

Definition of Greater Gulf Basin Lower Cretaceous Shale Gas Assessment Unit, United States Gulf of Mexico Basin Onshore and State Waters*

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Abstract

An assessment unit (AU) for undiscovered continuous “shale” gas in Lower Cretaceous (Aptian and Albian) and basal Upper Cretaceous (lower Cenomanian) rocks in the USA onshore Gulf of Mexico coastal plain recently was defined by the U.S. Geological Survey (USGS). The AU is part of the Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System (TPS) of the Gulf of Mexico Basin. Definition of the AU was conducted as part of the 2010 USGS assessment of undiscovered hydrocarbon resources in Gulf Coast Mesozoic stratigraphic intervals. The purpose of defining the Greater Gulf Basin Lower Cretaceous Shale Gas AU was to propose a hypothetical AU in the Cretaceous part of the Gulf Coast TPS in which there might be continuous “shale” gas, but the AU was not quantitatively assessed by the USGS in 2010.

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Introduction

The Greater Gulf Basin Lower Cretaceous Shale Gas assessment unit (AU) ([Figure 1](#)) was defined as part of an assessment of undiscovered hydrocarbon resources in Jurassic and Cretaceous stratigraphic intervals of the Gulf Coastal Plain and State waters that the USGS completed

in 2010 (Dubiel et al., 2010, 2011). The AU includes potential continuous accumulations in the Lower Cretaceous Sligo Formation, and the Trinity, Fredericksburg, and Washita Groups ([Figure 2](#)). The AU excludes continuous resources in the Pearsall Formation in the Maverick Basin area of south Texas ([Figure 3](#)), which were separately assessed [Maverick Basin Pearsall Shale Gas AU (50490165); Dubiel et al., 2011; Hackley, 2012]. Also excluded are undiscovered resources in separately assessed conventional accumulations of the same lithostratigraphic section. The Greater Gulf Basin Lower Cretaceous Shale Gas AU lies within the Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System of the Gulf of Mexico Basin, defined by the USGS in 2007 (Dubiel et al., 2007). The 2010 assessment updated portions of the 1995 USGS assessment of the Gulf of Mexico coastal region (Schenk and Viger, 1996a,b; USGS National Oil and Gas Resource Assessment Team, 1995).

Assessment Methodology

Total Petroleum System

The USGS Energy Resources Program periodically conducts geologically based assessments of the quantities of technically recoverable undiscovered oil and gas that have the potential to be added to proved reserves in the United States. These assessments are based on the definition of a total petroleum system (TPS) framework (Magoon and Dow, 1994; Schmoker and Klett, 1999), integrating an analysis of geologic elements such as hydrocarbon source rocks (source rock maturation, hydrocarbon generation and migration), reservoir rocks (sequence stratigraphy and petrophysical properties), and hydrocarbon traps (trap formation and timing). Using these criteria, the USGS defined the lateral extent of the Upper Jurassic-Cretaceous-Tertiary Composite TPS (Dubiel et al., 2007) that extends around the Gulf of Mexico Basin, including portions of both the United States and Mexico. USGS assessments include only undiscovered oil and gas resources in that portion of the TPS that lies onshore and in State waters of the United States.

The lithostratigraphic lower limit of the AU is the base of the Sligo Formation. The lithostratigraphic upper limit of the AU is the mid-Cenomanian unconformity at the top of the Washita Group [using the mid-Cenomanian unconformity as the upper limit extends the AU into the basal Upper Cretaceous; however, the name Greater Gulf Basin Lower Cretaceous Shale Gas AU (Dubiel et al., 2011) was used for simplicity]. Therefore, in terms of chronostratigraphic limits, the AU encompasses continuous accumulations in Hauterivian (?) to Lower Cenomanian rocks in the onshore Gulf Coast, excluding the Pearsall Formation of the Maverick Basin in south Texas. Potential continuous accumulations in the Travis Peak (Hosston) Formation previously were considered by Bartberger et al. (2003) and also were not included in the Greater Gulf Basin Lower Cretaceous Shale Gas AU. The primary units in the AU expected to contain undiscovered continuous hydrocarbon accumulations are, in ascending stratigraphic order: unnamed “shales” from the principally carbonate Sligo Formation, the Pine Island and Bexar shales of the Pearsall Formation, unnamed “shales” from the Glen Rose Limestone and equivalent Rodessa and Mooringsport Formations, the Kiamichi Formation of the upper Fredericksburg Group and equivalent McKnight Formation of the Maverick Basin, and the Del Rio Formation and equivalent Grayson Shale of the Washita Group. Also considered but not described in detail herein are the Walnut Clay of the Fredericksburg Group, and the Duck Creek Limestone, Denton Clay, Pawpaw Formation, Weno Limestone, and Maness Shale of the Washita Group. In general, the Lower Cretaceous section is dominated by carbonates in the northern Gulf of Mexico

