PS USGS Assessment of Undiscovered Oil and Gas Resources for the Oligocene Frio and Anahuac Formations, Onshore Gulf of Mexico Basin, USA*

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Authors' Note: This article contains the abstract, text, and figures presented in that poster session. This same material currently is in internal peer review at the U.S. Geological Survey. Previous reports on the assessment of the Frio and Anahuac formations include Swanson et al. (2007) and Swanson and Karlsen (2008). Readers of the current presentation are encouraged to contact the authors via email with their questions and comments.

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Abstract

The sand-rich, fluvio-deltaic Oligocene Frio Formation, a mature to supermature exploration trend, has been one of the largest hydrocarbon producers from Paleogene strata in the Gulf of Mexico Basin. The overlying Anahuac Formation is a transgressive marine shale having deltaic, shoreface, and slope sandstones in addition to carbonate sediments. In a recent U.S. Geological Survey assessment of undiscovered, technically recoverable oil and gas resources in Tertiary strata of onshore lands and State waters, estimated total mean values of undiscovered resources for the Frio and Anahuac Formations were 172 million barrels of oil (MMBO), 9384 billion cubic feet of natural gas (BCFG), and 542 million barrels of natural gas liquids (MMBNGL). Five assessment units (AUs) for the Frio (including equivalents preserved in the Hackberry embayment) and Anahuac Formations were quantitatively assessed. Three of the Frio AUs were defined based on the character of reservoirs in relation to structural and depositional features: (1) the "Frio Stable Shelf Oil and Gas AU", containing reservoirs with a mean depth of about 4800 ft in normally pressured intervals; (2) the "Frio Expanded Fault Zone Oil and Gas AU", containing reservoirs with a mean depth of about 9000 ft in overpressured intervals; and (3) the "Frio Slope and Basin Floor Gas AU", which currently has no production, but has potential for deep gas resources (>15,000 ft). AUs also were defined for the Hackberry embayment and the Anahuac Formation. Of the five units assessed, the "Frio Slope and Basin Floor Gas AU" shows the greatest potential for undiscovered gas resources, having an estimated mean of 5589 BCFG.

Introduction

In 2007, the U.S. Geological Survey (USGS) conducted an assessment of the technically recoverable, undiscovered conventional oil and gas resources in the Paleogene and Neogene strata and the unconventional coal bed gas resources in Cretaceous and Tertiary strata that underlie the U.S. Gulf of Mexico onshore coastal plain and state waters (Dubiel et al., 2007; Warwick et al., 2007; Dubiel and Warwick, 2008). Geochemical, geologic, geophysical, thermal maturation, burial history, and paleontologic studies, in addition to regional cross sections and geologic maps, were used to define the major petroleum systems for Tertiary rocks in the Gulf Coast.

Two proprietary, commercially available databases were used in the assessment. The first database (NRG Associates, Inc., 2006) contained reserve, cumulative production, and other types of information for most oil and gas fields of the United States larger than 0.5 million BOE. The data used were current as of December 31, 2004. The second database (IHS Energy Group, 2005a, 2005b) contained drilling and completion data. Data from these commercial databases are subject to proprietary license restrictions, and the USGS cannot publish, share, or serve any data from these databases.

The assessment was conducted using a Total Petroleum System (TPS) model. A TPS consists of all genetically related petroleum generated by a pod or closely related pods of mature source rocks (Schmoker and Klett, 2005). A TPS includes all of the important elements of a hydrocarbon fluid system needed to develop oil and gas accumulations, including source and reservoir rocks, hydrocarbon generation, migration, traps, seals, and discovered and undiscovered hydrocarbon accumulations (Klett et al., 2004). An assessment unit is a mappable volume of rock within a total petroleum system that encompasses discovered and undiscovered fields that share similar geologic characteristics and economics (Klett et al., 2004). The type of undiscovered hydrocarbon accumulations, discreet (conventional) or continuous-type (unconventional), determines the methodology to be used in a USGS assessment (Schmoker, 2005). All of the assessment units identified for the Frio and Anahuac Formations were assessed as conventional hydrocarbon accumulations. Discussion of the TPS for the undiscovered, conventional oil and gas resources in Paleogene and Neogene strata and the unconventional coal bed gas resources in Cretaceous and Tertiary strata that underlie the U.S. Gulf of Mexico onshore coastal plain and state waters is in the “Source Rock” section.

Stratigraphy

The Frio Formation is composed of a series of deltaic and marginal-marine sandstones and shales that are the downdip equivalent of the continental Catahoula Formation (Galloway et al., 1982, 1991; Figures 1 and 2). The Frio is underlain by the Oligocene Vicksburg Formation, which is thickest and best developed within the Rio Grande embayment in south Texas (Galloway et al., 1982). The subsurface Frio and Anahuac Formations of Texas and Louisiana are subdivided into paleontological zones based on the occurrence of benthic foraminifera (Table 1). The Chickasawhay and lower part of the Paynes Hammock formations of southeast Mississippi, southwest Alabama, and the west Florida panhandle are the equivalents of the subsurface Frio and Catahoula of Texas and Louisiana (Galloway et al., 1991; Salvador and Quezada Muñeton, 1991; Figure 2).

In southeast Texas and southwest Louisiana, a transgressive, deepwater shale and sandstone unit referred to as the “Hackberry” occurs in the middle part of the Frio Formation (Bornhauser, 1960; Paine, 1968, 1971; Benson, 1971; Berg and Powers, 1980; Ewing and Reed, 1984; Galloway et al., 1991, 2000; Cossey and Jacobs, 1992) (Figures 2 and 3). The name “Hackberry” was introduced by Garrett (1938) to designate a certain foraminiferal assemblage within the greater Frio interval, but it has also been referred to as a sequence, member, or formation in the literature (Bornhauser, 1960; Ewing and Reed, 1984; Cossey and Jacobs, 1992).
In places, the Frio is regionally overlain by the Anahuac Formation, an onlapping, transgressive marine shale that occurs in the subsurface of Texas, Louisiana, and southwestern Mississippi (Galloway et al., 1982; Galloway et al., 1991) (Figure 2). Previous studies have reported the Anahuac to be in either the upper Oligocene or lower Miocene (Warren, 1957; Krutak and Beron, 1990, 1993).

Structure contour and isopach maps (Figure 4) generated from published data (Bebout and Gutierrez, 1982, 1983; Dodge and Posey, 1981) for the USGS Tertiary Assessment (Swanson and Karlsen, 2007; 2008) indicate that the depth to the top of the Frio (including the Anahuac Formation) ranges from a minimum of less than 1000 ft in updip areas to a maximum of about 18,000 ft in southern Louisiana. The thickness of the Frio ranges from less than 1000 ft in southern Louisiana to close to 10,000 ft in coastal areas of Texas.

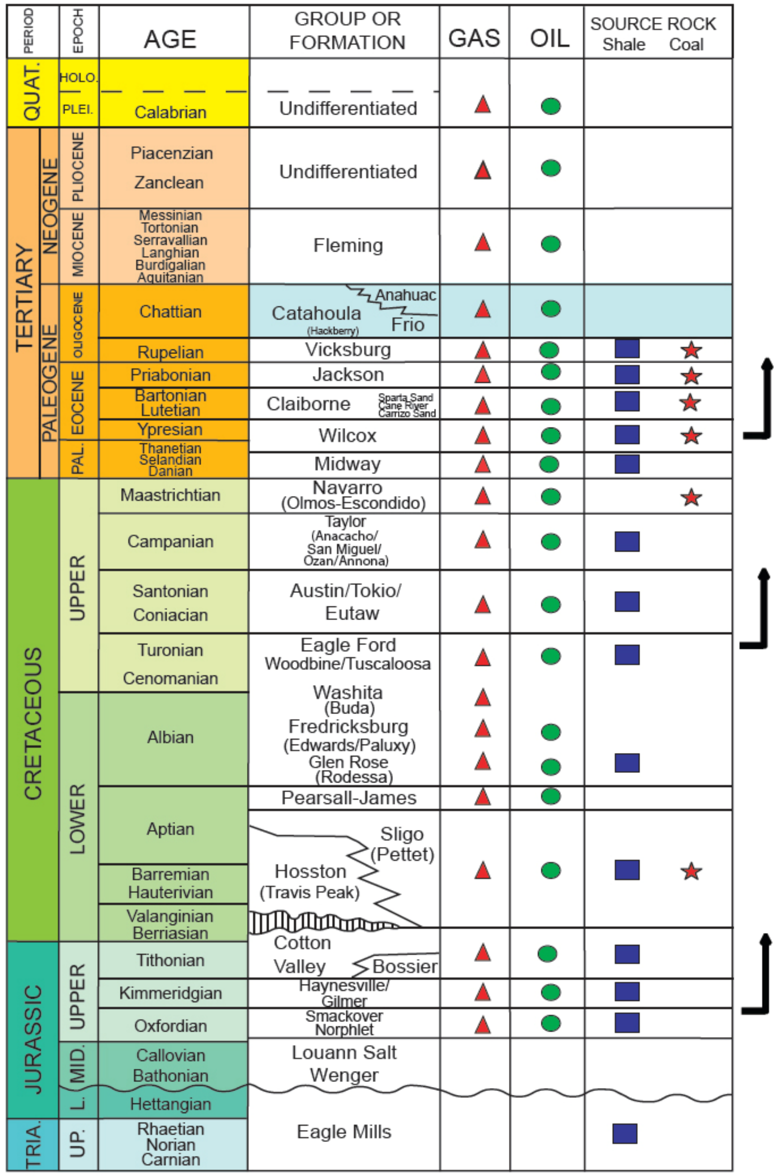

Figure 1. Stratigraphic section of the Tertiary and younger strata in the northern Gulf of Mexico coastal plain, with the Frio Formation (equivalent to the Catahoula Formation in updip areas) and Anahuac Formation highlighted in blue (modified from Warwick et al., 2007; Salvador and Quezada Muñeton, 1991). L. = Lower; Mid. = Middle; Up. = Upper; Tria. = Triassic; Pal. = Paleocene; Plei. = Pleistocene; Holo. = Holocene; Quat. = Quaternary; vertical lines = unconformity; wavy line = disconformity; jagged line = interfingering; dashed line = uncertain (modified after Salvador and Quezada Muneton, 1991; Nehring, 1991; Palmer and Geissman, 1999; Humble Geochemical Services et al., 2002; and Warwick et al., 2007).

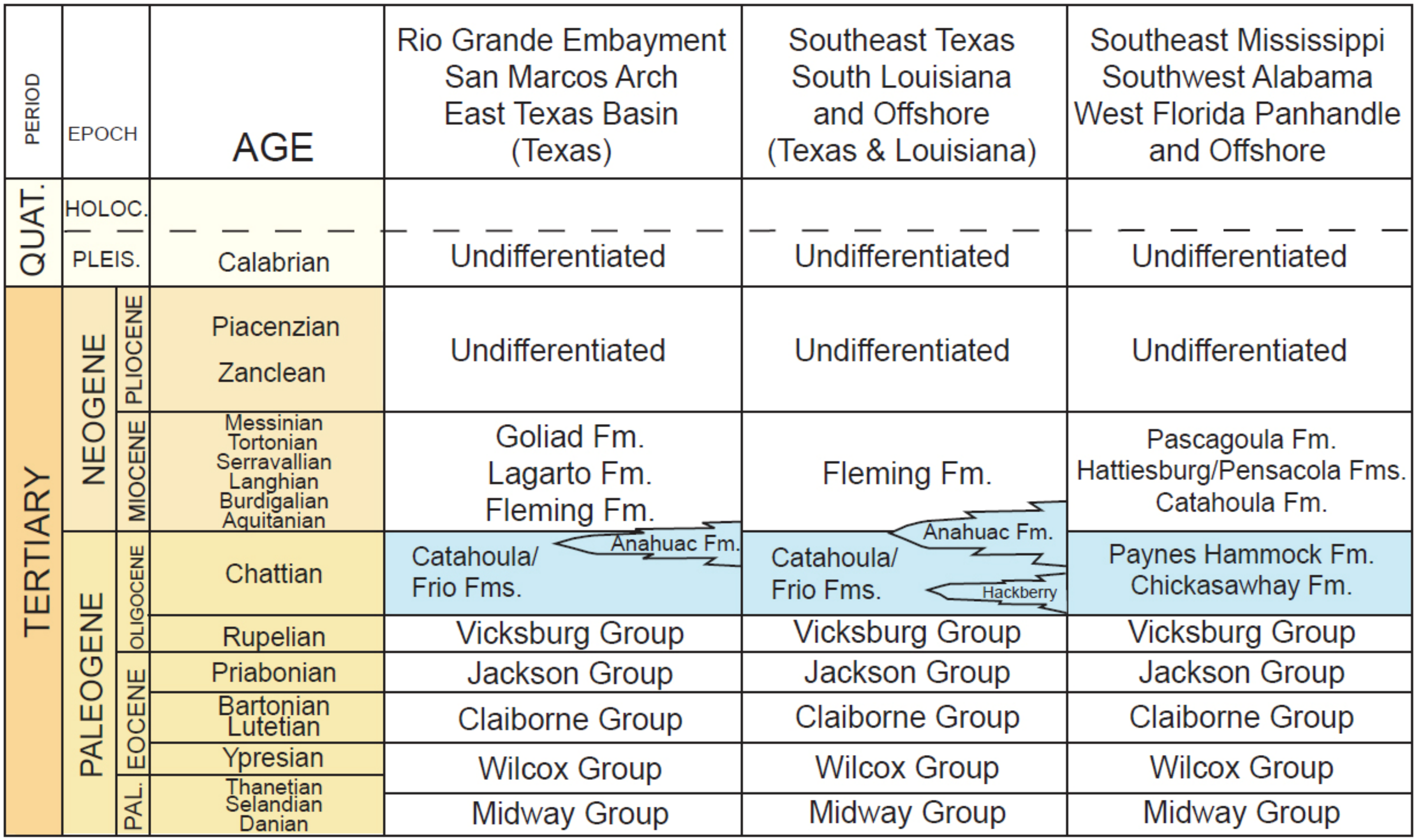

Figure 2. Expanded stratigraphic section of the Tertiary and younger strata in the northern Gulf of Mexico coastal plain (from Figure 1), with the Frio Formation (equivalent to the Catahoula Formation in updip areas) and Anahuac Formation highlighted in blue (modified from Warwick et al., 2007).

