Analysis of Rift Basins for Optimum Development: Mississippi Interior Salt Basin

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Introduction

The domestic petroleum industry in the United States continues to change principally because of economic and regulatory reasons. Small- and medium-sized independent companies have evolved into major players in the drilling of new exploration wells in domestic basins. These companies do not have the exploration or research staffs of the major international companies; and therefore, their drilling decisions many times may not be made on the best available data.

Rift basins, including the Mississippi Interior Salt Basin, remain significant targets to explore for oil and natural gas. To date, however, comprehensive basin analysis and petroleum system modeling studies have not been performed in many of these basins. Further, small- and medium-sized independent companies that are drilling the majority of the wells do not have the resources to conduct basin studies. These companies maintain that the accessibility of oil and natural gas information is the single-most important factor critical to the search for new hydrocarbon resources.

Objectives

The objectives of this study have been to increase the amount of public information on domestic rift basins and enhance the understanding of petroleum systems operating in these basins. Attainment of these objectives is consistent with the goals of the 1998 Comprehensive National Energy Strategy. The discovery of new hydrocarbon resources in rift basins serves to support national economic and energy security by reducing the vulnerability of the U.S. economy to disruptions in oil supply by boosting domestic production in an environmentally superior manner.

Approach

To facilitate petroleum exploration efforts in rift basins, a comprehensive analysis of the Mississippi Interior Salt Basin has been undertaken. This basin was selected for study because it is the largest rift basin in the eastern Gulf Coastal Plain, extending from Louisiana eastward into Alabama, has produced the most petroleum in the region, has the highest potential for identifying underdeveloped plays and reservoirs in the area, and represents the largest subsurface well log, core and geophysical database of the basins in the eastern Gulf Coastal Plain. Further, the Mississippi Interior Salt Basin is an excellent analog for the study of offshore Gulf of Mexico basins, such as the Apalachicola-DeSoto Canyon Salt Basin. The purpose of this paper is to provide the information gathered and analyses performed relating to the tectonic, depositional, burial and thermal histories of the Mississippi Interior Salt Basin. These results represent the work performed during Year 2 of this 5-year study.

Project Results and Discussion

Regional Framework

The burial and thermal histories of the Mississippi Interior Salt Basin (Fig. 1) are directly linked to the tectonic and depositional histories of the basin which are closely related to the origin of the Gulf of Mexico (Wood and Walper, 1974). The Gulf of Mexico is a divergent margin basin characterized by extensional rift tectonics and wrench faulting (Pilger, 1981; Miller, 1982; Salvador, 1987; Winkler and Buffler, 1988). The history of the Gulf of Mexico includes a phase of crustal extension and thinning, a phase of rifting and sea-floor spreading and a phase of thermal subsidence (Nunn, 1984). The structural and stratigraphic framework of the region, including the Mississippi Interior Salt Basin, was established during the Triassic and Jurassic (Salvador, 1987).

Based on the distribution of crust type, Sawyer et al. (1991) proposed the following as a model for the evolution of the Gulf of Mexico and related Mississippi Interior Salt Basin. A Late Triassic-Early Jurassic early rifting phase is characterized by large and small half-grabens bounded by listric normal faults and filled with nonmarine siliciclastic sediments (red-beds) and volcanics. A

Middle Jurassic phase of rifting, crustal attenuation and the formation of transitional crust is characterized by the evolution of a pattern of alternating basement highs and lows and the accumulation of thick salt deposits. A Late Jurassic phase of sea-floor spreading and oceanic crust formation in the deep central Gulf of Mexico is characterized by a regional 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 and thin transitional crust. During the Early Cretaceous, erosional events are recognized during the Valanginian (base of the Hosston Formation), in the Aptian (base of the Pine Island Shale), in the Albian (base of the Mooringsport Formation), and in the Albian (base of the Washita Group) reflecting times of sea-level fall in the Gulf (Yurewicz et al., 1993).

This pattern of deposition was broken by a period of igneous activity and global sea-level fall during the Late Cretaceous (mid-Cenomanian) which produced a major lowering of sea-level in the region and resulted in the exposure of the shallow Cretaceous platform margin that rimmed the Gulf (Salvador, 1991). This mid-Cenomanian unconformity is most pronounced in the northern Gulf of Mexico area.

Mesozoic and Cenozoic strata of the northeastern Gulf of Mexico were deposited as part of a seaward-dipping wedge of sediment that accumulated in differentially subsiding basins on the passive margin of the North American continent (Martin, 1978). Basement cooling and subsidence resulted in filling of the accommodation space throughout the Jurassic. Structural elements that affected the general orientation of these strata include basement features associated with plate movement and features formed due to halokinesis of Jurassic salt. The basement surface is dissected by the regional basement rift system which consists of a rift-related trend of divergent wrench-type basement faults and associated grabens and half grabens (Mink et al., 1990). The major basement faults are the northwest-southeast trending Florida-Bahamas and Pearl River transfer faults. The graben system is a result of rifting and its geometry is a reflection of the direction of plate separation (MacRae and Watkins, 1996). The major positive basement features that influenced the distribution and nature of Mesozoic deposits onshore are the Wiggins Arch complex, Choctaw ridge complex, the Conecuh ridge complex, the Pensacola ridge complex, and the Decatur ridge complex. These structural elements, such as 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 Wiggins Arch complex may represent an elevated horst block associated with crustal extensional and rifting (Miller, 1982; Sawyer et al., 1991). This basement feature may be a remnant of the rifted continental margin of North America. The Wiggins Arch consists of pre-rift Paleozoic metamorphic and granitic rocks (Cagle and Khan, 1983).

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., 1985b). The Mississippi Interior Salt Basin, which is a major negative structural feature in the northeastern Gulf of Mexico, is classified as the interior fracture portion of a margin sag basin, according to the classification of Kingston et al. (1983). This extensional basin was an actively subsiding depocenter throughout the Mesozoic and into the Cenozoic. Based on gravity data, Wilson (1975) interpreted the Mississippi Interior Salt Basin to be an area of attenuated granitic continental crust. Crustal thinning resulted from tectonic extension of the lithosphere during the rifting of the Gulf in the early Mesozoic. This attenuation of the crust established a subsiding basin cratonward of the rifted and elevated continental margin (Wood and Walper, 1974).

Halokinesis of the Jurassic Louann Salt has produced a complex of structural features in the northeastern Gulf of Mexico (Martin, 1978). Salt-related structures include diapirs, anticlines, and extensional fault and half graben systems. Structural elements resulting from salt movement include the regional peripheral fault trend, the lower Mobile Bay fault, the Mobile graben, Destin anticline, and numerous salt domes and anticlines. These features serve as petroleum traps in the region. Halokinetically-related structural deformation was initiated probably during the Late Jurassic and possibly as early as the Oxfordian (Dobson and Buffler, 1997). The Mississippi

Interior Salt Basin contains more than 50 documented salt domes with crests less than 6,000 ft from the surface and with two of the domes (Richton and Tatum salt domes) occurring less than 1,000 ft from the surface (Thieling and Moody, 1997).

