh Subbasin (Fig. 1) is directly linked to the evolution of the Gulf of Mexico basin (Wood and Walper, 1974). The Gulf of Mexico is a divergent margin basin dominated by extensional tectonics and wrench faulting (Pilger, 1981; Miller, 1982; Klitgord et al., 1984; Van Siclen, 1984; Pindell, 1985; Salvador, 1987; Winker and Buffler, 1988; Buffler, 1991). The origin of the Gulf of Mexico basin consists of phases of crustal extension and thinning, of rifting and sea-floor spreading, and of thermal subsidence (Nunn, 1984).

Sawyer et al. (1991) proposed the following as a model for the evolution of the Gulf of Mexico and related onshore interior salt basins and subbasins based on the distribution of crust type. A Late Triassic-Early Jurassic early rifting phase is typified by half-grabens bounded by listric normal faults and filled with nonmarine red bed sediments and volcanics. A Middle Jurassic phase of rifting, crustal attenuation and the formation of transitional crust is characterized by a pattern of alternating basement paleotopographic highs and lows and the accumulation of thick salt deposits. A Late Jurassic phase of sea-floor spreading and oceanic crust formation is typified by an extensive marine transgression as a result of crustal cooling and subsidence. Subsidence continued into the Early Cretaceous and a carbonate shelf margin developed along the tectonic hinge zone of differential subsidence between thick transitional crust and thin transitional crust.

This depositional pattern was interrupted by a time of igneous activity and global sea-level fall during the Late Cretaceous (mid-Cenomanian) that produced a major drop in sea level and resulted in the exposure of the shallow Cretaceous platform margin that rimmed the Gulf (Salvador, 1991). This mid-Cenomanian unconformity is well developed in the northern Gulf of Mexico area.

The Mesozoic and Cenozoic sediments of the northern Gulf of Mexico accumulated as a seaward-dipping wedge in differentially subsiding basins (Martin, 1978). Basement cooling and subsidence resulted in an infilling of the accommodation space. Structural elements that affected the deposition of these sediments included basement features associated with plate movement and features formed due to the movement of Jurassic salt. The graben system that developed is a result of rifting, and its geometry is a reflection of the direction of plate separation (MacRae and Watkins, 1996). The Lower Cretaceous shelf margin corresponds to a major basement hinge. This feature dominated carbonate deposition throughout the Early Cretaceous.

The chief positive basement features that influenced the distribution and nature of Mesozoic deposits are the Sabine Uplift, Monroe Uplift, Wiggins Arch, Choctaw Ridge, the Conecuh Ridge, the Pensacola Arch, and the Decatur Ridge. The Choctaw, Conecuh, Pensacola, and Decatur Ridge complexes are associated with the Appalachian fold and thrust structural trend that was formed in the late Paleozoic by tectonic events resulting from convergence of the North American and African-South American continental plates. The Sabine Uplift, Monroe Uplift and Wiggins Arch are associated with crustal extensional and rifting (Miller, 1982; Sawyer et al., 1991). These features may be remnants of the rifted continental margin of North America. Paleotopography had a significant impact on the distribution of sediment, and positive areas within basins and along basin margins provided sources for Mesozoic terrigenous sediments (Mancini et al., 1985). The North Louisiana Salt Basin and Mississippi Interior Salt Basin, which are major negative structural features are classified as the interior fracture portion of a margin sag basin using the classification of Kingston et al. (1983). These extensional basins were associated with early rifting linked with wrench faulting and were actively subsiding depocenters throughout the Mesozoic and into the Cenozoic.

Movement of the Jurassic Louann Salt has produced an array of structural features (Martin, 1978). Salt-related structures include diapirs, articlines, and entensional fault and half graben systems. Structural features resulting from halokinesis include the regional peripheral fault trend and numerous salt domes and anticlines. The regional peripheral fault trend consists of a series of en echelon extensional faults and half grabens that are associated with salt movement. Structural deformation related to salt movement was initiated probably during the Late Jurassic (Dobson and Buffler, 1997).

Sedimentation in the northern Gulf of Mexico was associated with rifted continental margin tectonics. Syn-rift Triassic graben-fill red-beds of the Eagle Mills Formation (Fig. 2) were deposited locally as the oldest Mesozoic strata above pre-rift Paleozoic basement during the early stages of extension and rifting (Tolson et al., 1983; Dobson, 1990).