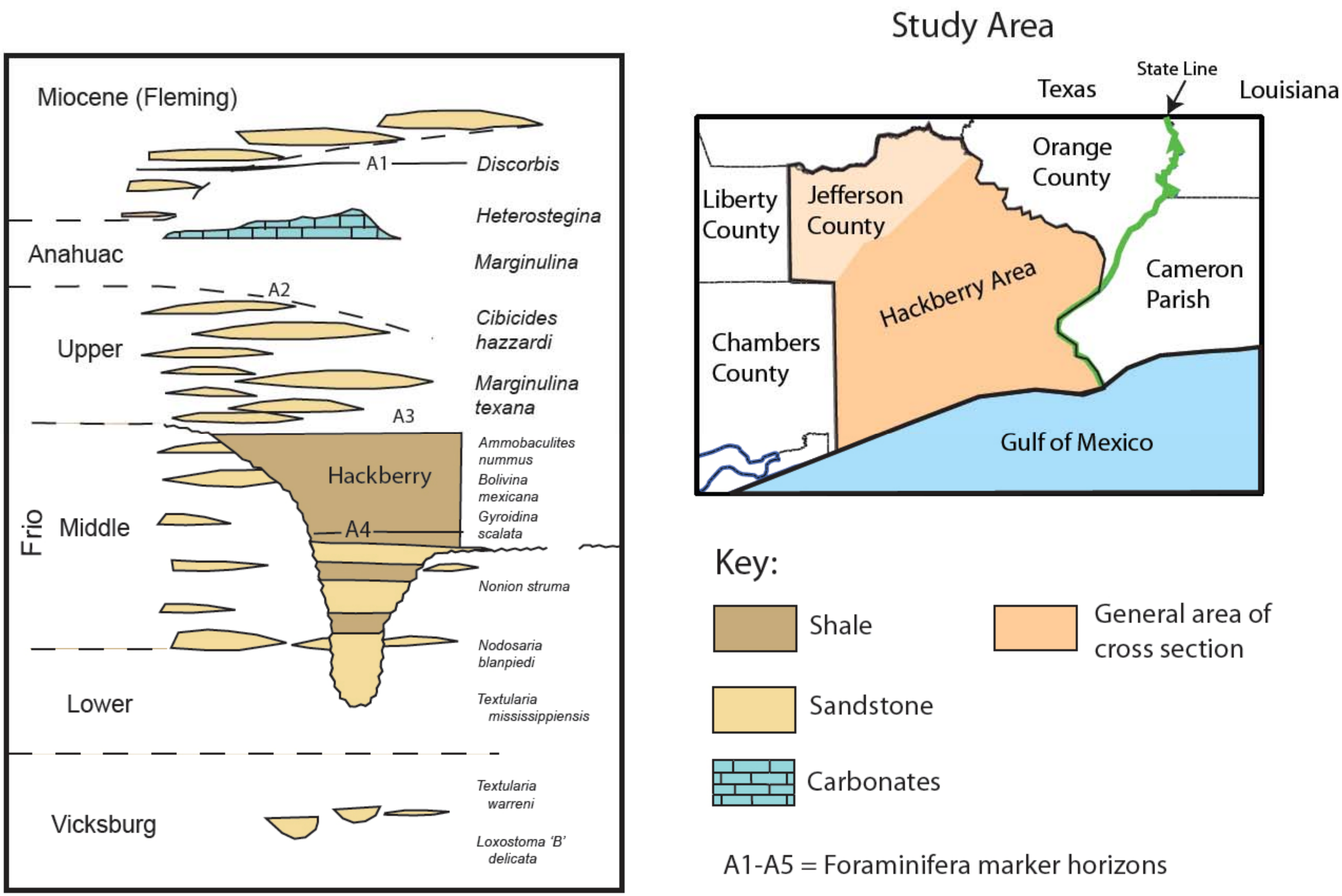

Figure 3. Schematic diagram of the Hackberry trend and related strata, Jefferson County area, Texas, and diagnostic foraminifera (modified from Ewing and Reed, 1984).

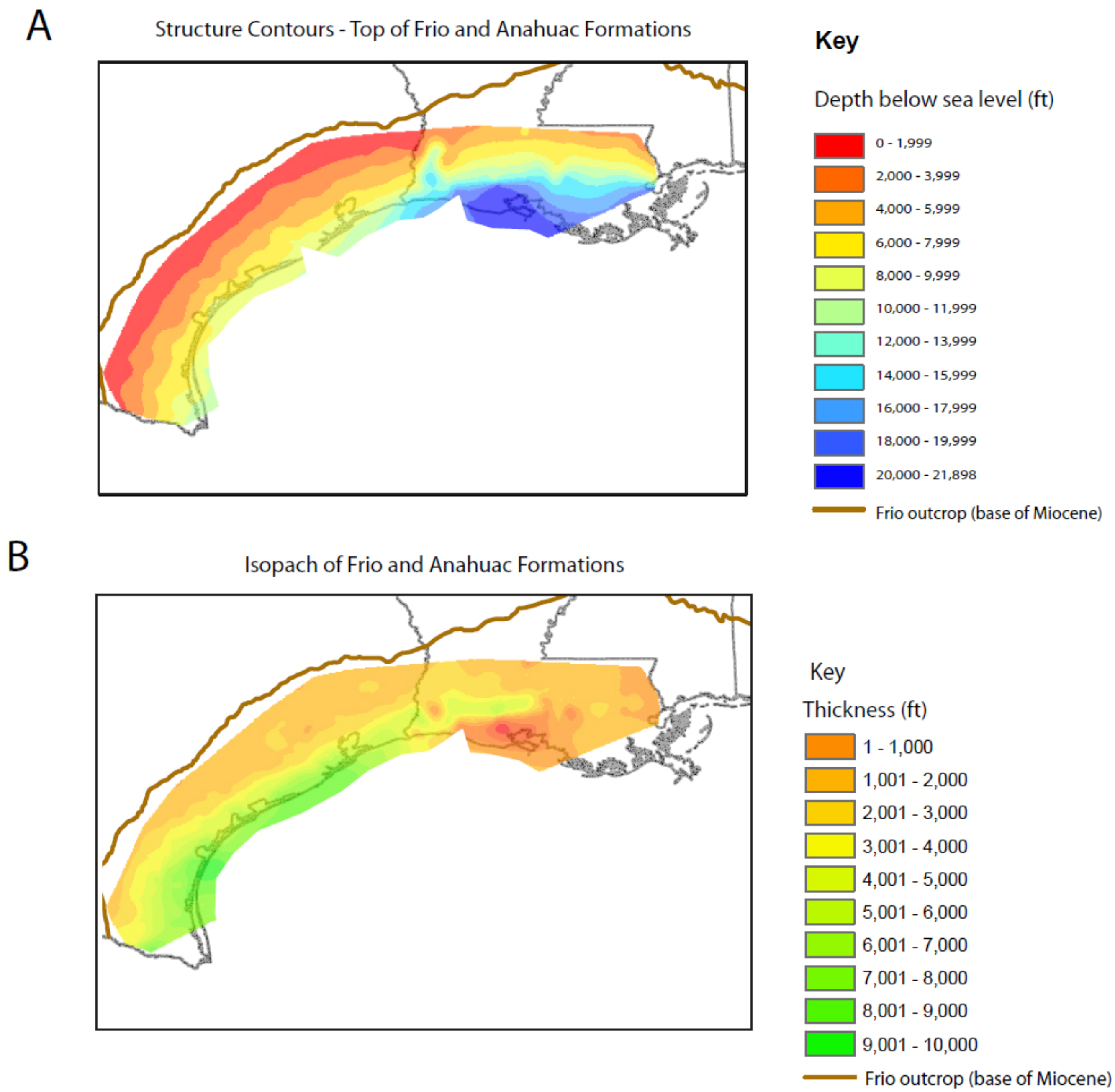

Figure 4. Structure contours showing depth (from sea level) to the top of the Frio Formation (A) and total thickness of the Frio Formation (B). The Anahuac Formation is included within the Frio in these maps. Maps were generated from published cross sections (Bebout and Gutierrez, 1982, 1983; Dodge and Posey, 1981).

System	Sub-System	Series/Epoch	Fm		Selected Biostratigraphic Horizons for Frio Formation
TERTIARY	NEOGENE	Miocene	Fleming/ Catahoula		
	PALEOGENE	Oligocene	Anahuac	Upper Lower	*Lenticulina (47) jeffersonensis* (Pope et al., 1992) *Discorbis (Ewing and Reed, 1984)* *Discorbis gravelli* (New Orleans Geological Society, 1983; Pope *et al.*, 1992) *Heterostegina* sp. (*Het* lime) (Goddard *et al.*, 2005; Pope *et al.*, 1992; Ewing and Reed, 1984) Cibicides jeffersonensis (Pope *et al.*, 1992) Bolivina perca (Goddard *et al.*, 2005; Pope *et al.*, 1992) *Marginulina* Zone (Desselle, 1992; Ewing and Reed, 1984; Goddard *et al.*, 2005) *Marginulina idiomorpha* (Desselle, 1992; Goddard *et al.*, 2005; Pope *et al.*, 1992) *Marginulina vaginata* (Desselle, 1992; Goddard *et al.*, 2005; Pope *et al.*, 1992) *Marginulina howei* (Desselle, 1992; Pope *et al.*, 1992)
			Frio (includes Catahoula, Chickasawhay and Paynes Hammock; refer to fig. 2)	Upper	*Camerina A* sp. (Paine *et al.*, 1968; Pope *et al.*, 1992;; Goddard *et al.*, 2005) *Miogypinoides(A) complanata* (Pope *et al.*, 1992) *Miogypsina* (Goddard *et al.*, 2005) *Cibicides hazzardi* (Ewing and Reed, 1984; Paine *et al.*, 1968; Galloway *et al.*, 1991; Pope *et al.*, 1992; Goddard *et al.*, 2005) * ** *Marginulina texana (Ewing and Reed, 1984)*
				Middle	*Marginulina texana* – (Paine *et al.*, 1968; New Orleans Geological Society, 1983; Pope *et al.*, 1992)
				Middle — Hackberry	*Ammobaculites nummus (Ewing and Reed, 1984)* *Bolivina mexicana* (New Orleans Geological Society, 1983; Ewing and Reed, 1984; Pope *et al.*, 1992) *Gyroidina scalata (Ewing and Reed, 1984)* *Nonion struma (Ewing and Reed, 1984;* Goddard *et al.*, 2005)
				Lower	*Nonion struma* (Galloway *et al.*, 1991; Pope et al., 1992; Goddard et al., 2005) * *Nodosaria blanpiedi* (Paine *et al.*, 1968; Ewing and Reed, 1984; Galloway, 1986; Galloway *et al.*, 1991; Goddard *et al.*, 2005; New Orleans Geological Society, 1983; Pope *et al.*, 1992; Warren, 1957)* *Discorbis D* sp. (Paine *et al.*, 1968; Pope *et al.*, 1992) *Textularia selegi* (Pope *et al.*, 1992) *Textularia mississippiensis* (Ewing and Reed, 1984; Galloway, 1986; Pope *et al.*, 1992) *Anomalina bilateralis* (Galloway, 1986)
			Vicksburg		

Table 1. Compilation of biostratigraphic zones for the Frio and Anahuac Formations from the literature. Although biostratigraphic markers are generally listed in stratigraphic order, there are differences in interpretations found in the geologic literature and differences based on geographic area. In this table, the Anahuac Formation is placed in the upper Oligocene, based on Galloway et al. (1991). Key: * denotes occurrence in Chickasawhay Formation; ** denotes occurrence in Paynes Hammock Formation.

Source Rocks

The source of oil and gas in Oligocene reservoirs has been controversial. Sassen (1990) reported that crude oils in Oligocene and younger reservoirs in southern Louisiana probably migrated vertically from deep, lower Tertiary source rocks, but that Mesozoic sources may also have also been included. Other potential sources in southern Louisiana were thought to be the upper Eocene Jackson Group and Vicksburg Groups (Tanner and Feux, 1990) and biogenic sources in coal beds (Nehring, 1991). Galloway et al. (1982) reported that although Frio mudstones contain low percentages of organic carbon and are dominated by gas-prone woody and herbaceous organic matter types, the volumes of potential source rock are immense. La Plante (1974) suggested that Oligocene rocks in south Louisiana contain disseminated, terrestrially derived kerogen that would be capable of generating hydrocarbons, if subjected to sufficiently high temperatures. Based on the content of total organic carbon, Bissada et al. (1990) suggested that Oligocene and younger rocks were not adequate petroleum source rocks.

In a model developed by Wenger et al. (1994) and Hood et al. (2002), the northern outer regions of the basin are characterized by oil generated primarily from the Jurassic Smackover Formation and Cretaceous Eagle Ford Formation, whereas the interior (coastal and nearshore) areas of the basin are characterized by oils produced from the Wilcox and Sparta source rock intervals (Figure 5). No significant Oligocene or younger source rocks were identified (Hood et al., 2002). Source rocks within Cenozoic petroleum systems in the northern, onshore Gulf Coastal region are thought to be primarily mudstone, claystone, and coaly intervals of the Wilcox Group (Paleocene-Eocene), with some contributions from the Sparta Formation of the Claiborne Group (Price, 1991; McDade et al., 1993; Wenger et al., 1994; Rowan et al., 2007). The USGS Tertiary Assessment Team, using both proprietary and public oil and gas geochemical data, concluded that although the mapped, two-dimensional petroleum systems of Wenger et al. (1994) and Hood et al. (2002) were generally valid, mixing of oils and gases sourced from other petroleum systems within each petroleum system area identified on the Wenger-Hood maps could not be ruled out (Lewan, written communication, 2006; Warwick et al., 2007). Thus, rather than subdivide the Gulf Coast province into three Total Petroleum Systems (Smackover, Eagle Ford, and Wilcox/Sparta), the USGS Assessment Team combined them into the Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System (Dubiel et al., 2007; Warwick et al., 2007) (Figure 6).

Depositional Systems

Frio Formation

The Frio Formation is one of the major Tertiary progradational wedges of the Texas Gulf coastal plain (Galloway et al., 1982). During the Oligocene, massive sediment influx from sources in Mexico and the southwestern United States occurred as a result of uplift and erosion that started in Mexico and was followed by uplift and erosion along the western margin of the Gulf basin itself (Galloway et al., 1982, 2000). Explosive volcanism and caldera formation along the Sierra Madre Occidental combined with the uplift to create a massive influx of recycled sedimentary rocks, volcaniclastics, and reworked ash into the western and central Gulf of Mexico (Galloway, 1977).

Sediment dispersal axes along the northwest to central Gulf margin resulted in the formation of the Norma delta, Norias delta (Rio Grande embayment), Houston delta (Houston Embayment), and central Mississippi delta (Galloway et al., 1982, 2000; Galloway, 1986) (Figure 7). Of these deltas, the sand-rich, wave-dominated Norias delta was the largest. To the south, it merged laterally with the smaller sand-rich, wave-dominated Norma delta (Galloway et al., 2000). The fluvial system that supplied the Norias delta was a single river that carried relatively coarse-grained sediments (Galloway et al., 1982). In contrast, the fluvial system that supplied the Houston delta system consisted of several rivers that carried a mixed load of sand, silt, and clay (Galloway et al., 1982). In the late Oligocene, the Houston delta retrograded from the shelf margin, and the central Mississippi delta shrank markedly in area (Figure 7) (Galloway et al., 2000).