The regional peripheral fault trend is comprised of a group of genetically related, *en echelon* extensional faults that are associated with salt movement. Onshore, this trend is composed of the Pickens, Gilbertown, West Bend, Pollard, and Foshee fault systems and offshore, the Pensacola-Destin fault system has been interpreted as part of this trend (Kemmer and Reagan, 1987). The trend approximates the updip limit of thick Jurassic salt (Martin, 1978). The faults of the regional peripheral fault trend are generally parallel or subparallel to regional depositional strike and are normal, down-to-the-basin or antithetic faults that form grabens that are generally 5 to 8 mi across (Murray, 1961). The faults are listric with fault dips ranging from 35˚ to 70˚ and with displacements on major faults ranging from 200 to 2,000 ft in the Jurassic section (Mancini et al., 1985a). The Mobile graben, which is considered to define the eastern limit of the Mississippi Interior Salt Basin, represents a more mature stage of halokinesis as evidenced by an association with diapiric features. The regional basement rift system influenced movement along the regional peripheral fault trend (Mink et al., 1990).

Sedimentation in the northeastern Gulf of Mexico was associated with rifted continental margin tectonics resulting from the breakup of Pangea and the opening of the Gulf of Mexico. Syn-rift Triassic graben-fill red-beds of the Eagle Mills Formation 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 with thick salt in the Mississippi Interior Salt Basin, and salt is absent over the Wiggins Arch (Wilson, 1975; Cagle and Khan, 1983). 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 the salt basin (Mancini and Benson, 1980; Mancini et al., 1985a).

The distribution of the Late Jurassic post-rift deposits of the Norphlet, Smackover, Haynesville and Cotton Valley were greatly affected by basement topography and progressively onlap the basement surface (Mancini and Benson, 1980; Dobson, 1990; Dobson and Buffler, 1997). The Norphlet Formation includes alluvial fan and plain, fluvial and wadi, eolian sheet, dune and interdune, and marine shoreface siliciclastic sediments (Mancini et al., 1985b). The Smackover Formation, which was deposited on a distally-steepened ramp surface during the major Jurassic marine transgression in the Gulf, consists of intertidal to subtidal laminated and microbial carbonate mudstones, subtidal peloidal wackestones and packstones, and subtidal to intertidal peloidal, ooid, oncoidal packstones and grainstones interbedded with laminated and fenestral carbonate mudstones (Mancini and Benson, 1980; Benson, 1988). This major transgression has been attributed to emplacement of oceanic crust in the Gulf and the resulting thermal subsidence due to crustal cooling (Nunn, 1984; Winkler and Buffler, 1988). Smackover microbial reefs developed updip of a basement hinge line detailing the boundary between continental crust and thick transitional crust and in association with horst blocks and salt structures in the zone of thick transitional crust (Dobson, 1990; Dobson and Buffler, 1997). The Haynesville Formation includes subaqueous to subaerial anhydrites, shelf to shoreline limestones, shales, and sandstones, and eolian, fluvial and alluvial sandstones (Tolson et al., 1983; Mann, 1988). The Cotton Valley Group consists of fluvial-deltaic and delta destructive sandstones and shales (Moore, 1983; Tolson et al., 1983).

The Early Cretaceous in the northeastern Gulf of Mexico was dominated by fluvial-deltaic to coastal siliciclastic 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; Winkler and Buffler, 1988; Sawyer et al., 1991). The development of a carbonate shelf margin during the Early Cretaceous, which does not conform to the basement structure, is believed to be a combination of a change in the slope of the basement which is marked by a crustal hinge zone and Jurassic sediment depositional patterns (Dobson, 1990; Sawyer et al., 1991). The hinge zone formed as a result of differential subsidence across the crustal boundary between thick and thin transitional crust (Corso, 1987). Although Norphlet, Smackover and Haynesville deposition patterns were greatly affected by basement topography, sediments deposited at the close of Cotton Valley times, such as the Knowles Limestone, reflect an infilling of the basement low areas and a general progradation (Dobson, 1990; Dobson and Buffler, 1997). This progradation has been interpreted by Dobson (1990) to produce the change from a carbonate ramp to a rimmed carbonate platform margin.

The Lower Cretaceous shelf margin was exposed during the early Late Cretaceous by a major lowering of sea level in the Gulf of Mexico. This sea-level fall has been attributed to a combination of regional igneous activity (Jackson Dome) and global sea level fall during the mid-Cenomanian (Salvador, 1991). A Late Cretaceous marine transgression followed this regional erosional event, and this transgression in combination with the Laramide orogeny affected deposition in the Late Cretaceous and into the Cenozoic (Salvador, 1991). Throughout the Cenozoic, the Mississippi Interior Salt Basin was the site of significant fluvial, deltaic and coastline siliciclastic sedimentation; the area experienced minor carbonate deposition (Salvador, 1991).

Burial History

Understanding burial history is important to interpreting the geohistory of a basin. Burial history is crucial in determining the generation, migration and preservation of hydrocarbons in the basin. This modeling is dependent upon a sound regional model for the geologic history of the basin (Waples, 1994a). Determination of the magnitude of depositional events, such as sedimentation and subsidence rates, are critical to interpreting burial history. The identification of erosion events and times of non-deposition are crucial in interpreting the burial and thermal histories of a basin. Burial history work for portions of the Mississippi Interior Salt Basin has been published by Nunn and Sassen (1986) and Driskill et al. (1988), but no comprehensive analysis has been published to date.

In this study, the tectonic and depositional histories of the Mississippi Interior Salt Basin form the foundation for interpreting the burial history of the basin. Five regional cross sections consisting of 48 key wells comprise the basis for the interpretation. The burial history for each well in the cross sections was determined using BasinMod® software. Information interpreted from these cross-sections, well logs, and other sources include biostratigraphic (geologic ages of selected units or horizons), paleoenvironmental (water depths), stratigraphic thickness of the units, lithologies, sediment accumulation and subsidence rates, unconformities and faulting.

The geologic ages for the Tertiary units in the Mississippi Interior Salt Basin were determined using the outcrop work of Mancini and Tew (1991) and for Upper Cretaceous strata using the outcrop work of Christopher (1982), Puckett (1995), Mancini et al. (1996) and the subsurface work of Mancini and Payton (1981). The geologic ages for the Lower Cretaceous units were estimated using the work performed in the western Gulf by Imlay (1940) and Young (1972). The geologic ages for the Upper Jurassic units were determined using the work done in the western Gulf by Imlay and Herman (1984) and Young and Oloritz (1993). Geologic age data published by Todd and Mitchum (1977) and Salvador (Salvador, 1987) were also used. Utilizing the geologic age data, the stratigraphic section was divided into five intervals: Jurassic (161-137 my), Early Cretaceous (137-99 my), Late Cretaceous (99-65 my), early Tertiary (65-30 my) and late Tertiary and Quaternary (30-0 my) for basin modeling. Major hiatuses were recognized in the Jurassic (195-176 my) and the Early Cretaceous (137-132 my). Fault displacements of 100 to 2,000 ft were found throughout the section in specific wells.

The total thickness of the sediment column was corrected for compaction utilizing the Sclater and Christie (1980) method. The thickness of key stratigraphic horizons was determined through well log study and by using BasinMod® software. The stratigraphic horizons were recognized by their characteristic well log signatures. Sediment accumulation rates and subsidence rates were determined based on these data by employing BasinMod“ software. In these determinations, the following constants were used: average mantle density of 3.30 g/cm^3; average water density of 1.02 g/cm^3; and average sediment densities of 2.64 g/cm^3 for sandstone, 2.60 g/cm^3 for shale, 2.72 g/cm^3 for limestone, 2.98 g/cm^3 for anhydrite and 2.15 g/cm^3 for salt. Paleowater depths ranged from 0-400 ft. These constants are consistent with those of Nunn and Sassen (1986).