The syn-rift Middle Jurassic Werner Formation and Louann Salt are evaporite deposits that formed during the initial transgression of marine water into the Gulf of Mexico (Salvador, 1987). Basement structure influenced the distribution and thickness of Louann Salt, resulting in thick salt in the interior salt basins, and salt being absent over basement paleohighs (Wilson, 1975; Cagle and Khan 1983, Dobson, 1990; Dobson and Buffler, 1991). The updip limit of thick salt and the location of the extensional faults associated with the regional peripheral fault trend coincide with a basement hinge line and occur in the northern part of these salt basins and subbasins (Mancini and Benson, 1980; Dobson, 1990; Dobson and Buffler, 1991).

The distribution of the Late Jurassic post-rift deposits of the Norphlet, Smackover, Haynesville and Cotton Valley have been affected by basement paleotopography (Mancini and Benson, 1980; Dobson, 1990; Dobson and Buffler, 1991). The Norphlet Formation consists of alluvial fan and plain, fluvial and wadi, eolian sheet, dune and interdune and marine shoreface siliciclastic sediments (Mancini et al., 1985; Dobson, 1990). The Smackover Formation, which was deposited on a ramp surface during the major Jurassic marine transgression in the Gulf, includes intertidal to subtidal laminated and microbial lime mudstone, subtidal peloidal wackestone and packstone, subtidal microbial boundstone, and subtidal to intertidal peloidal, ooid, oncoidal packstone and grainstone interbedded with fenestral lime mudstone (Mancini and Benson, 1980; Benson, 1988; Dobson, 1990). This transgression has been attributed to emplacement of oceanic crust in the Gulf and the resulting thermal subsidence due to crustal cooling (Nunn, 1984; Winker and Buffler, 1988). The Haynesville Formation consists of subaqueous to subaerial anhydrite, shelf to shoreline limestone, shale, and sandstone and eolian, fluvial, and alluvial sandstone (Tolson et al., 1983, Mann, 1988; Mancini et al., 1997). The Cotton Valley Group includes fluvial-deltaic and delta destructive sandstone and shale (Moore, 1983; Tolson, et al., 1983; Dobson, 1990). Deposition of the Early Cretaceous Knowles Limestone has been interpreted as the precursor to the development of the Lower Cretaceous carbonate shelf margin (Dobson, 1990).

The Early Cretaceous in the northern Gulf of Mexico consists of fluvial-deltaic to coastal silicilastic sedimentation updip and the development of a broad carbonate shelf with a low-relief margin downdip at the boundary between thick transitional crust and thin transitional crust (Eaves, 1976; Winker and Buffler, 1988; McFarlan and Menes, 1991; Sawyer et al., 1991). The development of a carbonate shelf margin during the Early Cretaceous, which does not conform to the basement structure, is the result of a combination of a change in the slope of the basement that is marked by a crustal hinge zone and Jurassic sediment depositional patterns (Dobson, 1990; Sawyer et al., 1991). The hinge zone has formed as a result of differential subsidence across the crustal boundary between thick transitional crust and thin transitional crust (Corso, 1987). Although Jurassic Norphlet, Smackover and Haynesville depositional patterns are greatly affected by basement paleotopography, sediments, such as the Lower Cretaceous

Knowles Limestone, reflect an infilling of the basement low areas and a general progradation of the ramp margin (Dobson, 1990). This progradation has been interpreted by Dobson (1990) to produce a change from a carbonate ramp to a rimmed platform margin. The hiatus between the Cotton Valley Group-Knowles Limestone and the Hosston Formation is represented by most of the Valanginian Stage. This unconformity and hiatus are recognized throughout the Gulf Coast (McFarlan and Menes, 1991).

The Lower Cretaceous shelf margin was exposed during the early Late Cretaceous by a major lowering of sea level. This sea-level fall has been attributed to a combination of igneous activity and global sea-level fall (Salvador, 1991). A Late Cretaceous marine transgression followed this regional erosional event, and this transgression in combination with the Laramide orogeny affected deposition from the Late Cretaceous to the Cenozoic (Salvador, 1991). Throughout the Cenozoic, the western Gulf was the site of significant fluvial, deltaic and coastline siliciclastic sediment influx, while the eastern Gulf experienced principally carbonate deposition (Salvador, 1991).