Hackberry Embayment (Frio Formation)

Early studies on the Hackberry trend of southwestern Louisiana identified two major units:
(1) an upper predominantly shale section ranging in thickness from less than 100 ft to more than 3000 ft, consisting of a deep water microfaunal assemblage, and (2) a lower predominantly sandstone section ranging in thickness from zero to 700 ft (Paine, 1968) (Figure 3). Numerous abrupt local changes in lithologic character make correlations within the Hackberry difficult (Paine, 1968). Paine (1971) established that the lower Hackberry sandstones were turbidites and that the lower Hackberry sandstone had two depositional patterns: an updip, north-south channel pattern, and a downdip blanket type sandstone pattern (Paine, 1971).

Shale and sandstone of the Hackberry sequence form a seaward-thickening wedge, which pinches out to the north along the Hartburg Flexure (Eubanks, 1987) (Figure 8). The Hartburg Flexure is defined as a zone of growth faulting that developed during the Oligocene, which may have represented the shelf margin and limited the updip extent of deep-water shale deposition (Berg and Powers, 1980; Bornhauser, 1960; Ewing and Reed, 1984). Over most of the embayment, the lower Hackberry consists of sand-rich channel filling units that were eroded as much as 800 ft into pre-Hackberry strata (Ewing and Reed, 1984). The Hackberry channel-fill sands were deposited in a submarine canyon-fan setting (Paine, 1968, 1971; Berg and Powers, 1980; Eubanks, 1987; Ewing and Reed, 1984; Cossey and Jacobs, 1992; Galloway et al., 2000) (Figure 9). Updip areas are described as an area of slope failure involving slide blocks, and downdip areas consist of channels where thick, turbidite sands were deposited (Cossey and Jacobs, 1992). Shelf margin slides may have been caused by a combination of salt withdrawal and a generally unstable shelf edge (Cossey and Jacobs, 1992).

Anahuac Formation

The Frio Formation is overlain by the Anahuac Formation, a transgressive marine shale, in Texas and Louisiana (Figure 2) (Galloway et al., 2000). The Anahuac onlaps the regressive Frio Formation in downdip areas, and it is overlain by the progradational sandstones of the lower Miocene (Galloway et al., 1982, 1991). Anahuac Formation strata of southwestern Louisiana and Texas are nearly identical, consisting of light- to dark- greenish gray calcareous shale interbedded with thin beds of locally calcareous sandstone and locally thin limestones (John et al., 1992a). Anahuac sediments are more calcareous from west to east (John et al., 1992a). Carbonates are found where clastic influx was minimal, in the eastern Gulf of Mexico (Galloway et al., 2000). In some areas of eastern Louisiana, the section consists of reef and detrital limestones containing minor sandstone and shale that grade into carbonate deposits. In the eastern Gulf, petrographic analyses indicate the presence of hermatypic framework and binding organisms that constructed reefal or algal mound accumulations (Krutak and Beron, 1993). These buildups accumulated along a late Oligocene-early Miocene rimmed accretionary carbonate shelf, in nearshore waters of southeastern Louisiana and western Mississippi in carbonates both above and below the *Heterostegina* Zone (Krutak and Beron, 1990, 1993). At the climax of the late Oligocene transgressive flooding, *Heterostegina* carbonate buildups in the Anahuac Formation occurred as far west as the Houston salt basin (Galloway et al., 2000).

John et al. (1992a) identified three depositional systems of the Anahuac Formation in south central and southwestern Louisiana, based on relative amounts of sandstone and shale within the section and character of the sandstones: proximal deltaic, distal deltaic, and slope environments. In West Baton Rouge Parish of southern Louisiana, the Anahuac has an average thickness of 750 ft (Goddard et al., 2005) and the uppermost *Heterostegina* strata include calcareous sandstone and limestone beds, indicating that deposition occurred in an inner-shelf, shallow-marine depositional environment (Goddard et al., 2005). Interbedded shales and calcareous sandstones underlying the *Heterostegina* zone are typical of middle shelf-intermediate open marine environments (Tipsword et al., 1966; Goddard et al., 2005). Progradational distal delta-front sandstones, shoreface, and shelf sandstones of the Anahuac Formation also occur in the Mustang Island and Matagorda Island areas in Texas (Desselle, 1997a, 1997b).

Reservoirs in Relation to Shelf Margin Deltas

Studies of the occurrence of reservoirs in relation to shelf-margin deltas, for the Frio and other large plays in the Gulf of Mexico, are abundant in the literature (Winker, 1982; Edwards, 2000, 2002, 2006; Galloway, 2002; Meckel, 2003; Brown et al., 2004, 2005, 2006). As reported by Winker (1982), growth faulting and rapid subsidence rates along Cenozoic shelf margins can be explained by large-scale, deep-seated gravity sliding of the continental slope, and shelf margin megafacies are characterized by deep geopressured gas reservoirs. Foundered shelf edges (FSEs), as described by Ewing and Vincent (1997), result from the sudden movement of the shelf edge to a more landward point, due to large-scale slumping, sliding and erosion. The deep water environments of the FSE form promising targets for future exploration; however, the seismic response of the deeply-buried slope-fan systems is complex and productive reservoirs in slope fan and basin fan environments are difficult to predict. Edwards (2000, 2006) suggests that shelf margin collapse and relocation of the shelf margin landward, behind the headwall of a strike-parallel slump scar, occasionally counteracted the prevailing pattern of shelf margin progradation basinward. This sequence of events created unique reservoir and trapping opportunities, such as in the emplacement of slump blocks into the collapse. Meckel (2003) suggests that deltas that cross the shelf, either by prograding during highstands of sea level or due to a lowstand in sea level, produce distinctive depocenters that are important exploration targets, in part because they contain downdip sands that are typically encased in basinal shales. In a sequence stratigraphic study of the Frio Formation, Brown et al. (2004, 2005, 2006) suggest that lowstands of sea level were the main trigger of growth faulting and that subbasins on the downthrown side of arcuate fault systems have been prolific targets for decades and are now the focus of prospecting for deep gas.

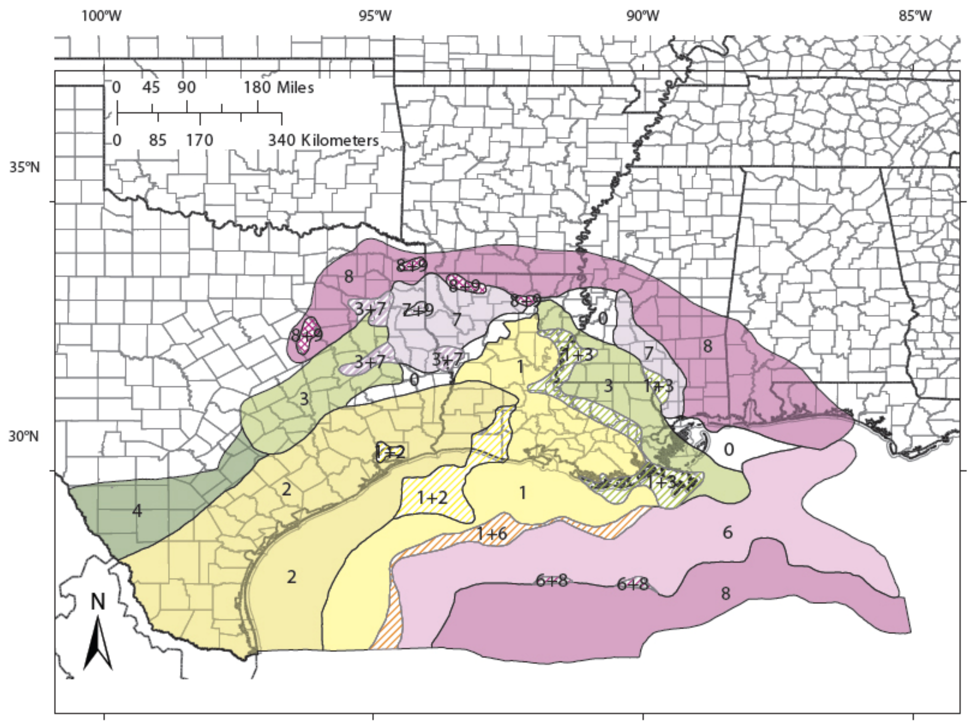

Figure 5. Map indicating the predominant hydrocarbon systems for oils produced in the northern Gulf of Mexico. "Intermediate" denotes depositional environments that are intermediate between marine and terrestrial (after Wenger et al., 1994; Hood et al., 2002; Warwick et al., 2007).

Hydrocarbon Systems Map Showing Extent of Oils and Gases from Common Source Intervals Explanation (source interval age and depositional environment, based on oil geochemistry characteristics of source rock extracts)

- 0 = Not designated
- 1 = Lower Tertiary (centered on Eocene) Marine and Intermediate
- 1+2 = Lower Tertiary (centered on Eocene) Terrestrial
- 1+3 = Lower Tertiary (centered on Eocene) marine and intermediate Upper Cretaceous (centered on Turonian) marine low sulfur
- 1+6 = Lower Tertiary (centered on Eocene) marine and intermediate uppermost Jurassic (centered on Tithonian) marine - moderate to high sulfur
- 2 = Lower Tertiary (centered on Eocene) Terrestrial
- 3 = Upper Cretaceous (centered on Turonian) Marine-low sulfur
- 3+7 = Upper Cretaceous (centered on Turonian) Marine-low sulfur Upper Jurassic or Lower Cretaceous? Marine
- 4 = Upper Cretaceous (centered on Turonian) and Lower Cretaceous (centered on Aptian) Calcareous-moderate sulfur
- 6 = Uppermost Jurassic (centered on Tithonian) Marine-Moderate to high sulfur
- 6+8 = Uppermost Jurassic (centered on Tithonian) marine - moderate to high sulfur Upper Jurassic carbonate - elevated salinity
- 7 = Upper Jurassic or Lower Cretaceous? Marine
- 7+9 = Upper Jurassic or Lower Cretaceous? Triassic (Eagle Mills) Lacustrine
- 8 = Upper Jurassic (Oxfordian) Carbonate-Elevated Salinity
- 8+9 = Upper Jurassic (Oxfordian) Carbonate-Elevated Salinity Triassic (Eagle Mills) Lacustrine

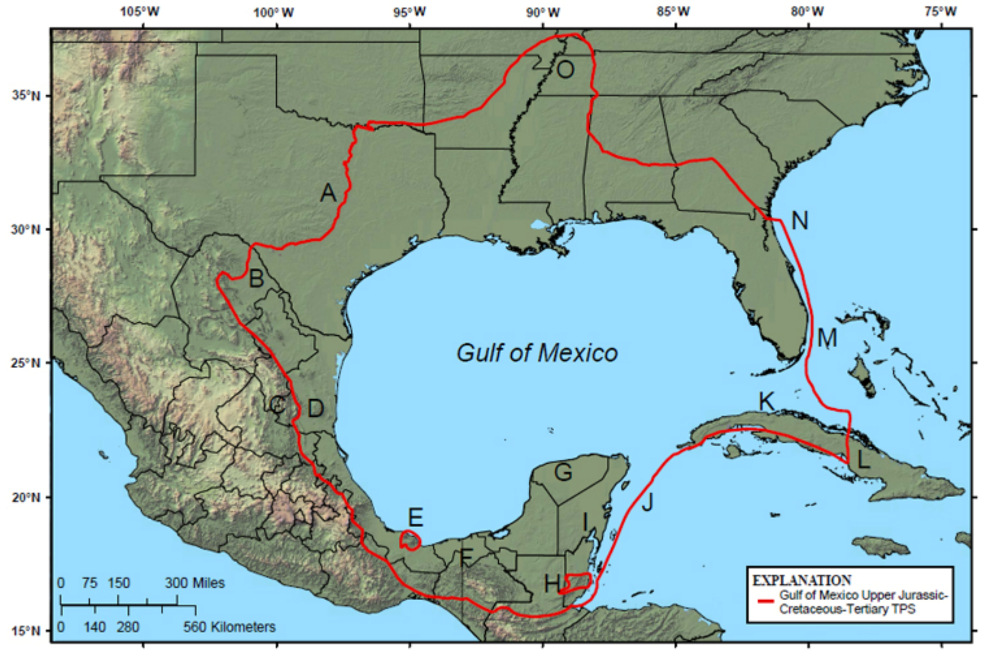

Figure 6. Upper Jurassic-Cretaceous-Tertiary Composite total petroleum system (TPS) for the Gulf of Mexico basin (from Warwick et al., 2007). The letters (A-O) refer to the following notes on how the TPS boundary was drawn. The boundary line: A, coincides with the Upper-Lower Cretaceous outcrop boundary (Schruben et al., 1998); this line may be somewhat arbitrary as the area may include some Interior Platform Paleozoic-derived oil that has migrated into Cretaceous reservoirs and is not part of the Gulf of Mexico TPS; B, includes both Maverick and Sabinas basins, which have Gulf of Mexico basin source and reservoir rock (Eguiluz de Antuñano, 2001; Scott, 2003); C, excludes Sierra Madre Oriental, which has stratigraphic equivalents to Gulf of Mexico basin source and reservoir rocks, but probably has experienced too much structural deformation and erosion to retain any significant hydrocarbon volumes (see Ewing, 1991,a); D, includes the Magiscatzin basin, which has production from units of the main Tampico-Misantla basin and contains similar strata and structural styles as found in the Gulf of Mexico basin (Nehring, 1991; USGS World Energy Assessment Team, 2000); E, excludes Tuxla Uplift, an Upper Cenozoic volcanic area (see Ewing, 1991a); F, includes the Pimienta-Tamabra TPS (USGS World Energy Assessment Team, 2000); G, includes north Yucatan, because hydrocarbons are present in Chicxulub Crater cores (Rosenfeld, 2003); H, excludes the Maya Mountains, a metamorphic orogenic complex (Ewing, 1991a; Ewing and Lopez, 1991); I, includes the south Yucatan because of the occurrence of isolated oil and gas production and shows (Rosenfeld, 2003); J, line drawn along major sea-floor crustal structural boundary between oceanic crust in the Yucatan basin and back-arc Cuban basins and ocean crust the Greater Antilles Deformed Belt (Ewing, 1991a; Rodriguez et al., 1995; James, 2004; and Schenk et al., 2005); K, includes north Cuba, where there are the same source rocks as in South Florida and the deep-water Gulf of Mexico (Schenk et al., 2000; 2005; French and Schenk, 2004); L, follows an arbitrary line to the TPS in the Gulf of Mexico basin; M, follows an arbitrary line drawn to separate the Bahamas from the Florida Platform (Ewing, 1991a); N, follows the Smackover-Austin-Eagle Ford TPS boundary of Condon and Dyman (2006); however, the potential occurrence of source rocks and hydrocarbons in this area is highly speculative; O, Mississippi Embayment - includes Tertiary and Cretaceous coal beds as potential sources of biogenic gas, although there is no known hydrocarbon production from this area. The TPS outline is based on data from French and Schenk (2005)