Mean stratigraphic thickness, sediment accumulation rates, and tectonic subsidence rates were determined using BasinMod“ software. The mean stratigraphic thickness for the five intervals is as follows: Jurassic (4,746 ft), Lower Cretaceous (6,242 ft), Upper Cretaceous (3,858 ft), lower Tertiary (4,939 ft) and upper Tertiary (2,926 ft). Mean sandstone sediment accumulation rates range from 311 ft/my for Lower Cretaceous sandstones to 170 ft/my for Jurassic sandstones. Mean shale sediment accumulation rates range from 108 ft/my for Upper Cretaceous clays to 90 ft/my for lower Tertiary shales. Mean limestone sediment accumulation rates range from 122 ft/my for Jurassic limestones to 57 ft/my for Upper Cretaceous chalks. Mean anhydrite sediment accumulation rates are 85 ft/my for Lower Cretaceous anhydrites. Mean tectonic subsidence rates for the intervals are: Jurassic (130 ft/my), Lower Cretaceous (72 ft/my), Upper Cretaceous (46 ft/my) and lower Tertiary (45 ft/my).

The burial history modeling (Fig. 2) is consistent with the rift-related geohistory of the Mississippi Interior Salt Basin. Lithospheric extension occurred during the Early to Middle Jurassic and was followed by a long period of thermal subsidence. Nunn (1984) determined that the crustal thickness underneath the basin was 30-35 km (approximately 98,400-115,000 ft), while the crustal thickness to the north of the basin and underneath the Wiggins Arch to the south was greater. Tectonic subsidence rates were greatest during the Jurassic and decreased progressively from the Jurassic to the late Tertiary, reflecting the syn-rift and post-rift history of the basin. According to Driskill et al. (1988), 42% of the tectonic subsidence in the basin occurred within 32 million years following the onset of thermal subsidence and an equal amount of subsidence required an additional 68 million years. These authors report tectonic subsidence amounts of 1.26 to >1.76 km (approximately 4,100 to >5,780 ft) for the Mississippi Interior Salt Basin. Tectonic subsidence probably exceeded 1.95 km (approximately 6,400 ft) in the Perry sub-basin (Driskill et al., 1988). Therefore, the greatest accommodation space was generated during the Jurassic.

The sedimentary rock record of the basin indicates that the deepest water depths occurred during the Late Jurassic (Oxfordian), Early Cretaceous (Hauterivian-Albian), Late Cretaceous (Cenomanian-Turonian), and Late Eocene (Priabonian). These events correspond to global rises in sea level. Therefore, eustasy also contributed to the generation of accommodation space.

Sediment accumulation acts to reduce available accommodation space. Sediment supply in concert with tectonics and eustasy are the principal controls on sediment accumulation and cyclicity in the basin.

Thermal History

The thermal history of a basin is a crucial element as to whether the basin has hydrocarbons in commercial quantities and as to whether those hydrocarbons are oil, natural gas or both. Thermal maturity modeling has become a standard in basin analysis and petroleum exploration. Maturity modeling builds on burial history modeling. Determination of present-day heat flow, paleoheat flows, and thermal conductivities are vital criteria along with the amount and type of kerogen and the element of timing (Waples, 1994b). Thermal history work for portions of the Mississippi Interior Salt Basin has been published by Wilson (1975), Koons et al. (1974), Smith et al. (1981), Nunn (1984), Oehler (1984), Nunn et al. (1984), Nunn and Sassen (1986), Sassen (1989), Sassen and Moore (1988), Driskill et al. (1988), Claypool and Mancini (1989), and Mancini et al. (1993), but no comprehensive analysis has been published to date.

In this study, the tectonic, depositional and burial histories of the Mississippi Interior Salt Basin form the foundation for interpreting the thermal history of the basin. Five regional cross-sections consisting of 48 key wells comprise the basis for the interpretation. The thermal history for each well and cross-section was determined using BasinMod® software. Information utilized includes bottom hole temperature, present-day geothermal gradient, present-day heat flow, vitrinite reflectance, thermal alteration, Tmax, paleogeothermal gradient, paleoheat flow, thermal conductivity, total organic carbon and kerogen type.

The thermal history modeling indicates that effective source rocks in the basin include Upper Jurassic Smackover carbonate mudstones throughout the basin area and Upper Cretaceous Tuscaloosa shales in the south central portion (Perry sub-basin area) of the basin. Upper Jurassic and Lower Cretaceous shales are possible source rocks in the south central portion (Perry sub-basin area) of the basin given the proper organic facies. Tertiary shales have not been subjected to favorable burial and thermal histories required for petroleum generation in the basin.

These observations are consistent with previous studies, such as those by Nunn (1984), Oehler (1984), Nunn and Sassen (1986), Sassen and Moore (1988), Driskill et al. (1988), Claypool and Mancini (1989), and Mancini et al. (1993). These previous works have recognized that the Smackover is an effective regional source rock, that the Tuscaloosa is an effective local source rock in the south central portion of the Mississippi Interior Salt Basin, and that the Tertiary shales in the basin are thermally immature and are unlikely to have served as source rocks for crude oil. However, previous workers have not speculated on the possibility of Lower Cretaceous shales having acted as petroleum source rocks.

Organic geochemical source rock analyses performed as part of this study, in combination with those of Oehler (1984), Sassen et al. (1987), and Claypool and Mancini (1989), indicate that the petroleum source rock potential of the lower and middle Smackover carbonate mudstones of the Mississippi Interior Salt Basin has been optimized by the combination of favorable conditions of deposition, preservation, and subsequent burial and thermal histories.

Smackover samples from the lower and middle carbonate mudstones average 0.81% total organic carbon (Claypool and Mancini, 1989). 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). Organic carbon contents of up to 2.52% have been reported from these carbonate mudstones (Oehler, 1984). Thermally immature Smackover mudstones with pyrolysis Tmax values of 422-424°C have hydrogen index values of 656 mg HC/g TOC, while mature Smackover mudstones with Tmax values of 447-453°C have hydrogen index values of 50 mg HC/g TOC (Sassen and Moore, 1988).

The dominant kerogen types in the Smackover are algal (cyanobacteria) and amorphous (Oehler, 1984; Sassen et al., 1987; Claypool and Mancini, 1989). In updip areas near the paleoshoreline the Smackover includes herbaceous kerogen (Wade et al., 1987). In the basin area, 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 3.0% (Sassen and Moore, 1988).