Potential Petroleum Source Rocks

Three active petroleum source rocks have been reported from the onshore north central and northeastern Gulf of Mexico area. The Upper Jurassic (Oxfordian) Smackover lime mudstone beds have been described as serving as source rocks in the North Louisiana Salt Basin, the Mississippi Interior Salt Basin, and the Manila and Conecuh Subbasins (Oehler, 1984; Sassen et al., 1987; Sassen and Moore, 1988; Claypool and Mancini, 1989; Mancini et al., 2003). The Upper Cretaceous (Cenomanian-Turonian) Tuscaloosa marine shale beds have been reported as serving as source rocks in Mississippi (Koons et al., 1974). The Lower Cretaceous (Albian) Sunniland lime mudstone beds have been described as serving as source rocks in south Florida (Palacas, 1978; Palacas et al., 1984). In addition, Sassen (1990) reported that lower Tertiary (Paleocene/Eocene) Midway, Wilcox, and Sparta shale beds are source rocks in southern Louisiana and that Paleocene/Eocene Wilcox lignite beds may be a petroleum source in southwestern Mississippi. Upper Jurassic (Tithonian) shale and carbonate beds are source rocks in Mexico (Mancini et al., 2001).

From source rock and oil characterization studies and from burial and thermal maturation history modeling, Mancini and Claypool (1989), Mancini et al., (1999), and the results from this work, have shown that the Paleocene/Eocene shale and lignite beds have not been subjected to favorable burial and thermal maturation histories required for petroleum generation in the North Louisiana Salt Basin (Fig. 3), Mississippi Interior Salt Basin (Fig. 4), Manila Subbasin (Fig. 5), and Conecuh Subbasin (Fig. 6). The Upper Cretaceous Tuscaloosa marine shale beds were an effective local petroleum source rock in parts of the Mississippi Interior Salt Basin and a possible local source bed in the North Louisiana Salt Basin given the proper organic facies but not in the Manila and Conecuh Subbasins. The uppermost Jurassic strata and the Lower Cretaceous lime mudstone and shale beds were possible local source beds in parts of the North Louisiana Salt Basin and Mississippi Interior Salt Basin given the proper organic facies. These beds probably were not source beds in the Manila and Conecuh Subbasins because the proper organic facies do not appear to be present.

Based on this assessment of potential petroleum source rocks in the onshore interior salt basins and subbasins of the north central and northeastern Gulf of Mexico area, only the Upper Jurassic Smackover lime mudstone beds were determined to be an effective regional petroleum source rock. Further, organic geochemical analyses, including C_{15+} chromatograms and biomarker data of the oils produced from Upper Jurassic, Lower Cretaceous and Upper Cretaceous reservoirs have shown that the oils produced from the Upper Jurassic, Lower Cretaceous and many of the Upper Cretaceous reservoirs were generated from organic matter that accumulated and was preserved in association with the Smackover lime mudstone beds (Koons et al., 1974; Claypool and Mancini, 1989; Mancini et al., 2001).

Smackover Source Rocks and Oils

The organic rich and laminated Smackover lime mudstone beds are the petroleum source rocks for most of the oils in these onshore interior salt basins and subbasins (Oehler, 1984; Sassen et al., 1987; Mancini and Claypool, 1989; Mancini et al., 2003). Organic geochemical analyses of the Smackover source beds (Tables 1-3) and of the oils (Tables 4-5) indicate that the Jurassic oils and many of the Cretaceous oils originated from the organic matter associated with the Smackover lime mudstone beds.

Smackover samples from the lower and middle lime mudstone beds average 0.81% total organic carbon according to Claypool and Mancini (1989). Organic carbon contents of up to 1.54% for the North Louisiana Salt Basin, 9.30% for the Mississippi Interior Salt Basin, and 1.76% for the Manila and Conecuh Subbasins have been measured in these lime mudstone beds (Sassen et al., 1987; Sassen and Moore, 1988). Because much of the Smackover has experienced advanced levels of thermal maturity, the total organic carbon values were higher in the past prior to the generation of crude oil (Sassen and Moore 1988).

The dominant kerogen types in the Smackover are algal (microbial) and microbial-derived amorphous (Oehler 1984; Sassen et al. 1987; Claypool and Mancini, 1989). In updip areas near the paleoshoreline, the Smackover includes herbaceous and woody kerogen (Wade et al. 1987). In the center areas of basins, Smackover samples exhibit thermal alteration indices of 2 to 4 (Oehler 1984; Sassen et al. 1987; Claypool and Mancini, 1989). These values represent an equivalent vitrinite reflectance (Ro) of 0.55 to 4.0% (Sassen and Moore 1988).