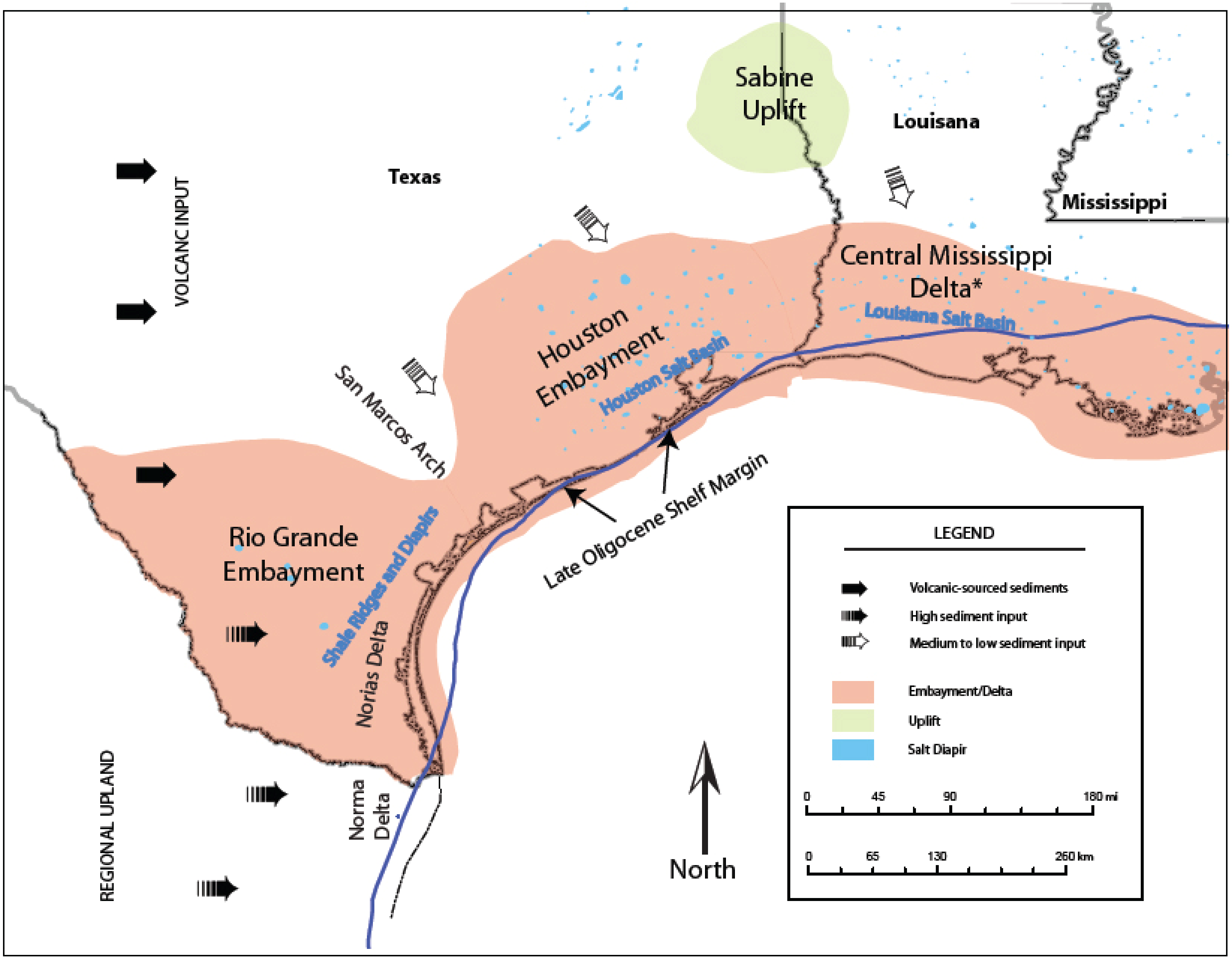

Figure 7. Principal sediment sources and depositional systems in the northern Gulf of Mexico during the late Oligocene (modified from Galloway *et al*., 2000) and location of salt diapirs (modified from Ewing and Lopez, 1991; Lopez, 1995, Martin, 1980).

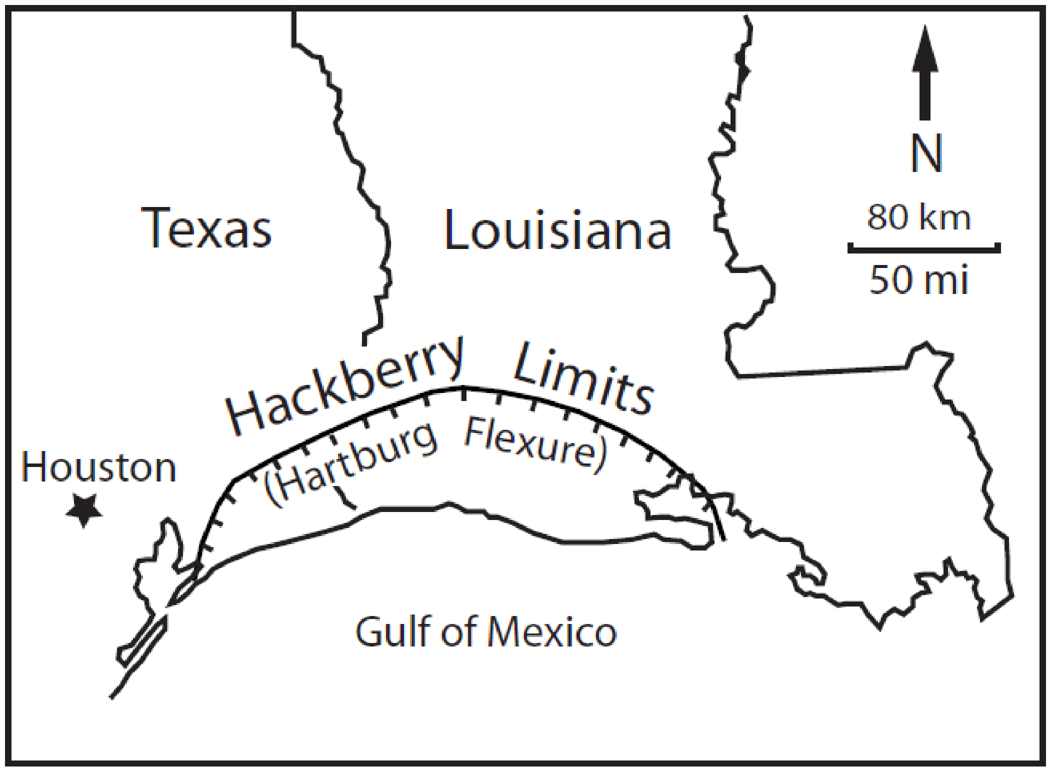

Figure 8. Diagram showing limits of the Hackberry Embayment, based on the Hartburg Flexure (Eubanks, 1987).

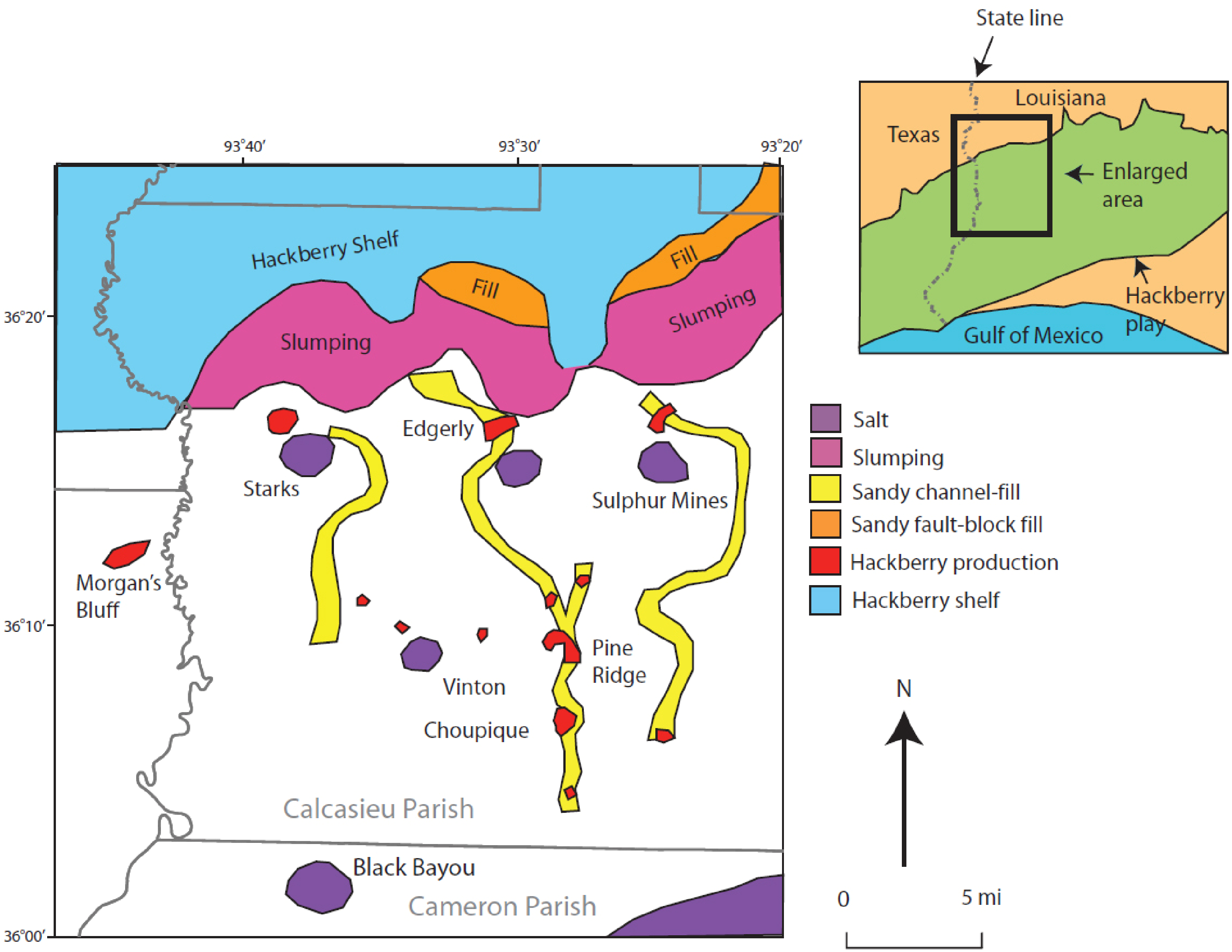

Figure 9. Generalized depositional environments of the Hackberry play and Hackberry production (field names) within western Calcasieu Parish, Louisiana (modified from Cossey and Jacobs, 1992).

Structural Features

During the Tertiary, large quantities of sand and mud were deposited along the margins of the Gulf of Mexico and these sediments accumulated in a series of wedges that thicken and dip gulfward (Bebout et al., 1978). Large growth fault systems formed near the downdip edge of each sediment wedge within the area of maximum deposition (Figure 10); these faults developed as a result of rapid sediment loading (Galloway et al., 1982). As a result of this loading, deeper, thick Jurassic salt was mobilized into a series of ridges and troughs (Bebout et al., 1978).

In Texas, three major structural provinces can be defined for the Frio (Figure 7): (1) the Houston Embayment, characterized by salt diapirism and associated faulting (Galloway et al., 1982); (2) the San Marcos arch and the area southward towards the Rio Grande Embayment, where underlying salt is mostly absent and long, linear belts of growth faults and associated shale ridges and shale diapirs are dominant (Galloway et al., 1982; Bruce, 1973); and (3) the Rio Grande Embayment, where large, but more discontinuous, belts of growth faults and deep-seated shale ridges and massifs occur (Galloway et al., 1982). As the Frio section thickens gulfward, major fault and diapiric displacement extends up into and through the unit (Bebout et al., 1978; Galloway et al., 1982).

A major deltaic progradation in south Texas and northern Mexico in the early Oligocene created the Vicksburg Fault Zone (Stanley, 1970; Ewing, 1991a, 1991b), which is a narrow fault zone characterized by vertical displacement of the underlying section (Galloway et al., 1982) (Figure 10). The Vicksburg Fault Zone, or flexure, forms the updip limit of significant structural deformation of the Frio Formation (Loucks, 1978; Galloway et al., 1982). The Frio Fault Zone, downdip of the Vicksburg Fault Zone (Figure 10), is a broad, deep listric system that consists of 5 to 10 major normal faults spaced 5 to 10 km (3 to 6 mi) apart, with intervening rollover anticlines (Ewing, 1991a). High-resolution cross sections by Galloway et al. (1994) in south Texas, based on closely-spaced well logs in addition to regional seismic data, demonstrate that the thickening and displacement of Frio sediments are significantly greater in the Frio Fault Zone than in the Vicksburg Fault Zone (Figure 11). This trend in thickening and vertical displacement of the Frio in the Frio fault zone is also evident in cross sections of Tertiary rocks in Texas (Dodge and Posey, 1981). In Louisiana, thickening and displacement of Frio sediments are indicated in cross sections by Bebout and Gutierrez (1982, 1983).

Geologic Model Used to Define Assessment Units

The USGS Paleogene assessment team used a geologic model (Figure 12) based on recurring regional-scale structural and depositional features in Paleogene strata to define assessment units. During progradation, deposition occurred in three general areas of the Gulf Coast basin, which we refer to as stable shelf, expanded fault, and slope and basin floor zones. The stable shelf zone occurs in the landward (updip) portions of the basin, where growth faulting is either absent or minimal in the stable shelf zones. The Frio interval is the exception to this model, and the Vicksburg Fault Zone was included in the stable shelf zone (refer to section in “Frio Stable Shelf Oil and Gas Assessment” for discussion). For all stratigraphic intervals assessed in the Paleogene, the expanded fault zone contains growth faults that formed at the dominant shelf edge of the underlying unit. Sediments in the expanded fault zone display extreme vertical displacement and thickening. For all stratigraphic intervals assessed, the slope and basin floor zone consists of environments formed basinward (downdip) of the shelf edge, an environment where growth faulting within the target interval was minimal and sediments were not extremely vertically displaced. As would be expected from the cyclical nature of these progradational systems for stratigraphic intervals assessed, there is overlap between stable shelf, expanded fault, and slope and basin floor zones through time. Each of these assessment units are described in more detail below.

Stable Shelf Assessment Units

The stable shelf assessment units of the Paleogene stratigraphic intervals assessed are composed primarily of fluvial and deltaic highstand and transgressive systems tracts (Figure 12). In the Frio Formation, barrier and shelf environments are also present. Reservoirs are generally at shallower drilling depths than those of the expanded fault zone and slope and basin floor assessment units. For the Frio Formation, the average depth to reservoirs is about 4800 ft and average thickness of reservoirs is about 34 ft in the Stable Shelf assessment unit. Stratigraphic vertical expansion is minor for most of the stratigraphic intervals assessed, and reservoir intervals are thin compared to those in the expanded fault zone assessment units. Exploration in the stable shelf assessment units is very mature, and production trends produce both oil and gas from reservoirs having normal temperature and pressure depth gradients. Exploration in the Frio Stable Shelf Oil and Gas Assessment Unit is mature to supermature (IHS, 2005a; NRG Associates, 2006). Based on thermal modeling studies (Rowan et al., 2007), stable shelf assessment units in Paleogene strata are generally thermally immature, suggesting that oil and gas produced in these areas migrated from deeper mature source rocks. This interpretation is supported by geochemical data collected by the U.S. Geological Survey (M.D. Lewan, written communication, 2006) and other proprietary sources (IHS, 2005a; NRG Associates, 2006).