The generation of crude oil from source rocks in the Mississippi Interior Salt Basin is interpreted to have been initiated at a level of thermal maturity of 0.55% Ro (435°C Tmax; 2 TAI) and concluded at a level of thermal maturity of 1.5% Ro (470°C Tmax; 3 TAI) (Nunn and Sassen, 1986; Sassen and Moore, 1988). This requires a depth of burial of 3 km or approximately 9,840 ft according to Driskill et al. (1988). Nunn and Sassen (1986) reported that the generation of crude oil in the Mississippi Interior Salt Basin was initiated at a depth of 3.5 km or approximately 11,500 ft. The generation of crude oil is believed to have been initiated from basinal Smackover carbonate mudstones in the Early Cretaceous, and the generation and migration of low to intermediate gravity crude oil is interpreted to have continued into the Tertiary (Nunn and Sassen, 1986; Driskill et al., 1988; Sassen and Moore, 1988). Updip Smackover carbonate mudstones are thought to have generated low gravity crude oil beginning in the Late Cretaceous or 20 my later than the basinal mudstones (Driskill et al., 1988). Post-Early Cretaceous shales (Tuscaloosa, Selma and Tertiary) have been interpreted as ineffective petroleum source rocks by Driskill et al. (1988) because of their thermal immaturity (0.4% Ro) in much of the Mississippi Interior Salt Basin area. However, the generation of crude oil is believed to have been initiated during the Tertiary locally from basinal Tuscaloosa shales, which have total organic carbon contents of up to 2.8% in the south central portion of the basin (Koons et al., 1974; Nunn and Sassen, 1986). Norphlet, Haynesville, Cotton Valley, and Rodessa shales analyzed by previous workers were found to have total organic carbon contents of less than 0.3% (Sassen and Moore, 1988; Claypool and Mancini, 1989). At a depth of burial of 5-6 km (approximately 16,400-19,700 ft), the Smackover mudstones are thought to be over-mature for the generation of crude oil (Nunn and Sassen, 1986; Driskill et al., 1988). The low to intermediate crude oils that migrated into reservoirs were subjected to thermal cracking with depth of burial and time (Sassen and Moore, 1988; Claypool and Mancini, 1989). Most authors agree that the Jurassic and Early Cretaceous sediments experienced a rapid rise in temperature associated with rifting (190-165 my) and that for the past 60 to 75 my there has been little change in paleotemperature (Nunn, 1984; Driskill et al., 1988). This trend translates into a paleogeothermal gradient of 72°C/km during the Jurassic, of 58°C/km during the Early Cretaceous and of 28-33°C/km today (Smith et al., 1981; Nunn, 1984). Conductivities of $3\text{-}5 \times 10^{(-3)}$ cal/cm°C have been measured for strata in the basin (Smith et al., 1981; Nunn, 1984). Heat flows of 1.0 μcal/cm^2 -sec are typical of the basin except in the vicinity of the Jackson Dome (1.5 μcal/cm^2 -sec) (Smith et al., 1981). Bottom hole temperatures for strata buried to 21,000 ft are 380°F in the basin area, and the present-day geothermal gradient is 1.0-1.6°F/100 ft (Wilson, 1975). As a result of thermal maturity modeling and calibration with thermal maturation indices, elevated heat flows are evident in the south central (Perry sub-basin) and east central (Washington County, Alabama) portions of the basin and in the vicinity of the Jackson Dome.

From thermal maturation profiles for wells in the study area, a hydrocarbon generation and maturation trend can be observed. In wells in much of the basin, the generation of hydrocarbons from Smackover carbonate mudstones is initiated at 8,000-11,000 ft during the Early Cretaceous and continuing into the Tertiary throughout much of the Mississippi Interior Salt Basin (Fig. 3). Locally, hydrocarbon generation commenced at 7,000-8,000 ft from Tuscaloosa shales during the Tertiary in the area of the Perry sub-basin (Fig. 4). In the vicinity of the Jackson Dome, hydrocarbon gas generation begins at a depth of 15,000 ft. This hydrocarbon generation and maturation trend can be seen on the cross section in Figure 5.

Application and Conclusions

1. The burial and thermal histories of the Mississippi Interior Salt Basin are directly linked to the tectonic and depositional histories of the basin, which are closely related to the origin of the Gulf of Mexico. Active rifting persisted through the Middle Jurassic and crustal

cooling and subsidence which was initiated in the Late Jurassic continued into the Cretaceous. This basin is classified as an extensional basin. Basement topography had a significant influence on the distribution of sediments. Syn-rift deposits include the Jurassic Werner and Louann Salt. Post-rift deposits include Upper Jurassic, Cretaceous and Tertiary evaporites, carbonate and siliciclastic sediments. Deposition was dominated by a ramp margin during the Jurassic and a shelf margin during the post-Jurassic.

2. The burial history modeling for the Mississippi Interior Salt Basin is consistent with the rift-related geohistory of the region. Lithospheric extension occurred during the Early and Middle Jurassic and was followed by a long period of thermal subsidence. Tectonic subsidence rates were greatest during the Jurassic and decreased progressively from the Jurassic to the late Tertiary. The greatest accommodation space was generated during the Jurassic as a combination of subsidence and eustasy.
3. The thermal history modeling indicates that effective petroleum source rocks include Upper Jurassic Smackover carbonate mudstones throughout much of the Mississippi Interior Salt Basin and Upper Cretaceous Tuscaloosa black shales locally in the south central portion of the basin (Perry sub-basin area). Lower Cretaceous shales are possible source rocks in the south central portion of the basin (Perry sub-basin area) given the proper organic facies. Tertiary shales, although high in organic content, have not been subjected to favorable burial and thermal histories required for petroleum generation.
4. By utilizing a multidimensional burial and thermal history modeling approach, petroleum companies searching to extend known oil and gas plays in the Mississippi Interior Salt Basin should be able to generate new prospects and improve their ability to drill successful exploration wells.

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References

Benson, D.J., 1988, Depositional history of the Smackover Formation in southwest Alabama: Transactions—Gulf Coast Association of Geological Societies, v. 38, p. 197-205.

Cagle, J.W., and M.A. Khan, 1983, Smackover-Norphlet stratigraphy, south Wiggins Arch, Mississippi and Alabama: Transactions—Gulf Coast Association of Geological Societies, v. 33, p. 23-29.

Christopher, R.A., 1982, Palynostratigraphy of the basal Cretaceous units of the eastern Gulf and southern Atlantic coastal plains, *in* D.D. Arden, B.F. Beck, and E. Morrow, eds., Proceedings of the Second Symposium on the Geology of the Southeastern Coastal Plain: Georgia Geologic Survey Information Circular 53, p. 10-23.

Claypool, G.E., and E.A. Mancini, 1989, Geochemical relationships of petroleum in Mesozoic reservoirs to carbonate source rocks of Jurassic Smackover Formation, southwestern Alabama: American Association of Petroleum Geologists Bulletin, v. 73, p. 904-924.

Corso, W., 1987, Development of the Early Cretaceous northwest Florida carbonate platform [unpublished Ph.D. dissertation]: The University of Texas, 136 p.

Dobson, L.M., 1990, Seismic stratigraphy and geologic history of Jurassic rocks, northeastern Gulf of Mexico [unpublished M. S. thesis]: The University of Texas, 165 p.

Dobson, L.M., and R.T. Buffler, 1997, Seismic stratigraphy and geologic history of Jurassic rocks, northeastern Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 81, p. 100-120.

Driskill, B.W., J.A. Nunn, R. Sassen, and R.H. Pilger, Jr., 1988, Tectonic subsidence, crustal thinning and petroleum generation in the Jurassic trend of Mississippi, Alabama and Florida: Transactions—Gulf Coast Association of Geological Societies, v. 38, p. 257-265.

Eaves, E., 1976, Citronelle oil field, Mobile County, Alabama: American Association of Petroleum Geologists Memoir 24, p. 259-275.

Imlay, R.W., 1940, Lower Cretaceous and Jurassic formations of southern Arkansas and their oil and gas possibilities: Arkansas Division of Geology Information Circular 12, 64 p.

Imlay, R.W., and G. Herman, 1984, Upper Jurassic ammonites of the subsurface of Texas, Louisiana, and Mississippi, *in* W.P.S. Ventress, D.G. Bebout, B.F. Perkins, and C.H. Moore, eds., The Jurassic of the Gulf Rim: Proceedings of the Third Annual Research Conference, Gulf Coast Section, Society of Economic Paleontologists and Mineralogists Foundation, p. 149-170.

Kemmer, D.A., and R.L. Reagan, 1987, Norphlet Formation (Upper Jurassic) sand erg—depositional model for northeastern DeSoto Salt Basin, eastern Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 71, p. 576.