Basin (McFarlan and Menes, 1991) and most of the “shales” present in the section are non-fissile argillaceous limestones (e.g., Hackley, 2012; Enomoto et al., 2012).

The updip boundary of the AU follows the TPS boundary northeastward from the USA-Mexico border in Texas to Arkansas ([Figure 1](#)). The updip boundary across the Mississippi Embayment in Louisiana, Mississippi and Alabama is the erosional subcrop of the Lower Cretaceous. The eastern boundary in Florida is defined by the limit of clastic deposition according to well data. In Texas and Louisiana, a line offset 10 miles downdip of the Lower Cretaceous shelf margin defines the downdip limit of the AU (off-shelf Lower Cretaceous basinal carbonates were separately assessed). Where the Lower Cretaceous shelf margin extends offshore from Mississippi, Alabama, and the panhandle of Florida, the AU boundary is the State waters boundary.

Elements of the Unconventional Petroleum System

As part of the USGS assessment methodology, a TPS is divided into assessment units, mappable rock units based on similar geologic characteristics within the TPS (Klett et al., 2003). This provides a framework for estimating volumes of hydrocarbons that may be discovered over the forecast period of the assessment. The forecast period used by the USGS for estimating volumes of undiscovered hydrocarbon accumulations currently is 30 years and assumes minimum accumulation sizes, resource quality, and ease of access relevant to current and future technologies and economic conditions (Schmoker and Klett, 2005).

Data Sources

Two proprietary, commercially available databases currently are used in USGS resource assessments. One database (Nehring Associates, Inc., 2009) contains reserves, cumulative production, and other types of information for most oil and gas fields of the United States that are larger than 0.5 million barrels of oil equivalent. The data used in the 2010 assessment were current as of December 31, 2007. The second database (IHS Energy Group, 2010) contains drilling, well completion, and hydrocarbon production data (current through March, 2010). Publicly available State oil and gas databases also were checked to confirm information on individual wells contained in the IHS database (IHS Energy Group, 2010).

Continuous or Unconventional Petroleum Accumulations

The following provides current USGS definitions of continuous hydrocarbon accumulations in general and a brief description of their characteristics (Schmoker, 2005). Continuous hydrocarbon accumulations have large spatial dimensions, indistinct boundaries, and do not collect on the surface of associated water ([Figure 4](#)). These accumulations consist of large volumes of low-permeability rock including sandstone, shale, chalk, or coal which are pervaded with adsorbed oil or gas. These accumulations can lack traps and seals, their hydrocarbon producibility may depend on fracture permeability, and if not self-sourcing, they typically are closely associated with source rocks. Shallow biogenic gas accumulations, coalbed methane, gas hydrates, and oil and gas hosted in shale and low-porosity limestone and sandstones are examples of continuous hydrocarbon accumulations.

Common production characteristics of continuous hydrocarbon accumulations include large in-place hydrocarbon volumes, low-recovery factors, absence of truly dry holes, production characteristics that depend on fracture permeability, and “sweet spots” with generally better production.