Expanded Fault Zone Assessment Units

The expanded fault zone assessment units of Paleogene intervals assessed contain stratigraphic intervals that display extreme thicknesses and vertical displacement resulting from syndepositional growth faulting (Figure 12). The expanded fault zone assessment units are mostly comprised of deltaic and marine highstand and lowstand systems tracts. Drilling depths to reservoirs are generally greater than for the stable shelf assessment units. Reservoir intervals range from thin to thick, and hydrocarbon exploration and production trends are characterized as mature to frontier. For the Frio Formation, the average depth to reservoirs is about 9000 ft, and average thickness of reservoirs is about 56 ft in the expanded fault zone assessment unit. Reservoir pressures and temperatures range from normal to high due to the onset of overpressure zones at depth. Based on production data (IHS 2005a; NRG Associates, 2006) and thermal modeling studies (see Rowan et al., 2007), Paleogene strata in the expanded fault zone assessment units are generally mature to overmature with respect to oil and gas generation. Although both oil and gas are produced from the expanded fault zones in the Paleogene units assessed, gas production is dominant for some of the intervals assessed. In the expanded fault zone for the Frio Formation (including the overlying Anahuac Formation), both oil and gas have been produced to a significant degree (Nehring, 1991). The updip margin of the expanded fault zone, for most of the Paleogene intervals assessed, was defined as the location of the shelf margin of the underlying stratigraphic unit. For the Frio Formation, the updip margin of the expanded fault zone was defined based on the occurrence of the Frio Fault Zone in Texas (Ewing et al., 1990; Ewing, 1991a, 1991b), unstable shelf margins in Louisiana (Paine et al., 1968; John et al., 1992 b,c,d), and occurrence of overpressure zones.

Slope and Basin Floor Assessment Units

The slope and basin floor assessment units of Paleogene intervals assessed have minimum to moderate fault-related expansion for the uppermost beds and are comprised mostly of delta front and marine distal highstand and lowstand systems tracts. Reservoir intervals are thin to moderate as compared to the stable shelf and expanded fault zone assessment units (Figure 12). The Paleogene Assessment Team defined the slope and basin floor assessment units as frontier to hypothetical hydrocarbon production areas, due to the lack of drilling and production data from these areas. Reservoirs are expected to be overpressured, with associated high temperatures. Based on thermal modeling studies (Rowan et al., 2007), Paleogene strata in the slope and basin floor assessment units are generally overmature, suggesting that gas would be the dominant hydrocarbon produced.

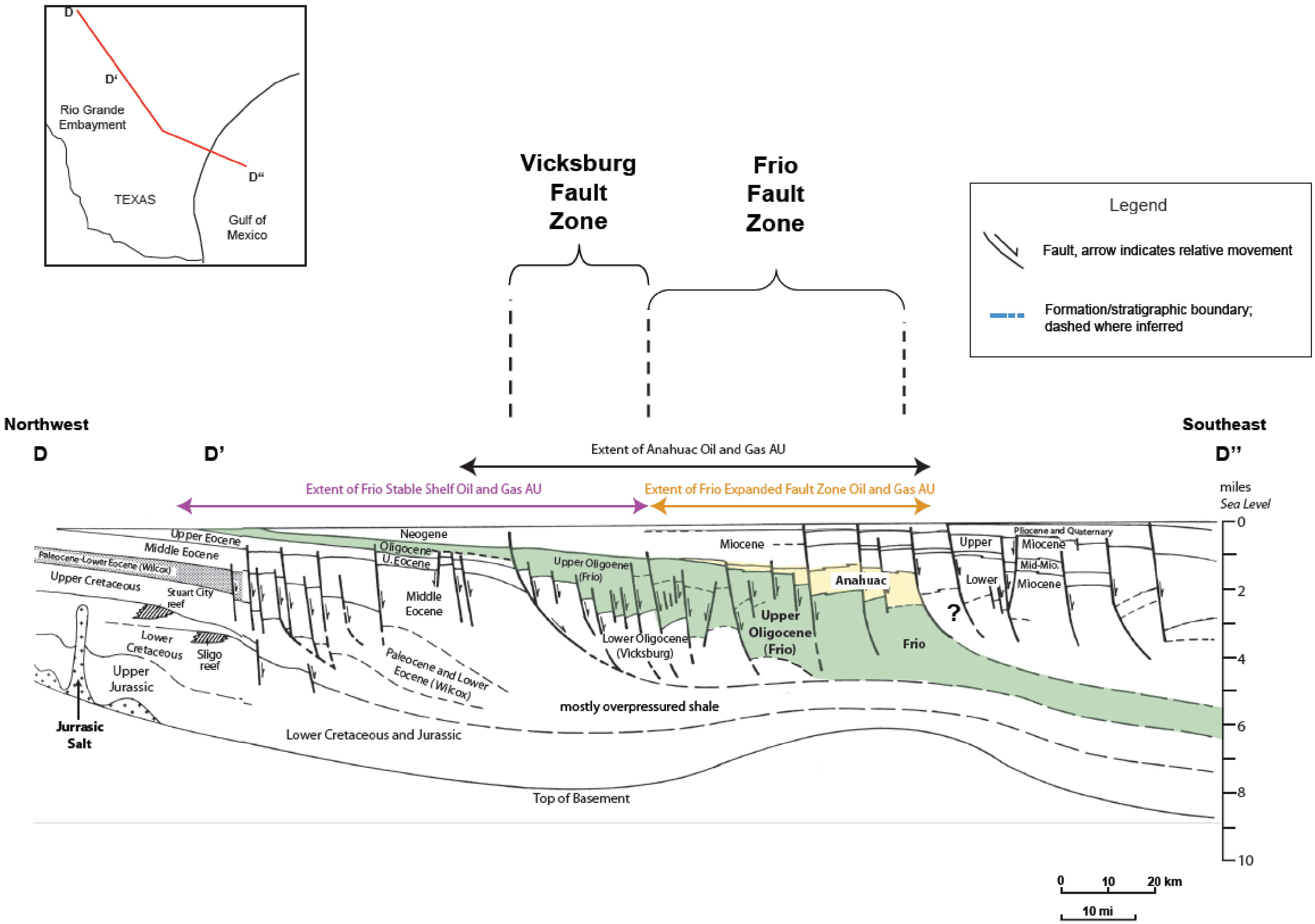

Figure 10. Schematic cross section though central Texas from the Early Cretaceous shelf margin to the present shelf margin, showing growth faults, the Vicksburg and Frio Fault Zones (modified from Ewing, 1991a, 1991b), and assessment units (AU). Frio and Anahuac Formations are highlighted in green and yellow, respectively. Fault zones are defined based on Ewing *et al*. (1990). Updip Frio (green) also includes updip Vicksburg Group.

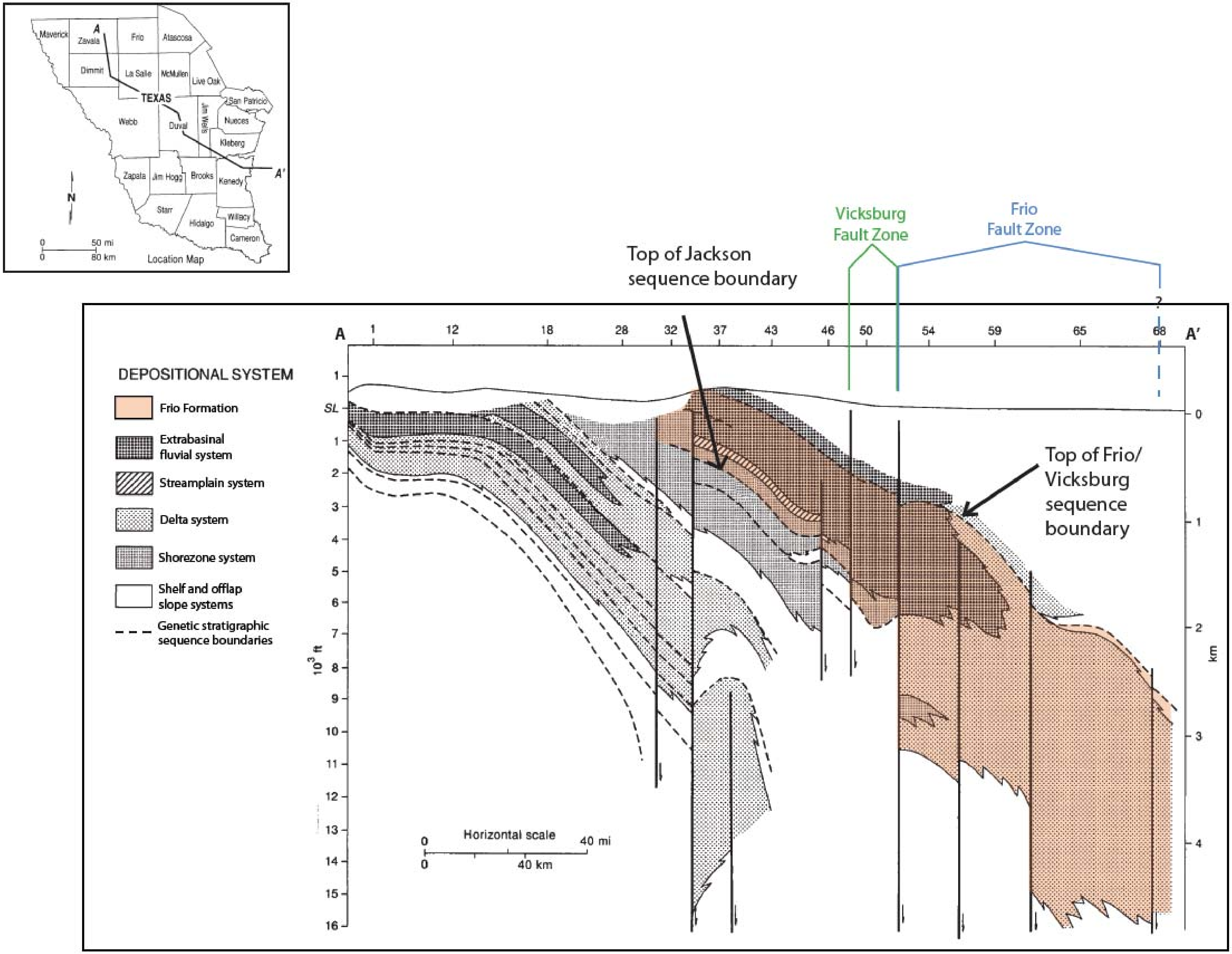

Figure 11. Cross section of the Frio Formation showing thickening and vertical displacement in the Vicksburg and Frio fault zones in south Texas (modified from Galloway et al., 1994; positioning of Vicksburg and Frio Fault zones based on Ewing et al., 1990).

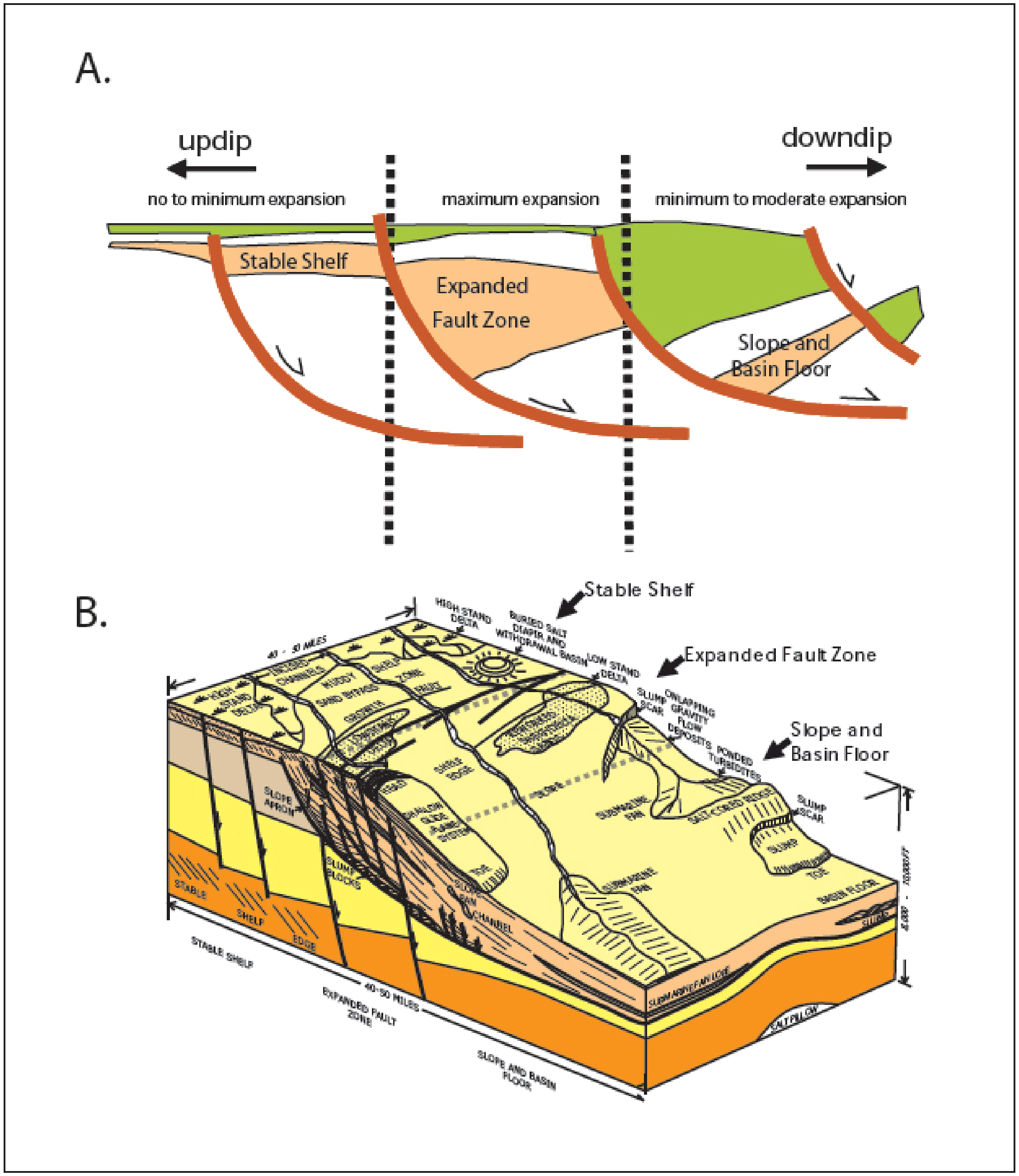

Figure 12. Geologic model used to define the assessment units. A) diagram showing stable shelf, expanded fault, and slope and basin floor zones, and B) generalized diagram with structural and depositional systems associated with each zone (modified from Edwards, 1991).