Kingston, D.R., C.P. Dishroon, and P.A. Williams, 1983, Global basin classification system: American Association of Petroleum Geologists Bulletin, v. 67, p. 2175-2193.

Koons, C.B., J.G. Bond, and F.L. Peirce, 1974, Effects of depositional environment and postdepositional history on chemical composition of Lower Tuscaloosa oils: American Association of Petroleum Geologists Bulletin, v. 58, p. 1272-1280.

MacRae, G., and J.S. Watkins, 1996, Desoto Canyon Salt Basin: tectonic evolution and salt structural styles, *in* J.O. Jones, and R.L. Freed, eds., Structural Framework of the Northern Gulf of Mexico: Special Publication of Gulf Coast Association of Geological Societies, p. 53-61.

Mancini, E.A., and D.J. Benson, 1980, Regional stratigraphy of Upper Jurassic Smackover carbonates of southwest Alabama: Transactions—Gulf Coast Association of Geological Societies, v. 30, p. 151-163.

Mancini, E.A., R.M. Mink, and B.L. Bearden, 1985a, Upper Jurassic Norphlet hydrocarbon potential along the regional peripheral fault trend in Mississippi, Alabama, and the Florida Panhandle: Transactions—Gulf Coast Association of Geological Societies, v. 35, p. 225-232.

Mancini, E.A., R.M. Mink, B.L. Bearden, and R.P. Wilkerson, 1985b, Norphlet Formation (Upper Jurassic) of southwestern and offshore Alabama: environments of deposition and petroleum geology: American Association of Petroleum Geologists Bulletin, v. 69, p. 881-898.

Mancini, E.A., and J.W. Payton, 1981, Petroleum geology of South Carlton Field, Lower Tuscaloosa "Pilot Sand", Clarke and Baldwin Counties, Alabama: Transactions—Gulf Coast Association of Geological Societies, v. 31, p. 139-147.

Mancini, E.A., T.M. Puckett, and B.H. Tew, 1996, Integrated biostratigraphic and sequence stratigraphic framework for Upper Cretaceous strata of the eastern Gulf Coastal Plain, USA: Cretaceous Research, v. 17, p. 645-669.

Mancini, E.A., and B.H. Tew, 1991, Relationships of Paleogene stage and planktonic foraminiferal zone boundaries to lithostratigraphic and allostratigraphic contacts in the eastern Gulf Coastal Plain: Journal of Foraminiferal Research, v. 21, p. 48-66.

Mancini, E.A., B.H. Tew, and R.M. Mink, 1993, Petroleum source rock potential of Mesozoic condensed section deposits of southwest Alabama, *in* B.J. Katz, and L.M. Pratt, eds., Source Rocks in a Sequence Stratigraphic Framework: American Association of Petroleum Geologists Studies in Geology, v. 37, p. 147-162.

Mann, S.D., 1988, Subaqueous evaporites of the Buckner Member, Haynesville Formation, northeastern Mobile County, Alabama: Transactions—Gulf Coast Association of Geological Societies, v. 38, p. 187-196.

Martin, R.G., 1978, Northern and eastern Gulf of Mexico continental margin: stratigraphic and structural framework: American Association of Petroleum Geologists Studies in Geology, v. 7, p. 21-42.

Miller, J.A., 1982, Structural control of Jurassic sedimentation in Alabama and Florida: American Association of Petroleum Geologists Bulletin, v. 66, p. 1289-1301.

Mink, R.M., B.H. Tew, S.D. Mann, B.L. Bearden, and E.A. Mancini, 1990, Norphlet and pre-Norphlet geologic framework of Alabama and panhandle Florida coastal waters area and adjacent federal waters area: Geological Survey of Alabama Bulletin 140, 58 p.

Moore, T., 1983, Cotton Valley depositional systems of Mississippi: Transactions—Gulf Coast Association of Geological Societies, v. 33, p. 163-167.

Murray, G.E., 1961, Geology of the Atlantic and Gulf Coastal Province of North America: New York, Harper & Brothers, 692 p.

Nunn, J.A., 1984, Subsidence histories for the Jurassic sediments of the northern Gulf Coast: thermal-mechanical model, *in* W.P.S. Ventress, D.G. Bebout, B.F. Perkins, and C.H. Moore, eds., The Jurassic of the Gulf Rim: Proceedings of the Third Annual Research Conference, Gulf Coast Section, Society of Economic Paleontologists and Mineralogists Foundation, p. 309-322.

Nunn, J.A., and R. Sassen, 1986, The framework of hydrocarbon generation and migration, Gulf of Mexico continental slope: Transactions—Gulf Coast Association of Geological Societies, v. 36, p. 257-262.

Nunn, J.A., A.D. Scardina, and R.H. Pilger, Jr., 1984, Thermal evolution of the north-central Gulf Coast: Tectonics, v. 3, p. 723-740.

Oehler, J.H., 1984, Carbonate source rocks in the Jurassic Smackover trend of Missisippi, Alabama, and Florida, *in* J.G. Palacas, ed., Petroleum Geochemistry and Source Rock Potential of Carbonate Rocks: American Association of Petroleum Geologists Studies in Geology, v. 18, p. 63-69.

Pilger, R.H., Jr., 1981, The opening of the Gulf of Mexico: implications for the tectonic evolution of the northern Gulf Coast: Transactions—Gulf Coast Association of Geological Societies, v. 31, p. 377-381.

Puckett, T.M., 1995, Planktonic foraminiferal and ostracode biostratigraphy of the late Santonian through early Maastrichtian strata in Dallas County, Alabama: Geological Survey of Alabama Bulletin 164, 59 p.

Salvador, A., 1987, Late Triassic-Jurassic paleogeography and origin of Gulf of Mexico Basin: American Association of Petroleum Geologists Bulletin, v. 71, p. 419-451.

Salvador, A., 1991, Origin and development of the Gulf of Mexico Basin, *in* A. Salvador, ed., The Gulf of Mexico Basin: Geological Society of America, Decade of North American Geology, v. J, p. 389-444.

Sassen, R., 1989, Migration of crude oil from the Smackover source rock to Jurassic and Cretaceous reservoirs of the northern Gulf rim: Organic Geochemistry, v. 14, p. 51-60.

Sassen, R., and C.H. Moore, 1988, Framework of hydrocarbon generation and destruction in eastern Smackover trend: American Association of Petroleum Geologists Bulletin, v. 72, p. 649-663.

Sassen, R., C.H. Moore, J.A. Nunn, F.C. Meendsen, and E. Heydari, 1987, Geochemical studies of crude oil generation, migration, and destruction in the Mississippi salt basin: Transactions—Gulf Coast Association of Geological Societies, v. 37, p. 217-224.

Sawyer, D.S., R.T. Buffler, and R.H. Pilger, Jr., 1991, The crust under the Gulf of Mexico, *in* A. Salvador, ed., The Gulf of Mexico Basin: Geological Society of America, Decade of North American Geology, v. J, p. 53-72.

Sclater, J.G., and P.A.F. Christie, 1980, Continental stretching: an explanation of the post mid-Cretaceous subsidence of the central North Sea basin: Journal of Geophysical Research, v. 85, p. 3711-3739.

Smith, D.L., W.J. Dees, and D.W. Harrelson, 1981, Geothermal conditions and their implications for basement tectonics in the Gulf Coast margin: Transactions—Gulf Coast Association of Geological Societies, v. 31, p. 181-190.

Thieling, S.C., and J.S. Moody, 1997, Atlas of shallow Mississippi salt domes: Mississippi Office of Geology Bulletin 131, 328 p.