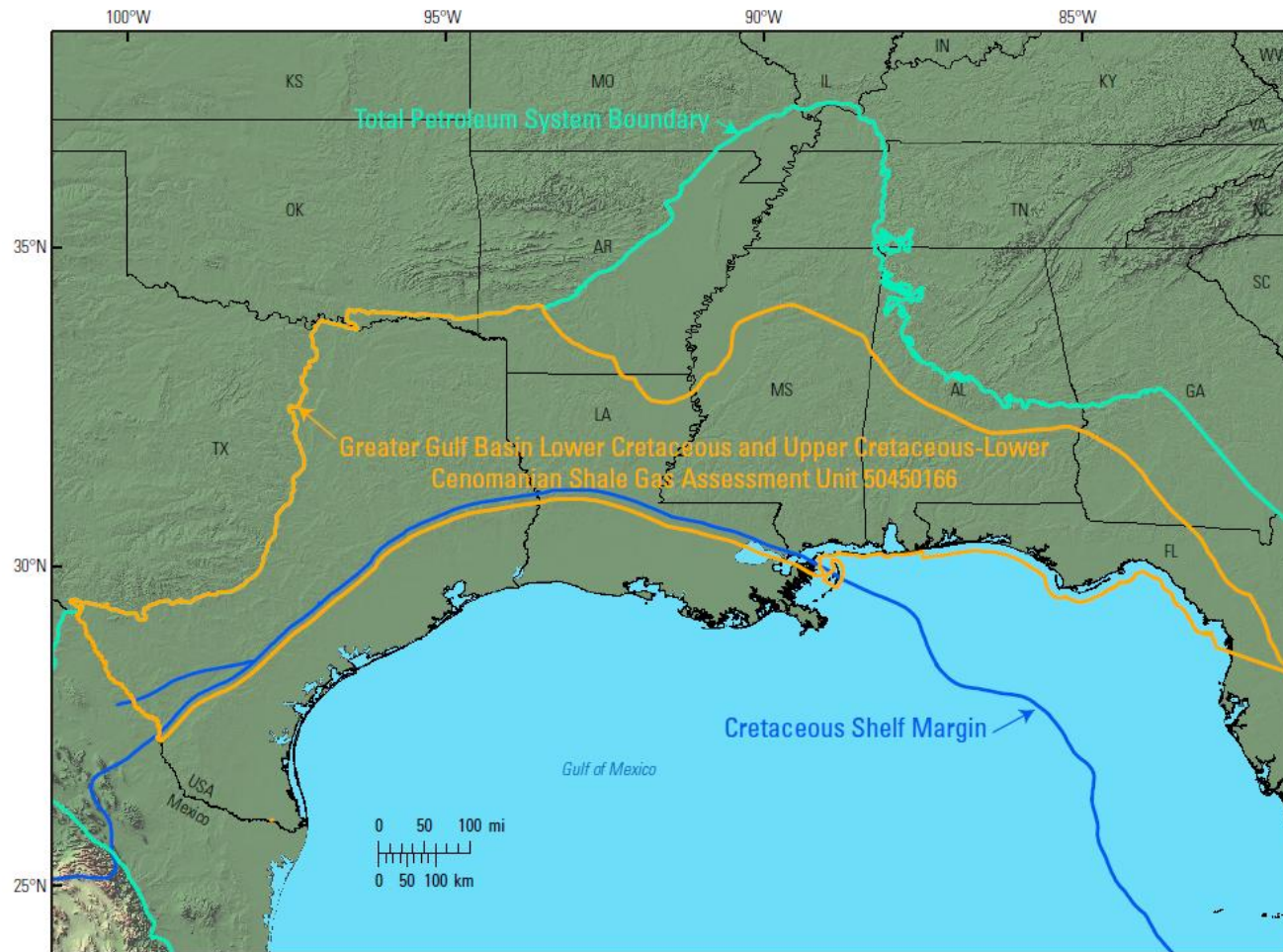


Figure 1. Map showing the Greater Gulf Basin Lower Cretaceous Shale Gas AU boundaries and the Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System boundary for the U.S. Gulf Coast region (Dubiel et al., 2007). Lower Cretaceous shelf margin from Galloway et al. (2000).