Assessment Units

Boundaries Used to Define Assessment Units

A number of geologic and political boundaries were used to define assessment units in the Frio and Anahuac Formations (Figures 13 and 14). Each of these boundaries is described below; previous publications on definition of the assessment units include Swanson et al. (2007) and Swanson and Karlsen (2008).

Limit of Thermally Mature Source Rocks

The Early Cretaceous shelf margin (Ewing and Lopez, 1991) was used to define assessment units (Figure 14). Because the Early Cretaceous shelf margin marks the updip limit of Wilcox Group or Sparta Formation shales that are thermally mature (Rowan et al., 2007), it was used as a limiting boundary for the Frio Stable Shelf Oil and Gas Assessment Unit and Frio Expanded Oil and Gas Assessment Units.

Limit of Potential for Biogenic Gas

The 10,000 mg/l total dissolved solids (TDS) isoline (Pettijohn, 1996) was also used as a defining boundary for assessment units in the Frio Formation, to indicate the limits of potential for production of biogenic gas (Figure 14). Previous studies indicate the presence of biogenic gas accumulations in the Frio Formation of southwestern Mississippi and southeastern Louisiana (Champlin, 1995; Goddard and Zimmerman, 2003). Because isotopic data for coal gas samples collected from recent Wilcox coalbed gas exploration wells in Louisiana suggest that coal gases are produced primarily by the bacterial reduction of CO_2 in a saline aquifer system (Warwick, 2004), we have hypothesized that microbes producing biogenic gas in the Frio Formation would have required saline aquifer systems. The U.S. Environmental Protection Agency standard for an underground source of drinking water (<10,000 mg/l TDS) (U.S. Environmental Protection Agency, 2002) was used to represent the saltwater/freshwater interface.

Outcrop Boundary

Because the outcrop of the Frio Formation is not continuous and could not be used as a boundary, the base (northern boundary) of the Miocene (Schruben et al., 1998; based on King and Beikman, 1974) (Figure 14) was used in determining the updip limit of some of the assessment units.

State/Federal Water Boundaries

The offshore State/Federal water boundary or USGS petroleum region and/or province boundaries (U.S. Geological Survey, 2004) also were used to define assessment units.

Frio Basin Margin Assessment Unit

The updip limit of the Frio Basin Margin Assessment Unit is defined by the boundary of the basal Miocene outcrop, whereas the downdip limit of the Frio Basin Margin Assessment Unit is based on a combination of factors including the 10,000 mg/l TDS isoline, Early Cretaceous shelf margin, and known production in certain areas (Figures 13 and 14). Because there is no known production in the Frio Basin Margin Assessment Unit (based on data from NRG Associates, Inc., 2006), and because the potential for biogenic gas is negligible, it was not formally assessed.

Frio Stable Shelf Oil and Gas Assessment Unit

In much of the Frio Stable Shelf Oil and Gas Assessment Unit (Figure 15), growth faults are minimal, particularly within updip areas. However, the Vicksburg Fault Zone in south Texas is the exception, and in this area, growth faults commonly cut through the Frio. Although there is significant vertical expansion of the Frio within the Vicksburg Fault Zone, it is not as great as that in the Frio Fault Zone farther downdip (Figure 11). For this reason, the Vicksburg Fault Zone was included in the Frio Stable Shelf Oil and Gas Assessment Unit. The Frio Stable Shelf Zone is also characterized by normally pressured reservoirs.

In most parts of the assessment unit, the updip margin follows the 10,000 mg/l TDS isoline (Figure 15), which is a possible indicator of the potential updip limit of biogenic methane. In south Texas, the base (northern boundary) of the Miocene outcrop was used as the updip limit of the assessment unit, due to the presence of oil and gas fields near the saltwater/freshwater interface. In eastern Louisiana and southern Mississippi, the assessment unit extends updip of the Early Cretaceous shelf margin, due to the potential for lateral migration of biogenic gas. In southwestern Mississippi, the assessment unit boundary extends beyond (north of) the 10,000 mg/l TDS isoline to account for known production in the area. Because the Early Cretaceous shelf margin marks the updip limit of Wilcox Group or Sparta Formation shales that are thermally mature (Rowan et al., 2008), it was also used as a defining boundary for the assessment unit.

The downdip boundary of the Frio Stable Shelf Oil and Gas Assessment Unit was determined based on the updip extent of the Frio Fault Zone in Texas (Ewing, 1986, 1991a, 1991b; Ewing et al., 1990) and the updip boundary of unstable shelf areas in Louisiana, as reported in previous studies (Paine et al., 1968; John et al., 1992 b,c,d). The downdip boundary of the Frio Stable Shelf Oil and Gas Assessment Unit also generally marks the limit of known production in Frio well intervals in normally pressured zones.

The average depth to the top of reservoirs in this assessment unit is about 4800 ft, and the average thickness of reservoirs is 34 ft. Porosity values average approximately 28 percent. Permeability averages about 740 md. Average reservoir pressures are 2127 psi, and average temperature (including both reservoir and bottomhole temperatures) are 156°F (based on data from NRG Associates, Inc.; 2006).

Frio Expanded Fault Zone Oil and Gas Assessment Unit

In Texas, the updip boundary of the Frio Expanded Fault Zone Oil and Gas Assessment Unit (Figure 16) was determined based on (1) the updip extent of the Frio Fault Zone (Figure 10), a growth fault system occupying a belt about 64 km wide and having great potential for geopressured resources (Ewing, 1986, 1991a, 1991b; Ewing et al., 1990) ; and (2) the updip limit of production in Frio well intervals in the overpressured zone (greater than 0.5 psi/ft) (based on data from the IHS Energy Group, 2005a and Wallace et al., 1978, 1981). In Louisiana, the updip boundary was based on the updip limit of production in Frio well intervals in the overpressured zone (greater than 0.5 psi/ft) and unstable shelf areas in the Frio (Paine et al., 1968; John et al., 1992 b, c, d). The eastern boundary of the Frio Expanded Fault Zone Assessment Unit is delimited by the trace of the Early Cretaceous shelf margin.

The downdip boundary for this assessment unit is the late Oligocene shelf margin at maximum progradation (Galloway et al., 2000). The shelf margin marks the downdip limit of siliciclastic shelf, carbonate shelf, and deltaic depositional systems (Galloway et al., 2000). Delta-fed aprons, shelf-fed aprons, and basin floor aprons are found downdip of the shelf margin (Galloway et al., 2000); these depositional areas would have had minimum expansion from growth faulting, as indicated in the geologic model used by the USGS Paleogene Assessment Team (see discussion in “Geologic Model” section).

This assessment unit is characterized by maximum vertical thickening due to growth faulting (refer to discussion in “Geologic Model” section). Reservoirs are thicker on average than those in the Frio Stable Shelf Oil and Gas Assessment Unit, having an average thickness of 56 ft (based on data from NRG Associates, Inc., 2006). Structure maps generated from published data (Bebout and Gutierrez, 1982, 1983; Dodge and Posey, 1981) (Figure 4) indicate that the depth (from sea level) to the top of the Frio in the assessment unit ranges from a minimum of about 5000 ft in south Texas to a maximum of nearly 16,000 ft in southern Louisiana. Isopach maps generated from published data (Bebout and Gutierrez, 1982, 1983; Dodge and Posey, 1981) (Figure 4) indicate that the thickness of the Frio ranges from less than 1000 ft in Louisiana to close to 10,000 ft in the state waters of south Texas.

The average depth to the top of reservoirs in this assessment unit is about 9050 ft. Porosity has an average value of 27 percent. Permeability averages approximately 636 md. In general, fields in the Frio Expanded Fault Zone Oil and Gas Assessment Unit are overpressured. Average reservoir pressures are 5116 psi and average temperatures (including both reservoir and bottomhole temperatures) are 226^{o}F (based on data from NRG Associates, Inc.; 2006).

Frio Slope and Basin Floor Gas Assessment Unit

The updip boundary of the Frio Slope and Basin Floor Gas Assessment Unit (Figure 17) is the late Oligocene shelf margin (Galloway et al., 2000), whereas the downdip boundary is the State/Federal water boundary.

Well data are sparse in this assessment unit, and the assessment unit does not contain any discovered hydrocarbon reservoirs greater than the minimum cutoff of 0.5 million barrels of oil equivalent (MMBOE) (based on data in NRG Associates, Inc., 2006). Only general estimates of depth and thickness of the Frio are possible. Based on structure contour and isopach maps generated from published data (Bebout and Gutierrez, 1982, 1983; Dodge and Posey, 1981), depth (from sea level) to the top of the Frio in this assessment unit ranges from about 8000 ft in Texas to approximately 18,000 ft in southern Louisiana, and the thickness of the Frio ranges from less than 1000 ft in southern Louisiana to about 9000 ft in central Texas. The Hackberry Oil and Gas Assessment Unit, discussed in the next section, was used as an analog for estimating the numbers and sizes of undiscovered hydrocarbon accumulations in the Frio Slope and Basin Floor Assessment Unit.

Hackberry Oil and Gas Assessment Unit

As described by Cossey and Jacobs (1992), the Hackberry play has an abrupt northern boundary where the Hackberry sharply onlaps the unfaulted margin of the lower Frio shelf sediments. The northern boundary defined by Cossey and Jacobs (1992) was used as the updip limit of the assessment unit (Figure 18). The eastern and western boundaries defined by Cossey and Jacobs (1992) were extended to include known Hackberry field data and well production information (based on data from the IHS Energy Group, 2005a, 2005b; and NRG Associates, Inc., 2006). Eastern and western boundaries of the assessment unit include field data reported by Bornhauser (1960), Paine (1968), and Ewing and Reed (1984).

The southern extent of the Hackberry play as described by Cossey and Jacobs (1992) was limited by drilling economics to where the base of the Hackberry was at approximately 15,000 ft. For the USGS assessment, the southern boundary of the Hackberry Oil and Gas Assessment Unit was extended to the State/Federal water boundary for two reasons (Figure 18). First, previous work (Paine, 1968, 1971; Benson, 1971; Ewing and Reed, 1984; Cossey and Jacobs, 1992; Galloway *et al*., 2000) suggested that the downdip Hackberry was deposited in a slope environment. Based on geologic models from other areas, it seems reasonable to suggest that the slope system may extend as far as the State/Federal water boundary. Second, recent initial production tests and producing wells in the Hackberry are found at depths greater than 15,000 ft in downdip areas (based on data from IHS Energy Group, 2005a, 2005b).

The average depth to the top of reservoirs is about 9700 ft, and the average thickness of reservoirs is about 60 ft. Moreover, reservoir porosity averages about 31 percent, and reservoir permeability averages about 820 md. Average reservoir pressures are about 6500 psi, and average temperatures (including both reservoir and bottomhole temperatures) are 211^{o}F (based on data from NRG Associates, Inc.; 2006).

Anahuac Oil and Gas Assessment Unit

The lateral extent of the Anahuac Oil and Gas Assessment Unit (Figure 19) across the Gulf Coast is based, in part, on the area defined as the “Anahuac Sea” by Burke (1958) and the position of the shoreline during the late Oligocene (Rainwater, 1964). In Louisiana, the updip limit of the assessment area was modified to encompass producing fields of Anahuac deltaic, shelf, and slope environments (John et al., 1992a) and to include the *Heterostegina* shelf margin (Krutak and Beron, 1990). Structural contours of the top of the *Heterostegina* Zone (Warren, 1957) were used to estimate the northern extent of potential hydrocarbon-producing Anahuac sandstones. The assessment unit extends downdip to the offshore State/Federal water boundary. The assessment unit in eastern and south-central Texas was extended updip of the late Oligocene paleoshoreline as defined by Rainwater (1964) to accommodate known producing reservoirs and initial production tests. In southern Texas, the updip limit of the assessment unit was defined primarily on the basis of the thickness of sandstones, as indicated by Galloway et al. (1982).

The updip limit of the Anahuac Oil and Gas Assessment Unit generally lies south of the Early Cretaceous shelf margin and the 10,000 mg/l TDS isoline (Pettijohn, 1996). However, in southeastern Louisiana, the assessment unit boundary extends updip of the Early Cretaceous shelf boundary to accommodate potential for biogenic gas. In south Texas, the boundary of the assessment unit extends slightly updip of the 10,000 mg/l TDS isoline due to the presence of known Anahuac reservoirs in this area (based on data from the IHS Energy Group, 2005a, 2005b; NRG Associates, Inc., 2006).

Reservoir depths of the Anahuac range from about 4000 to 16,000 ft (Nehring, 1991). Based on data from NRG Associates, Inc. (2006), the average depth to the top of Anahuac reservoirs is about 8300 ft. The average thickness of Anahuac reservoirs is about 100 ft (based on data from NRG Associates, Inc., 2006).

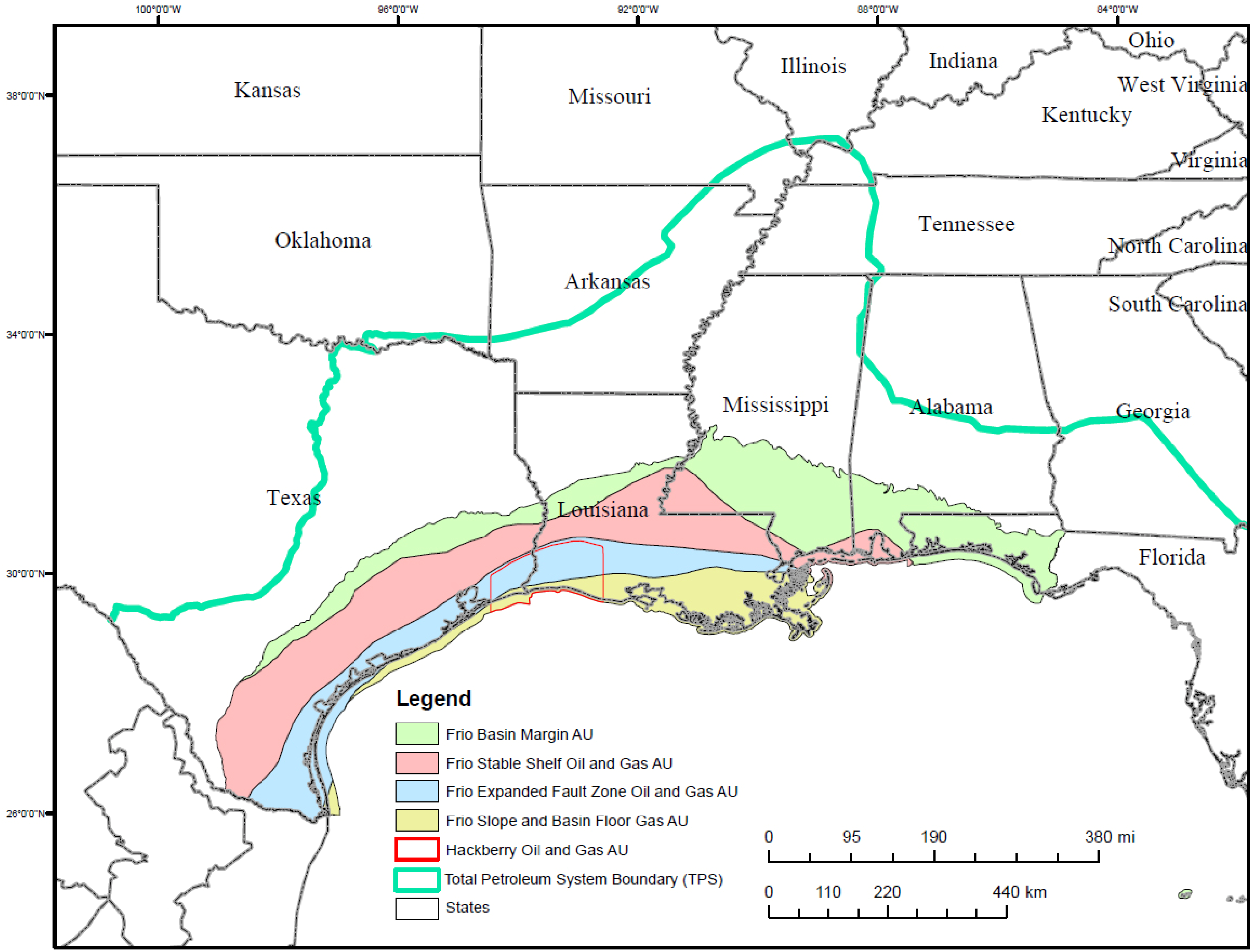

Figure 13. Assessment units for the Frio Formation. AU = assessment unit.