Todd, R.G., and R.M. Mitchum, Jr., 1977, Seismic stratigraphy and global changes of sea level; Part 8, Identification of Upper Triassic, Jurassic, and Lower Cretaceous seismic sequences in Gulf of Mexico and offshore West Africa, *in* C.E. Payton, ed., Seismic stratigraphy: applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 145-163.

Tolson, J.S., C.W. Copeland, and B.L. Bearden, 1983, Stratigraphic profiles of Jurassic strata in the western part of the Alabama coastal plain: Geological Survey of Alabama Bulletin 122, 425 p.

Wade, W.J., R. Sassen, and E.W. Chinn, 1987, Stratigraphy and source potential of the Smackover Formation of the northern Manila Embayment, southwest Alabama: Transactions—Gulf Coast Association of Geological Societies, v. 37, p. 277-285.

Waples, D.W., 1994a, Maturity modeling: thermal indicators, hydrocarbon generation and oil cracking, *in* L.B. Magoon, and W.G. Dow, eds., The Petroleum System--From Source to Trap: American Association of Petroleum Geologists Memoir 60, p. 285-306.

Waples, D.W., 1994b, Modeling of sedimentary basins and petroleum systems, *in* L.B. Magoon, and W.G. Dow, eds., The Petroleum System—From Source to Trap: American Association of Petroleum Geologists Memoir 60, p. 307-322.

Wilson, G.V., 1975, Early differential subsidence and configuration of the northern Gulf Coast basin in Southwest Alabama and Northwest Florida: Transactions—Gulf Coast Association of Geological Societies, v. 25, p. 196-206.

Winkler, C.D., and R.T. Buffler, 1988, Paleogeographic evolution of early deep-water Gulf of Mexico and margins, Jurassic to middle Cretaceous (Cenomanian): American Association of Petroleum Geologists Bulletin, v. 72, p. 318-346.

Wood, M.L., and J.L. Walper, 1974, The evolution of the interior Mesozoic basin and the Gulf of Mexico: Transactions—Gulf Coast Association of Geological Societies, v. 24, p. 31-41.

Young, K., 1972, Cretaceous paleogeography: implications of endemic ammonite faunas: Texas Bureau of Economic Geology Geological Circular 72-2, 13 p.

Young, K., and F. Oloriz, 1993, Ammonites from the Smackover Limestone, Cotton Valley field, Webster Parish, Louisiana, U.S.A.: Geobios, v. 15, p. 401-409.

Yurewicz, D.A., T.B. Marler, K.A. Meyerholtz, and F.X. Siroky, 1993, Early Cretaceous carbonate platform, north rim of the Gulf of Mexico, Mississippi and Louisiana, *in* J.A.T. Simo, R.W. Scott, and J.P. Masse, eds., Cretaceous Carbonate Platforms: Association of Petroleum Geologists Memoir 56, p. 81-96.

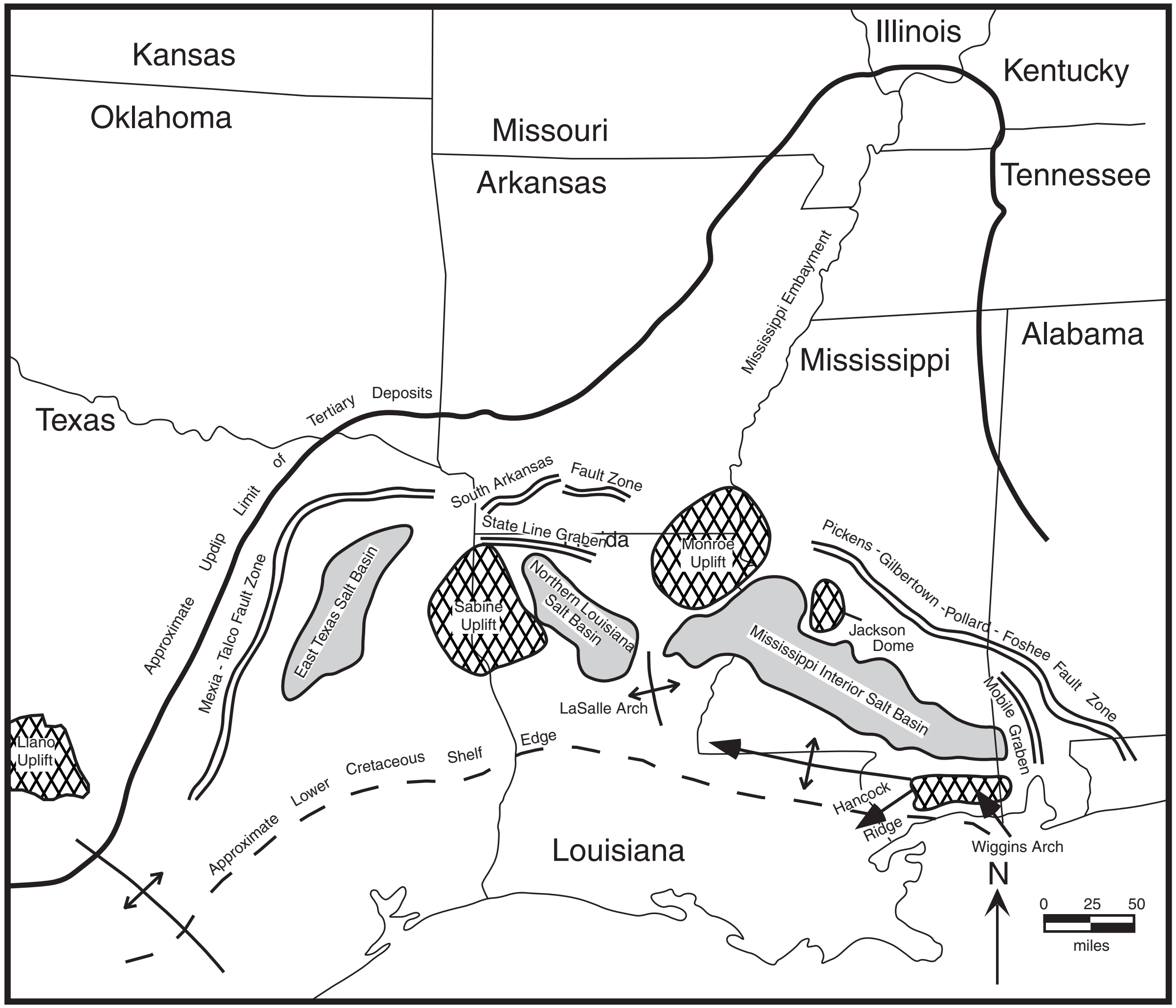

Figure 1. Basins and uplifts in the northern Gulf Coastal Plain. Modified from Pilger (1981).