The generation of crude oil from the source rocks in the North Louisiana Salt Basin, Mississippi Interior Salt Basin and Manila and Conecuh Subbasins has been interpreted to have been initiated at a level of thermal maturity of 0.55% Ro (435°C T_{max}; 2 TAI) and concluded at a level of thermal maturity of 1.5% Ro (470°C T_{max}; 3 TAI) (Nunn and Sassen 1986; Sassen and Moore 1988). This requires a depth of burial of 3 km or 9,840 ft according to Driskill et al. (1988). Nunn and Sassen (1986) reported that the generation of crude oil was initiated at a depth of 3.5 km or 11,500 ft. The generation of crude oil was determined to have been initiated from basinal Smackover lime mudstone beds in the Early Cretaceous, and the generation and migration of low to intermediate gravity crude oil is interpreted to have continued into Cenozoic time (Nunn and Sassen 1986; Driskill et al. 1988; Sassen and Moore 1988). Updip Smackover lime mudstone beds have been reported to have generated low gravity crude oil beginning in the Late Cretaceous or 20 my later than the basinal lime mudstone (Driskill et al. 1988). At a depth of burial of 5 to 6 km (16,400 to 19,700 ft), the basinal Smackover lime mudstone beds were determined to be over-mature for the generation of crude oil (Nunn and Sassen 1986; Driskill et al. 1988). The low to intermediate gravity crude oils that migrated into reservoirs were subjected to thermal cracking with increasing depth of burial and time (Sassen and Moore 1988; Claypool and Mancini 1989).

From burial history and thermal maturation history profiles for wells in the North Louisiana Salt Basin, Mississippi Interior Salt Basin and Manila and Conecuh Subbasins (Figs. 7 and 8), hydrocarbon generation and maturation trends can be observed. In wells in much of the North Louisiana Salt Basin, the generation of hydrocarbons from Smackover lime mudstone was initiated at 1,829 to 2,896 m (6,000 to 9,500 ft) during the Early Cretaceous and continued into the Tertiary (Fig. 8A). In wells in much of the Mississippi Interior Salt Basin, the generation of hydrocarbons from Smackover lime mudstone was initiated at 2,438 to 3,353 m (8,000 to 11,000 ft) during the Early Cretaceous and continued into the Tertiary (Fig. 8B). In wells in much of the Manila and Conecuh Subbasins, the generation of hydrocarbons from Smackover lime mudstone was initiated at 2,591 to 3,811 m (8,500 to 12,500 ft) during the Late Cretaceous and continued into the Tertiary (Fig. 8 C,D). The thermal maturation profiles for wells located updip or along the updip margins of the basins and subbasins indicate that the Smackover source rocks in this area are thermally immature to mature and did not generate oil throughout much of this area, whereas, wells located in the centers of the basins and subbasins are late mature to overmature.

Hydrocarbon expulsion from Smackover source rocks in the North Louisiana Salt Basin and the Mississippi Interior Salt Basin commenced during the Early Cretaceous and continued into the Tertiary (Fig. 9). Initiation of oil expulsion began first in the central portion of the basin in Early Cretaceous and peaked in mid Early Cretaceous in this area. Hydrocarbon expulsion from Smackover source rock in the Manila and Conecuh Subbasins commenced during the Late Cretaceous and continued into the Tertiary. The hydrocarbon expulsion profiles for the wells are in agreement with the thermal maturation profiles. The timing of commencement of oil expulsion is consistent with the tectonic, depositional, burial and thermal histories of the basins and subbasins. The Smackover hydrocarbon expulsion profiles support an intermediate range (80 km or 50 mi) migration model for Smackover crude oil in that the thermal maturity and hydrocarbon expulsion profiles for wells located in fields producing low gravity crude oil show that the local Smackover source beds, to date, have not reached the thermal maturity level to expel Smackover oil. Smackover hydrocarbon migration into overlying strata was facilitated by vertical migration along faults. Evans (1987), Sassen (1990) and Zimmerman and Sassen (1993) also published information in support of combined long range and vertical hydrocarbon migration in this area.

Conclusions

1. The Upper Jurassic Smackover lime mudstone beds served as an effective regional petroleum source rock in the north central and northeastern Gulf of Mexico area.
2. The Upper Cretaceous Tuscaloosa marine shale was an effective local petroleum source rock in the Mississippi Interior Salt Basin and a possible local source bed in the North Louisiana Salt Basin given the proper organic facies.
3. The uppermost Jurassic and Lower Cretaceous shale and lime mudstone beds were possible petroleum source rocks in the North Louisiana Salt Basin and the Mississippi Interior Salt Basin given the proper organic facies.

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