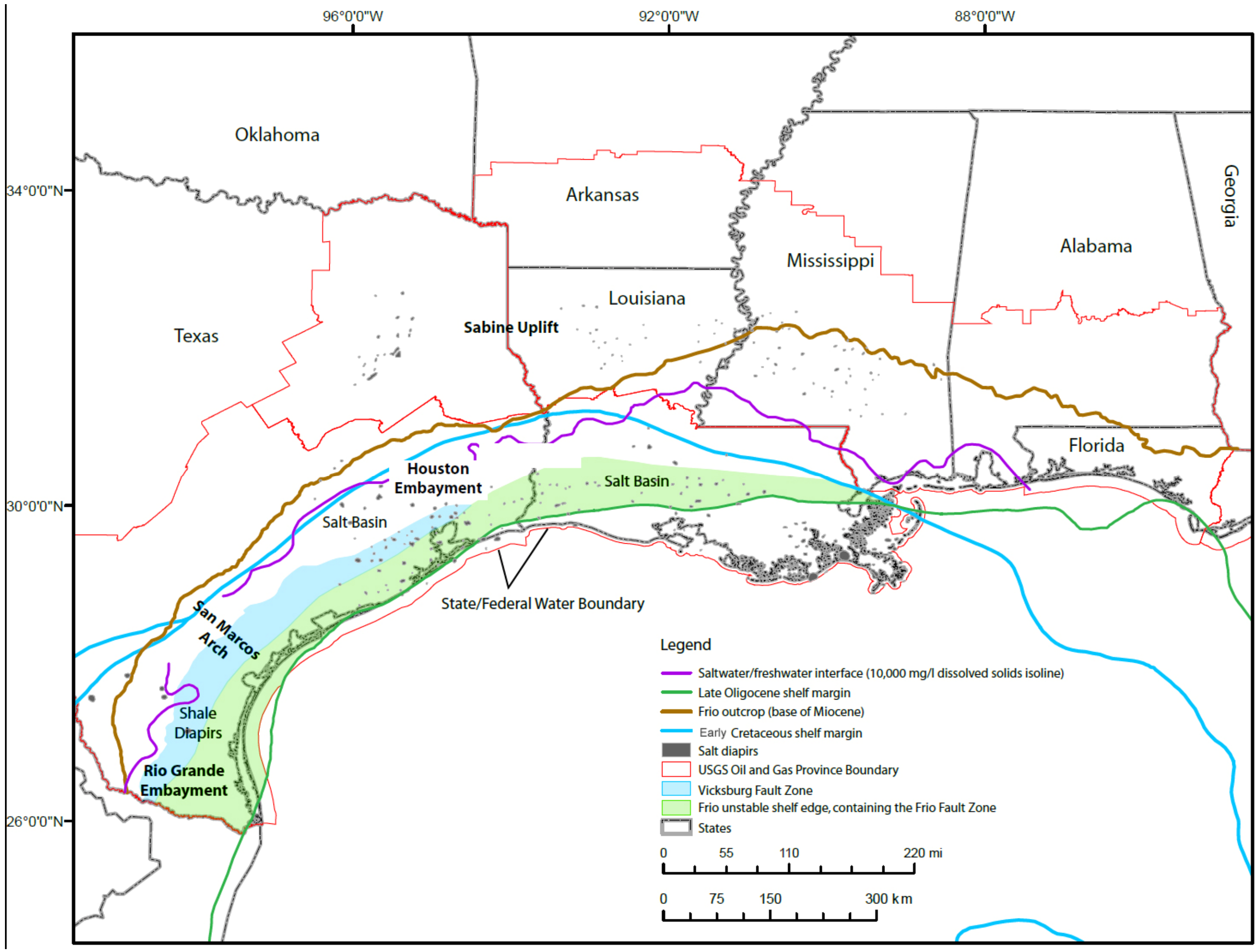

Figure 14. Boundaries and areas used to define assessment units for the Frio and Anahuac Formations. The Frio outcrop (base of Miocene) is from Schruben et al. (1998), based on King and Beikman, 1974; the Early Cretaceous shelf margin is modified from Ewing and Lopez (1991); the saltwater/freshwater interface (10,000 mg/L dissolved solids isoline) is from Pettijohn (1996); salt diapirs are from Lopez (1995), Ewing and Lopez (1991), and Martin (1980); the USGS Oil and Gas Province Boundary is from USGS (2004); the Vicksburg Fault Zone is from Ewing et al. (1990); and the Frio unstable shelf edge is based on the Frio Fault Zone (Ewing, 1986, 1991b; Ewing et al., 1990) and unstable shelf areas (Paine et al., 1968, John et al., 1992 b,c,d).

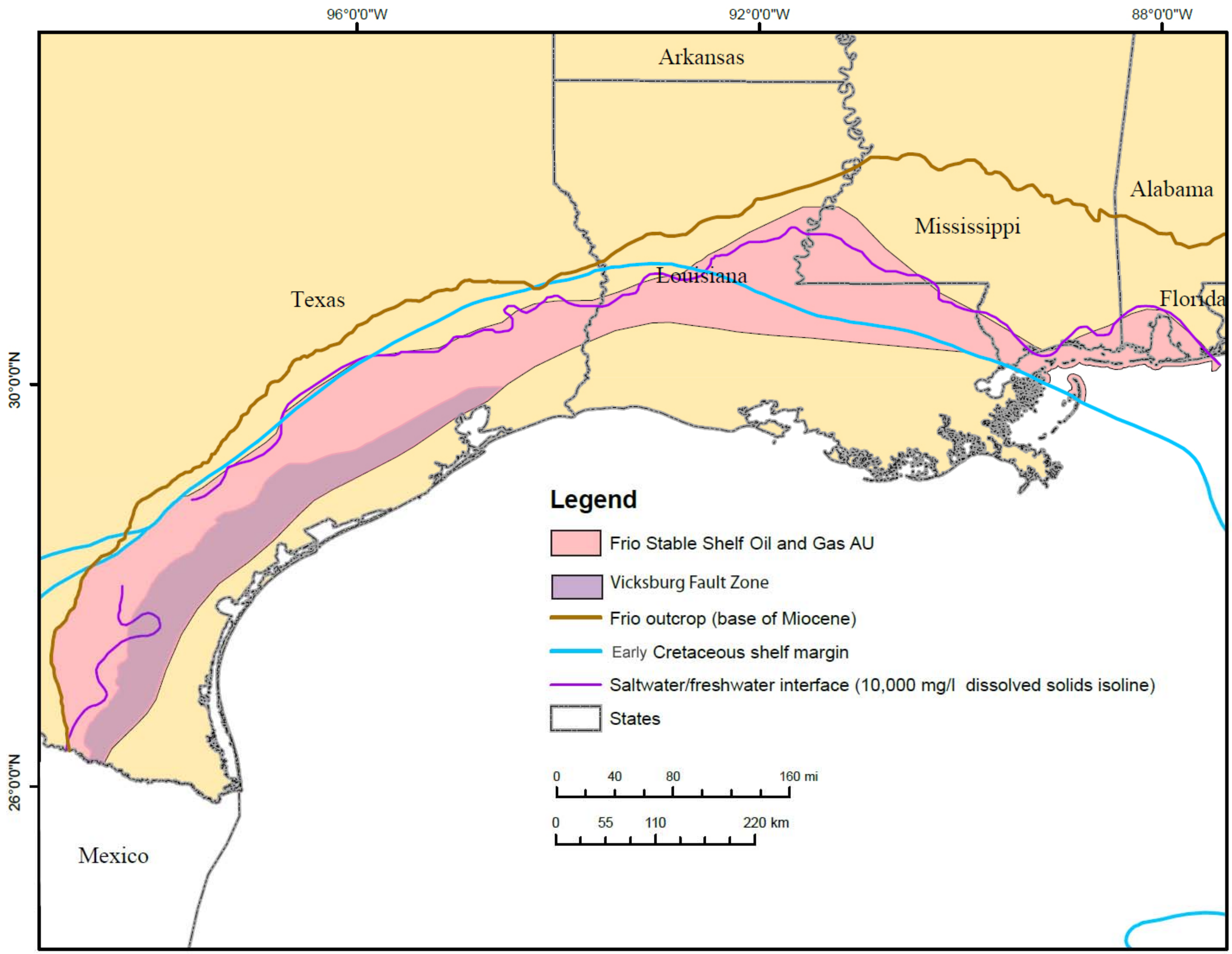

Figure 15. The Frio Stable Shelf Oil and Gas Assessment Unit, with boundaries used to define the assessment unit. AU = assessment unit. The Frio outcrop (base of Miocene) is from Schruben et al. (1998), which is based on King and Beikman, 1974; the Early Cretaceous shelf margin is modified from Ewing and Lopez (1991); and the saltwater/freshwater interface (10,000 mg/L dissolved solids isoline) is from Pettijohn (1996).

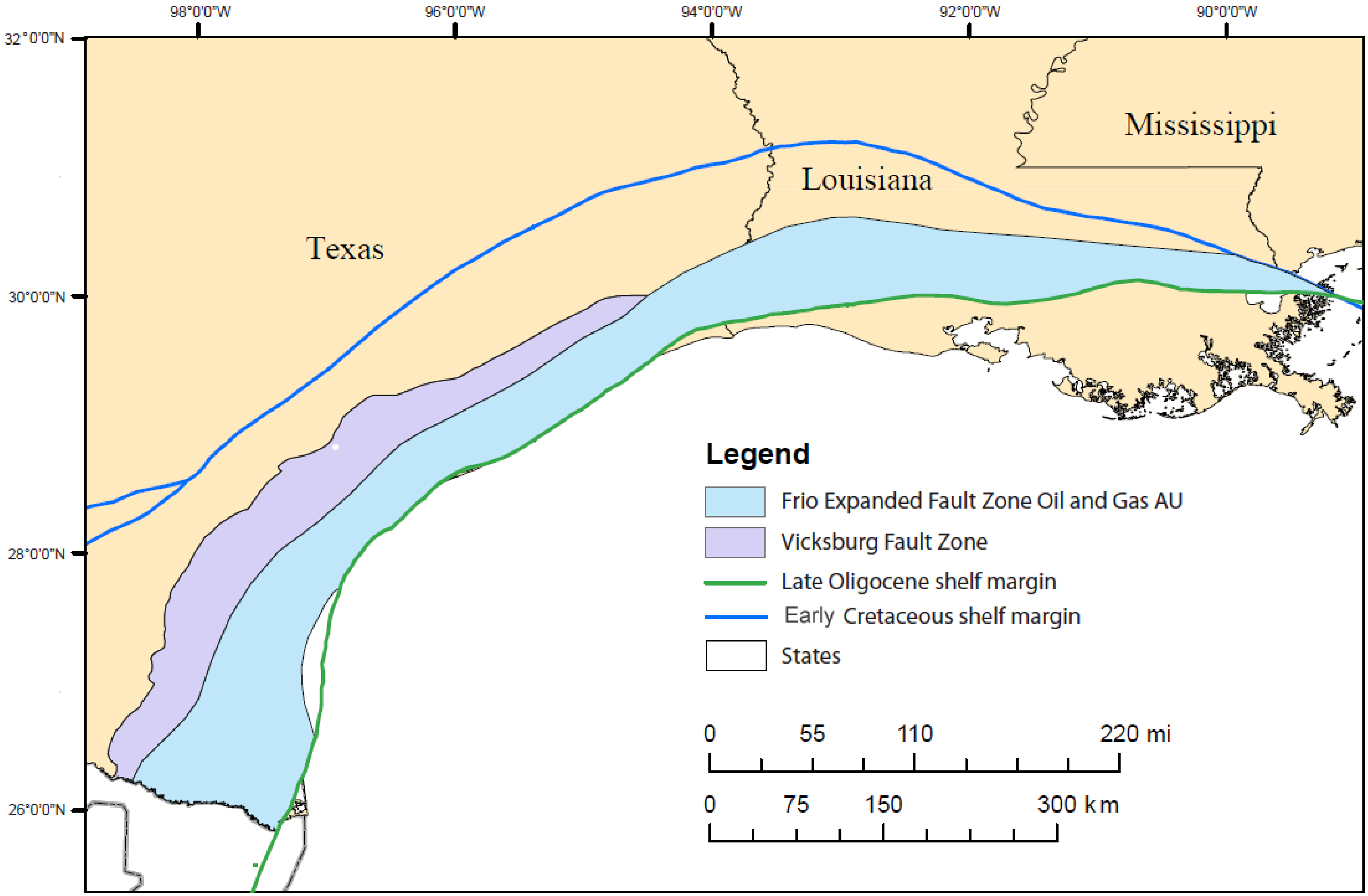

Figure 16. The Frio Expanded Fault Zone Oil and Gas Assessment Unit, with boundaries used to define the assessment unit. AU = assessment unit. The Vicksburg fault zone is modified from Ewing et al. (1990); the Early Cretaceous shelf margin is modified from Ewing and Lopez (1991); and the late Oligocene shelf margin is modified from Galloway et al. (2000).