**Generalized Stratigraphy of Gulf Coast Region
showing oil and gas production and source rocks**

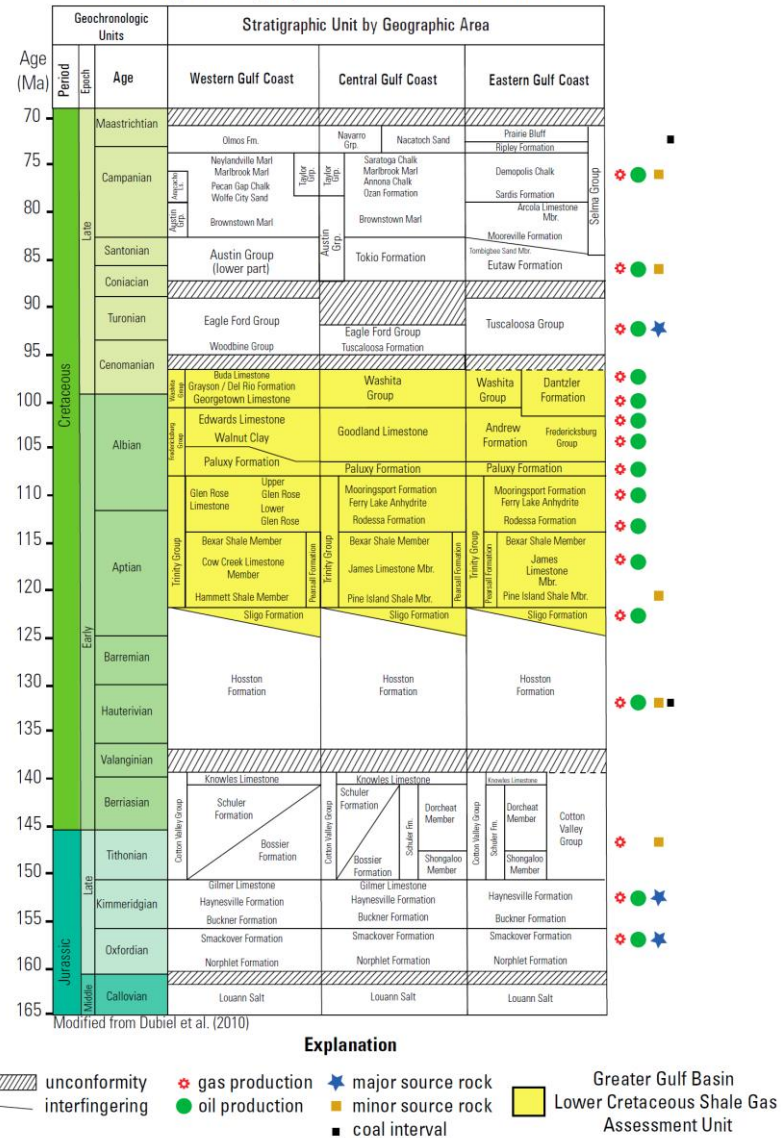


Figure 2. Generalized Mesozoic stratigraphy of the Gulf Coast region showing oil and gas production and source rocks. The stratigraphic interval included within the Lower Cretaceous Shale Gas AU is highlighted in yellow (conventional accumulations and unconventional Maverick Basin Pearsall Formation shale gas excluded). Modified from Dubiel et al. (2010).