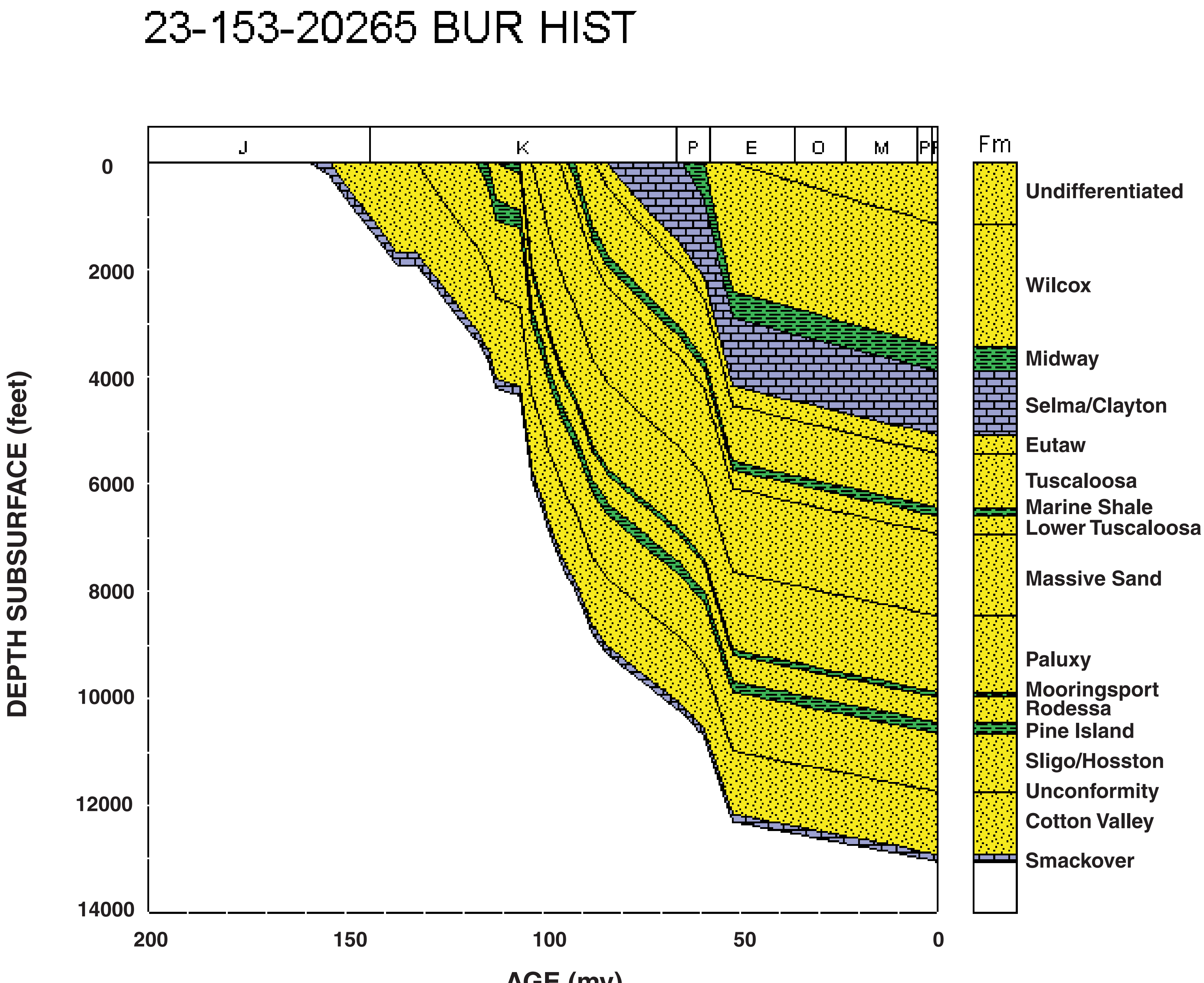

Figure 2. Burial history curve for well API 23-153-20265, located in Wayne County, Mississippi.

23-153-20265 MATURITY

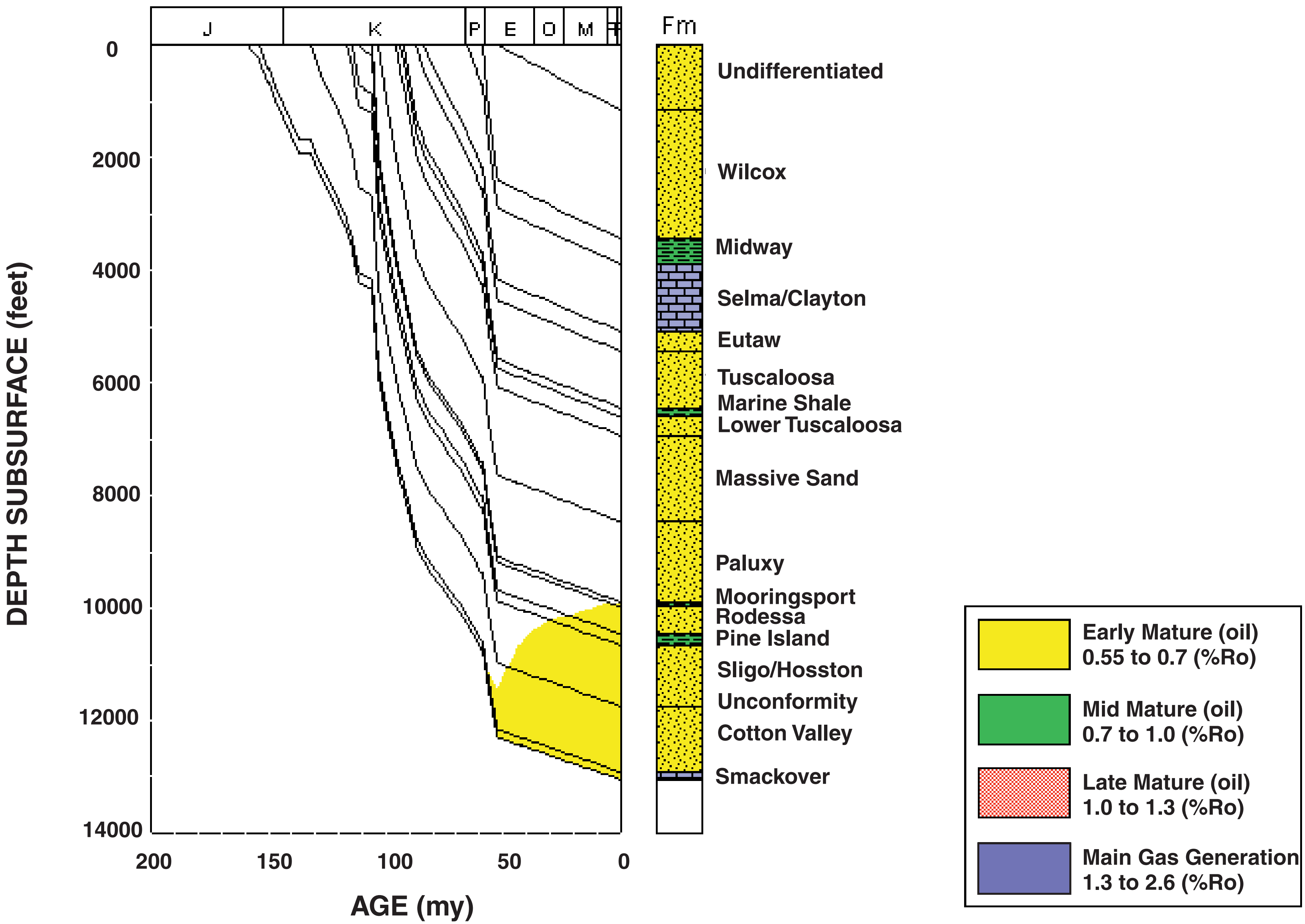

Figure 3. Hydrocarbon maturation curve for well 23-153-20265, located in Wayne County, Mississippi.