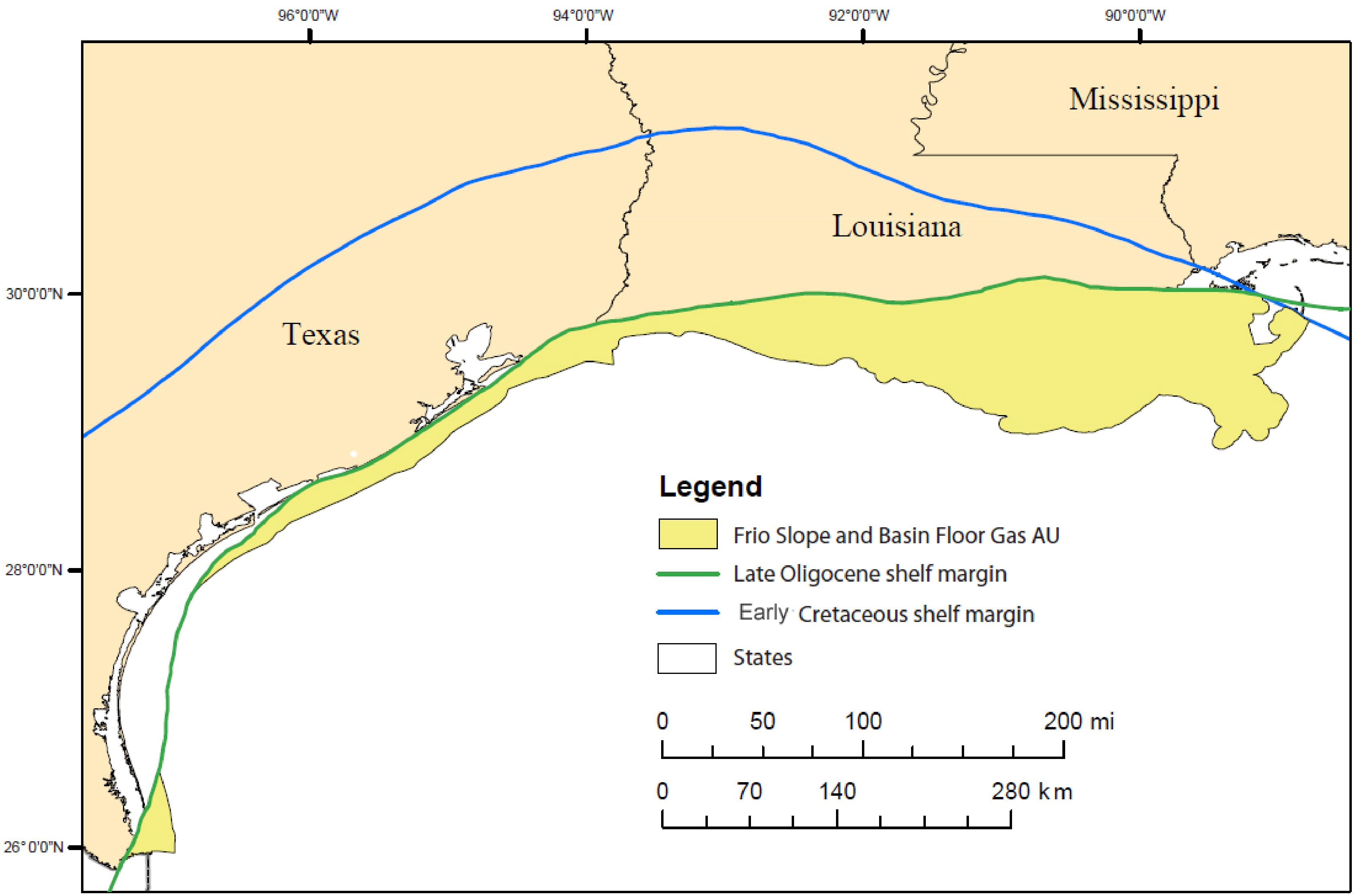

Figure 17. The Frio Slope and Basin Floor Gas Assessment Unit, with boundaries used to define the assessment unit. AU = assessment unit. The Early Cretaceous shelf margin is modified from Ewing and Lopez (1991); and the late Oligocene shelf margin is modified from Galloway et al. (2000).

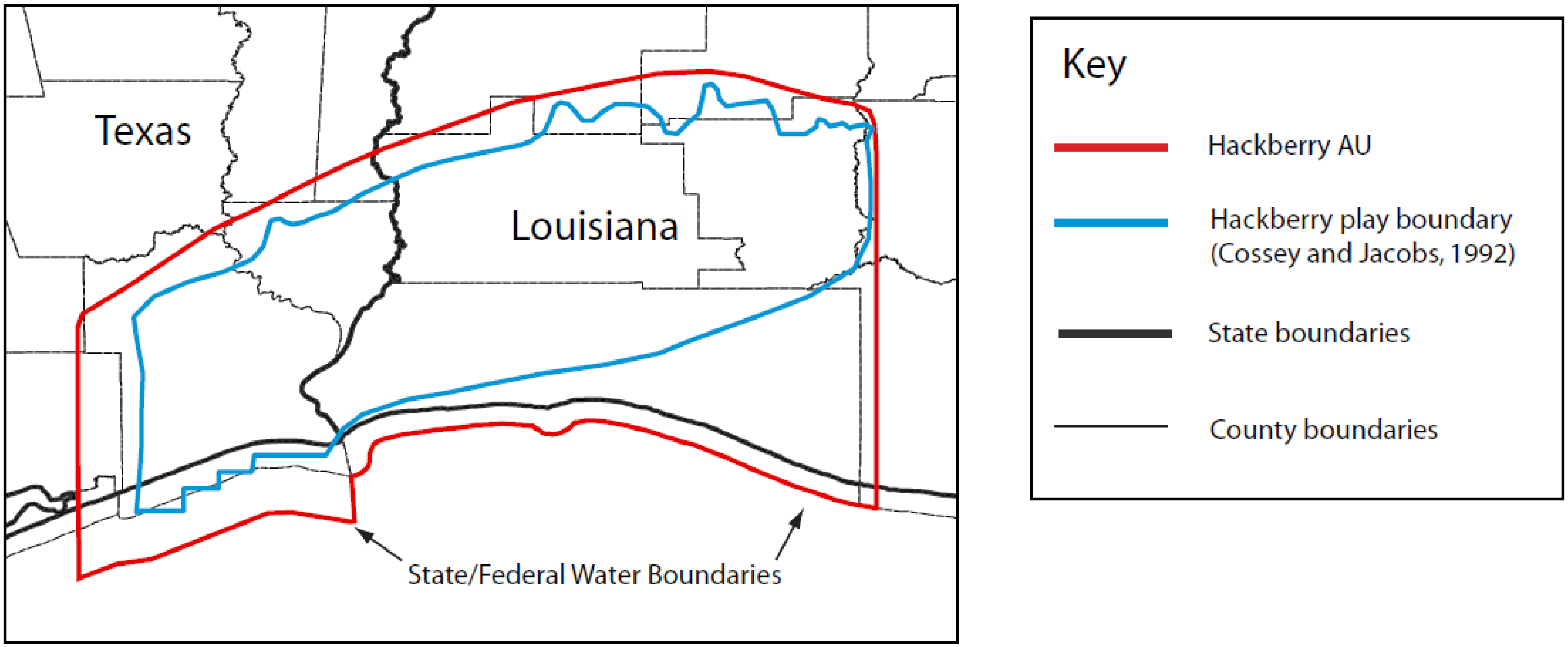

Figure 18. Map of southeast Texas and southwest Louisiana showing location of the Hackberry play and Hackberry Oil and Gas Assessment Unit. Northern limit of the play outline represents the Hackberry subcrop. The southern boundary of the play, as reported by Cossey and Jacobs (1991), was limited by drilling economics to where the base of the Hackberry Formation was at about 15,000 ft. The southern boundary for the Hackberry Oil and Gas Assessment Unit was extended to the State/Federal water boundary.

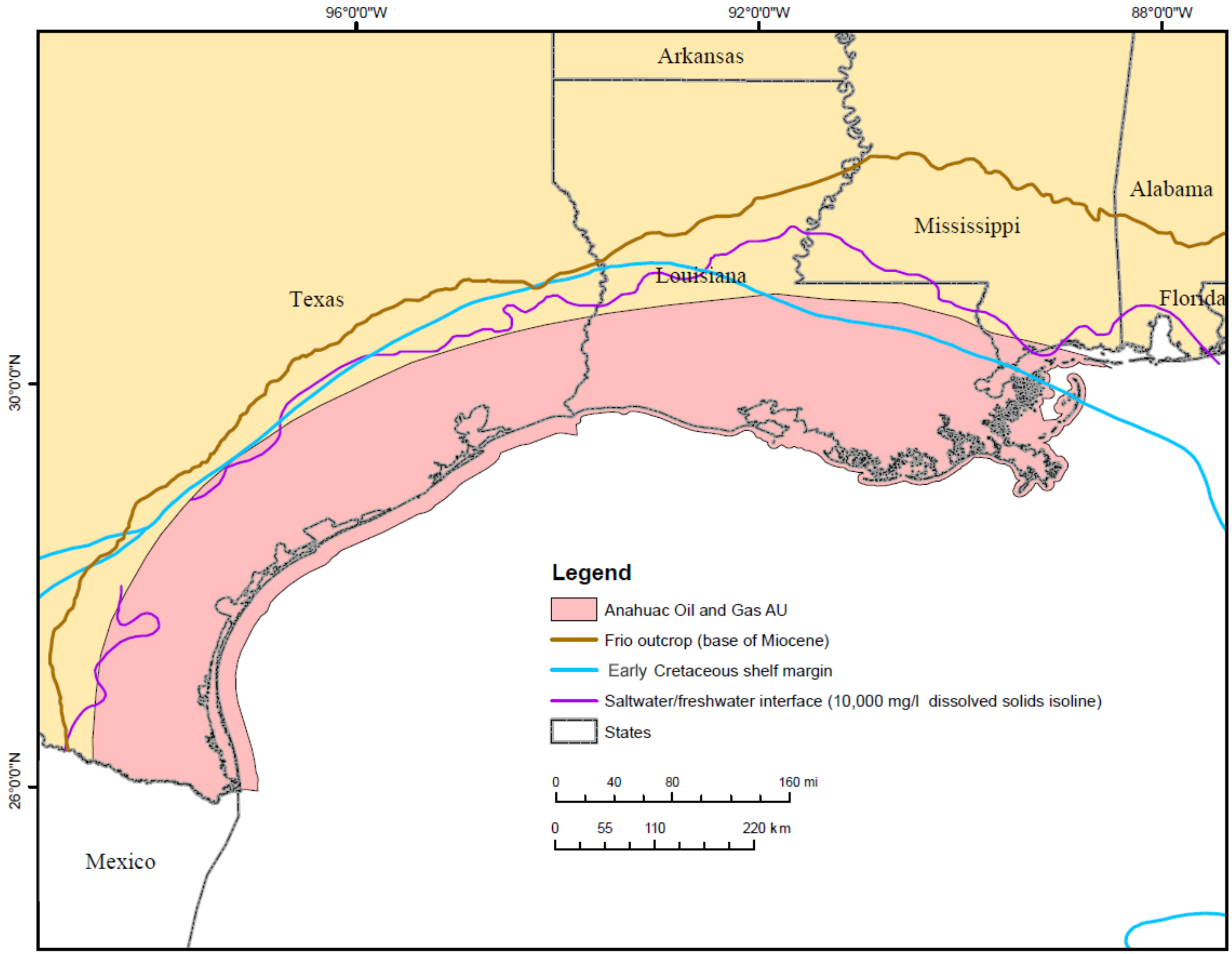

Figure 19. Assessment unit for the Anahuac Formation, with boundaries used to define the assessment unit. AU = assessment unit. The Frio outcrop (base of Miocene) is from Schruben et al. (1998), which is based on King and Beikman, 1974; the Early Cretaceous shelf margin is modified from Ewing and Lopez (1991); and the saltwater/freshwater interface (10,000 mg/L dissolved solids isoline) is from Pettijohn (1996).

Assessment Results

Table 2 is a summary of the assessment results for the four assessment units in the Frio Formation and the one assessment unit in the Anahuac Formation by resource type (crude oil, natural gas, natural gas liquids). The total estimated means for undiscovered conventional oil resources, gas resources, and natural gas liquids are 172 million barrels of oil (MMBO), 9384 billion cubic feet of gas (BCFG), and 542 million barrels of natural gas liquids (MMBNGL), respectively. The results of the USGS assessment of Tertiary strata in the Gulf Coast are also reported in Dubiel et al. (2007).

The total estimated mean for undiscovered conventional gas resources in all of the Frio and Anahuac assessment units is 9384 billion cubic feet (BCFG), ranging from 18,166 BCFG (F5) to 2609 BCFG (F95), where F5 represents a 1 in 20 chance and F95 represents a 19 in 20 chance of the occurrence of at least the amount specified. This resource includes both nonassociated gas in gas fields and associated gas in oil fields. Only 594 BCFG of the total mean estimated resource value (9384 BCFG) represents associated gas in oil fields. Of the five units assessed, the “Frio Slope and Basin Floor Gas AU” shows the greatest potential for undiscovered gas resources, having an estimated mean of 5589 BCFG, and ranging from 11,153 BCFG (F5) to 1355 (F95). The Hackberry Oil and Gas Assessment Unit shows the second highest potential for gas of the five units assessed, having an estimated mean of 1807 BCFG, and ranging from 3365 BCFG (F5) to 556 BCFG (F95).

The total estimated means for undiscovered conventional oil resources in all of the Frio and Anahuac assessment units is 172 million barrels (MMBO), ranging from 352 MMBO (F5) to 43 MMBO (F95). The largest undiscovered, conventional crude oil resource was estimated for the Frio Slope and Basin Floor Gas AU, having an estimated mean of 110 MMBO, and ranging from 220 MMBO (F5) to 28 (F95). The total estimated means for undiscovered natural gas liquids is 542 million barrels of natural gas liquids (MMBNGL); ranging from 1124 MMBNGL (F5) to 135 MMBNGL (F95).

Total Petroleum Systems (TPS) and Assessment Units (AU)	Field Type	Total Undiscovered Resources											
		Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Upper Jurassic-Cretaceous-Tertiary Composite, TPS 504701													
Frio Stable Shelf Oil and Gas, AU 50470135	Oil	2	5	11	5	7	22	52	25	0	0	1	0
	Gas					88	227	437	241	2	5	11	6
Frio Expanded Fault Zone Oil and Gas, AU 50470136	Oil	4	14	30	16	24	82	186	90	1	2	5	2
	Gas					509	1,265	2,292	1,321	13	34	68	36
Frio Slope and Basin Floor Gas, AU 50470137	Oil	28	102	220	110	84	320	756	358	2	9	24	11
	Gas					1,271	4,829	10,397	5,231	81	322	757	358
Anahuac Oil and Gas, AU 50470138	Oil	3	13	39	16	8	33	103	41	0	1	2	1
	Gas					62	240	578	270	2	7	17	8
Hackberry Oil and Gas, AU 50470139	Oil	6	22	52	25	17	69	178	80	0	2	6	2
	Gas					539	1,632	3,187	1,727	34	109	233	118
Grand Total		43	156	352	172	2,609	8,719	18,166	9,384	135	491	1,124	542

Table 2. Summary of the assessment results for the four assessment units for the Frio Formation and one assessment unit for the Anahuac Formation by resource type (crude oil, natural gas, natural gas liquids).

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