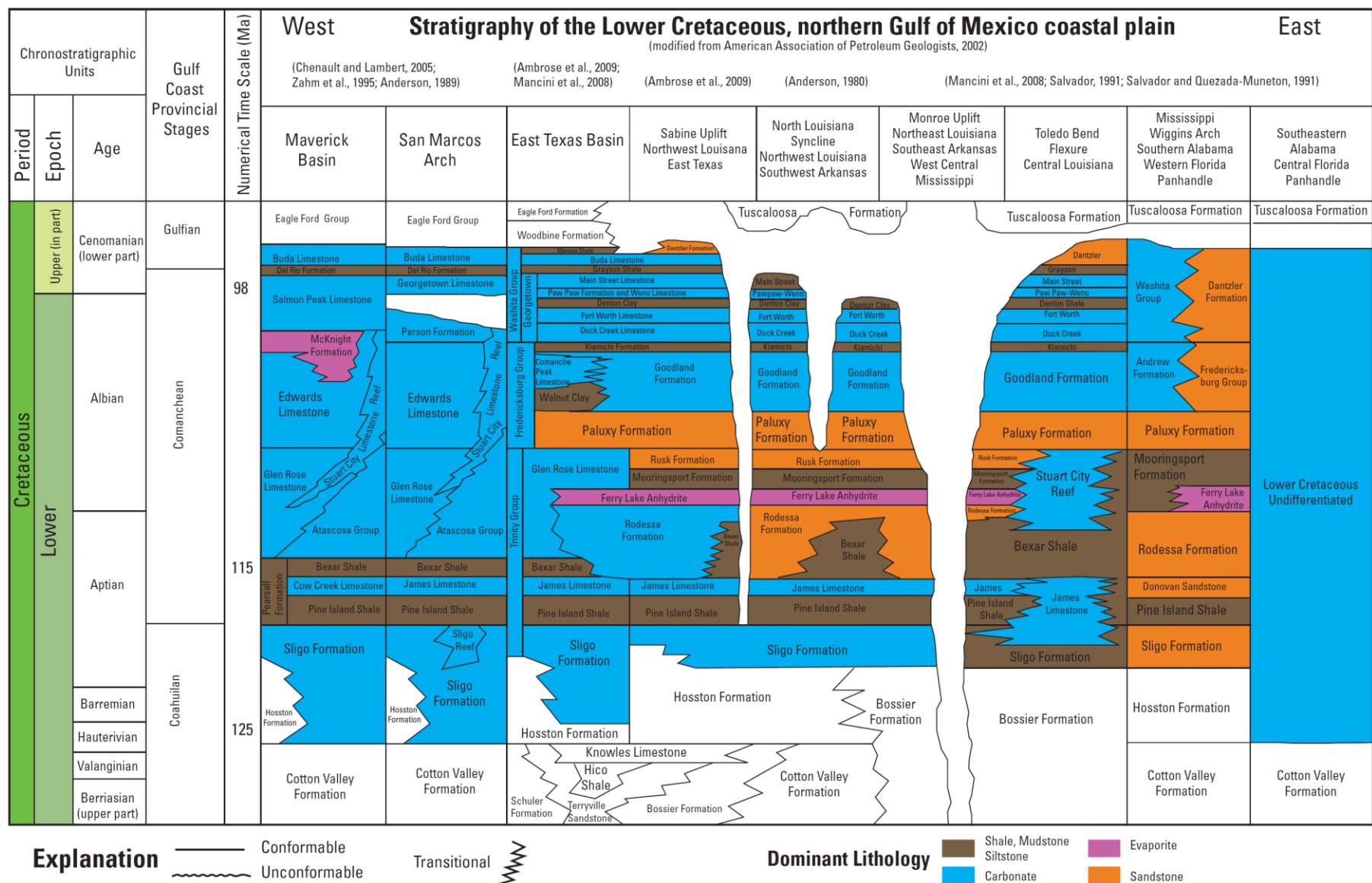


Figure 3. Stratigraphic chart of the northern Gulf of Mexico onshore region showing distribution and dominant lithology of formations in the Greater Gulf Basin Lower Cretaceous Shale Gas AU. Modified from Ambrose et al. (2009); American Association of Petroleum Geologists (2002); Anderson (1980); Anderson (1989); Chenault and Lambert (2005); Mancini et al. (2008); Salvador (1991); Salvador and Quezada-Muñeton (1991); Zahm et al. (1995).