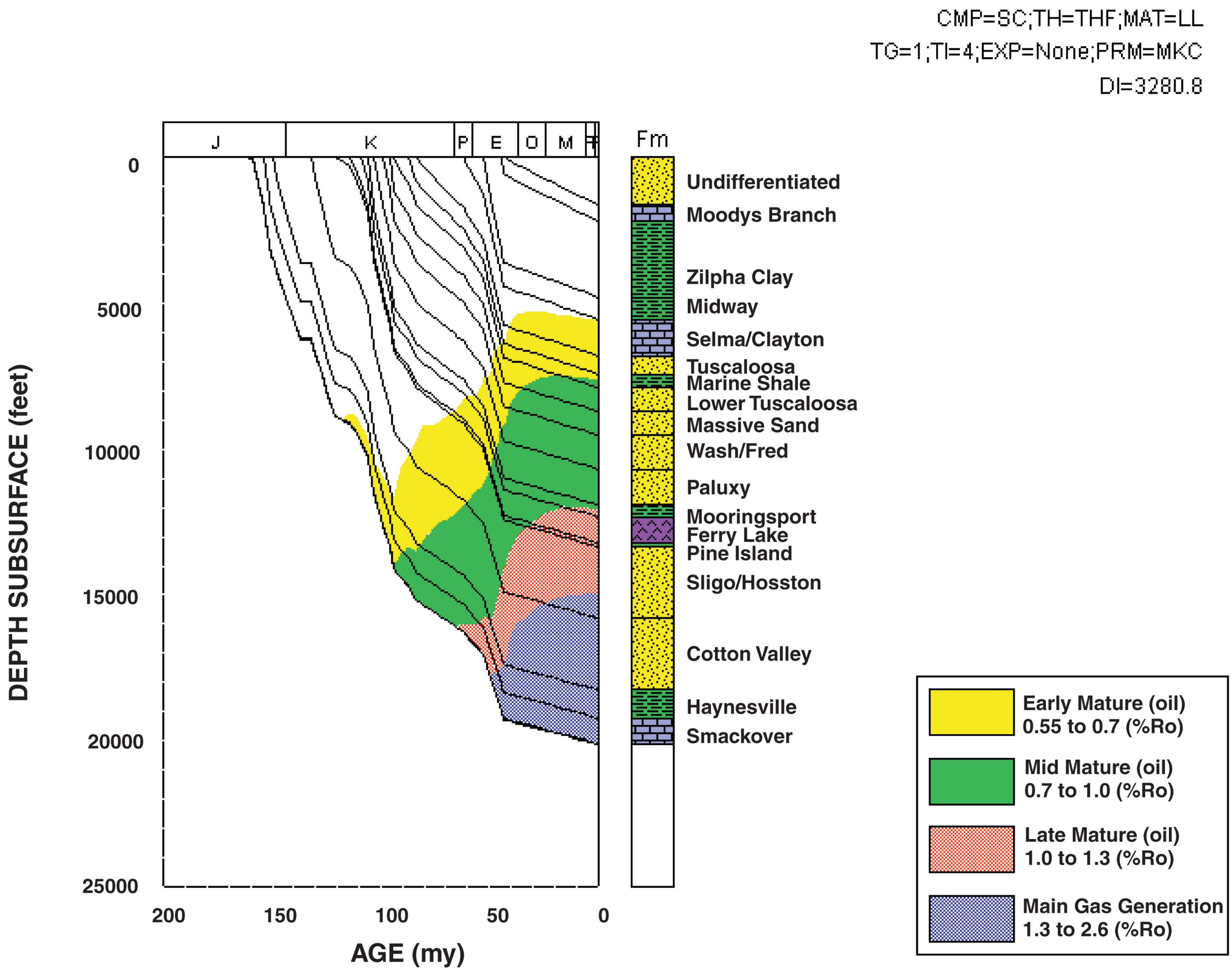

Figure 4. Hydrocarbon maturation curve for well API 23-111-00069, located in Perry County, Mississippi.

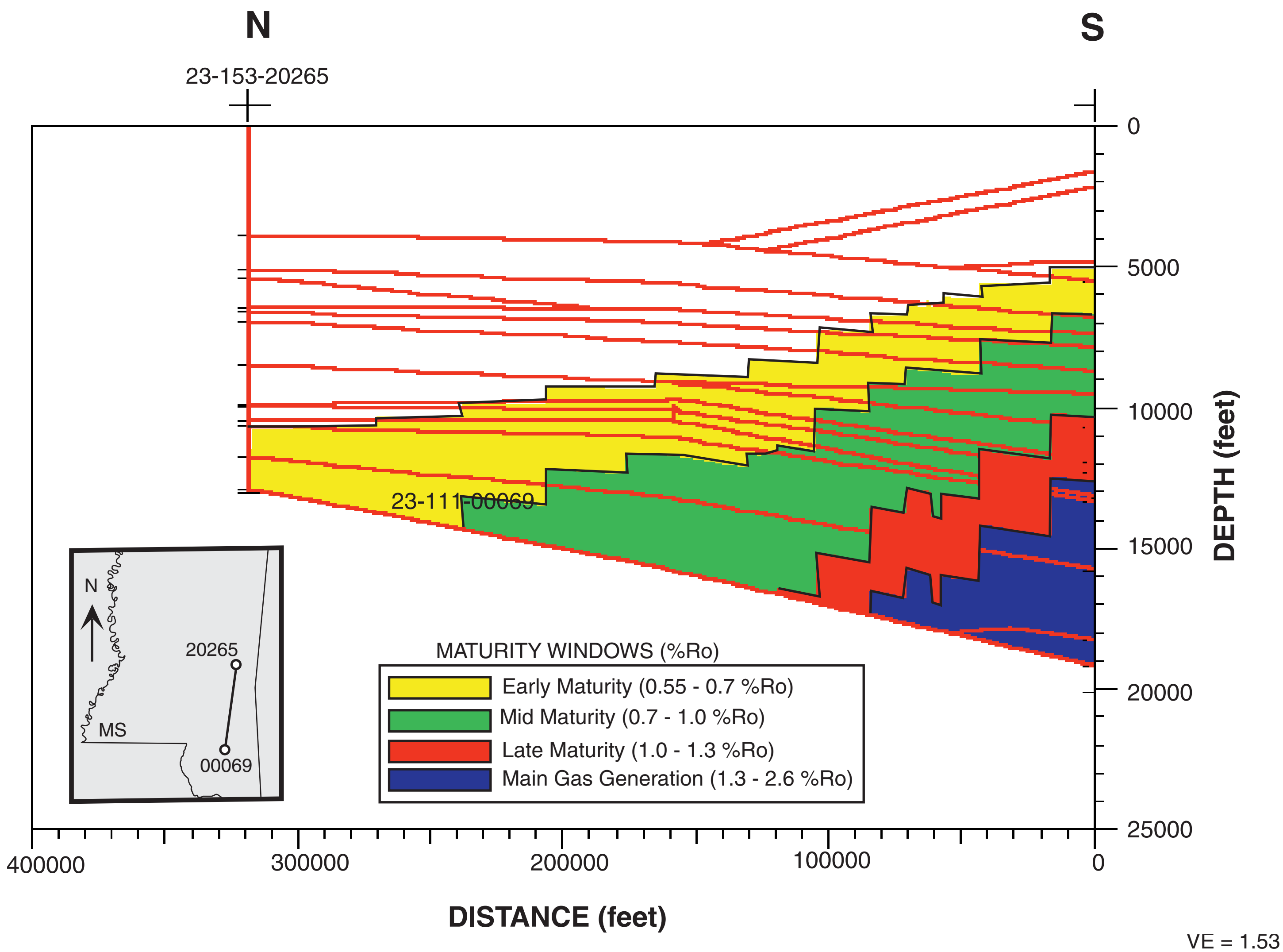

Figure 5. Hydrocarbon generation and maturation trend from Perry County to Wayne County, Mississippi.