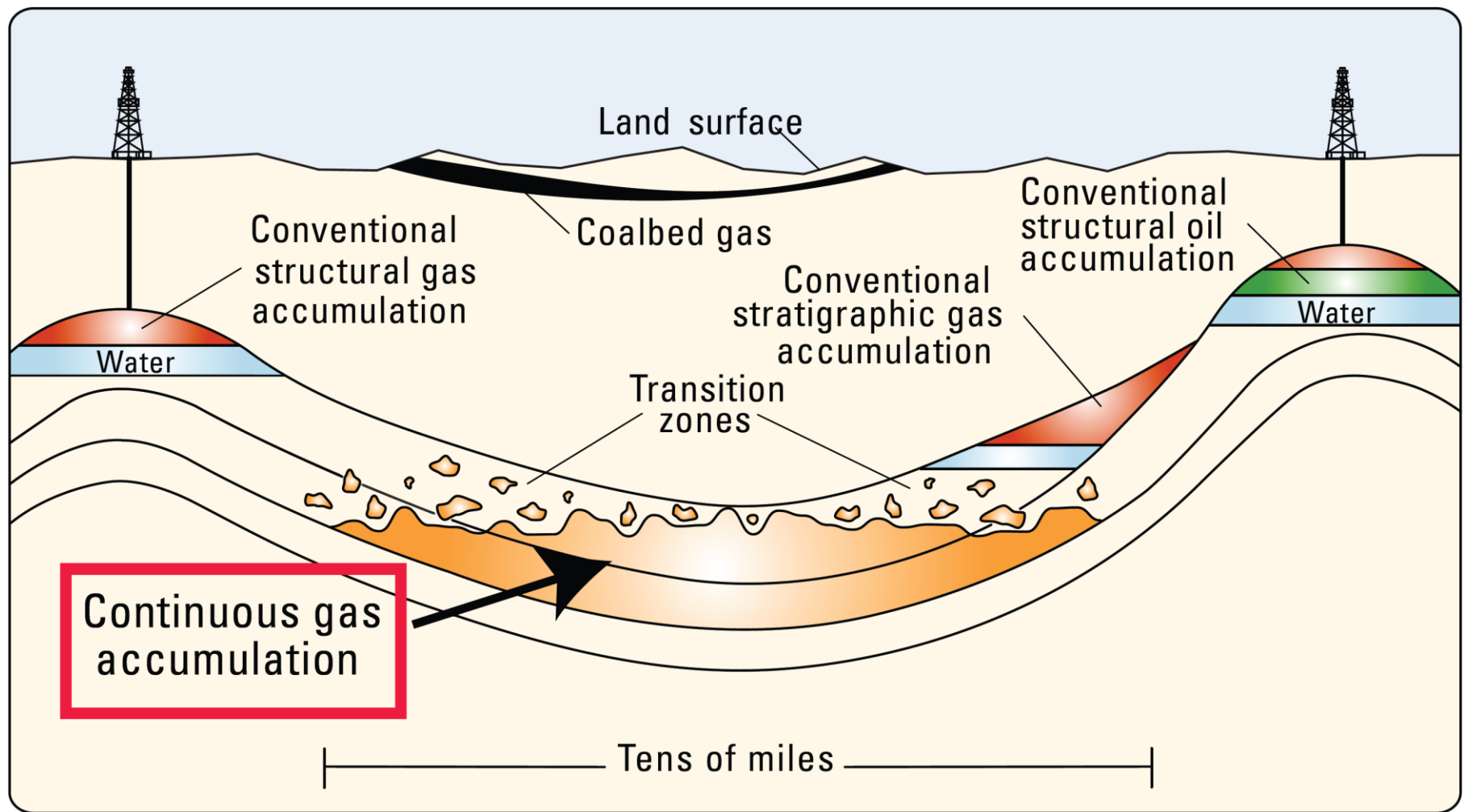


Figure 4. Characteristics of conventional and continuous hydrocarbon accumulations. Continuous or unconventional accumulations lack water contacts and conventional traps (from Schmoker, 2005).

Regional Geologic and Structural Setting

General Gulf of Mexico Basin Structure

The Gulf of Mexico Basin is a small ocean basin created by Mesozoic sea-floor spreading and crustal extension (Galloway, 2008). Northwest-southeast-trending transfer faults related to Mesozoic rifting most likely influenced depositional patterns throughout the history of the Gulf of Mexico Basin (Stephens, 2009). The Cretaceous continental shelf margin developed on a hinge zone between thicker and thinner crust where an extensive reef system developed (Galloway, 2008) ([Figure 5](#)). The uplifts, arches, embayments, and salt basins around the northern edge of the basin are the result of differential subsidence between the thicker and thinner crust, Late Cretaceous volcanism, and the movement of salt in combination with pre-existing structures that are possibly as old as Precambrian (Galloway, 2008; Culotta et al., 1992).

Gulf Coast Paleohighs

In the central and eastern Gulf Coast onshore region, major basement paleohighs that influenced distribution and thickness of Mesozoic deposits include the Sabine Uplift, Monroe Uplift, Jackson Dome, Wiggins Arch, Choctaw Ridge, and Conecuh Ridge (Mancini et al., 2008) ([Figure 5](#)). Of these paleohigh features, the Sabine Uplift was a structural low during the Early Cretaceous and uplifted during the Late Cretaceous to Eocene (Laubach and Jackson, 1990). The Jackson Dome and Monroe Uplift are cored by volcanic rocks of Cenomanian age, 65-80 Ma, but there is a suggestion of doming during the Paleozoic (Ewing, 2009). The rest of the paleohighs were present during the Paleozoic (Halbouty, 1966; Cagle and Khan, 1983; Lawless and Hart, 1990; Mink and Mancini, 1995; Li, 2006; Ewing, 2009).

Major Gulf Coast Depositional Centers

Cretaceous sediments surround the Gulf of Mexico basin, thicken basinward, and pinch-out on the updip edges of the basin (McFarlan and Menes, 1991). This pattern of deposition is modified by basins and embayments of the Gulf Coast onshore region, many of which are due to salt withdrawal that formed depositional centers relative to the adjacent paleohighs ([Figure 5](#)). A major embayment of the Gulf of Mexico, the East Texas Basin, is bounded on the northeast by the Sabine Arch and was separated from the Gulf of Mexico by the Angelina-Caldwell Flexure during the Late Cretaceous and Paleogene (Ambrose et al., 2009; Stehli et al., 1972). In the deep central part of the East Texas Basin, syn-depositional salt movement created accommodation space that outpaced uplift associated with the Sabine Arch and changes in sea level (Salvador 1991; Ambrose et al., 2009). The Maverick Basin in southern Texas and northern Mexico formed slowly due to regional subsidence during the middle Albian (Chenault and Lambert, 2005; Hentz and Ruppel, 2010).

The North Louisiana Salt Basin, the Mississippi Interior Salt Basin, and the Manila and Conecuh sub-basins were extensional basins modified by movement of the Jurassic Louann Salt during the Late Jurassic and Early Cretaceous (Mancini et al., 2008). The Apalachicola Embayment overlies an extension of the South Georgia Basin, is related to Triassic-Jurassic rifting, and contains more than 6000 feet of Cretaceous clastic sediments (Ewing and Lopez, 1991).

Cretaceous Shelf Edge

During the early part of the Cretaceous an almost continuous rimmed carbonate shelf formed that extended from the Bahamas and Florida westward to Texas and southward into northwestern Mexico (Scott, 2010) ([Figure 5](#)). The margin of the shelf was established along a subsidence hinge on the boundary between thicker crust to the north and thinner crust basinward (Galloway, 2008). Landward of the shelf edge, a shallow carbonate depositional regime dominated on a broad, relatively flat platform with reefs and banks at the margin, and accumulation of dark argillaceous carbonates in the deeper forereef (Fisher and Rodda, 1969; Bebout, 1974; Yurewicz et al., 1993). In south and central Texas, shelf-margin development reduced the amount of wave energy reaching the inner shelf platform and changed the depositional regime from high-energy tidal complexes to lower energy, mud-dominated complexes with extensive evaporite beds (Phelps et al., 2010). Differential tectonic uplift of the basin margin during the mid-Cenomanian, plus tilting and subsidence of the shelf margin and outer shelf, resulted in drowning of the shelf and development of the mid-Cenomanian unconformity at the top of the Washita Group (Galloway, 2008).

Faults

Surrounding the northern Gulf of Mexico Basin there are systems of peripheral grabens that generally parallel the Cretaceous shelf margin and which are related to: 1) regional tectonic movements associated with the Ouachita and Appalachian orogenic belts, 2) regional downwarping of the Gulf Coast Basin due to Tertiary sediment loading, and 3) movement of the Jurassic Louann Salt. Major peripheral graben systems related to the AU are shown in [Figure 5](#) and are, from west to east, the Charlotte-Jourdanton, Balcones, Luling, Karnes, Milano, Mexia, Talco, Pickens, Gilbertown, and Pollard fault zones (Murray, 1957; Mancini et al., 1986; Ewing and Lopez, 1991). The Angelina-Caldwell Flexure in eastern Texas and southern Louisiana resulted from Tertiary sediment loading in the area of the Sabine Uplift (Ewing and Lopez, 1991). Other more localized fault systems are related to salt domes and salt movement in the East Texas Basin and the Louisiana and Mississippi salt basins.

Depositional Models

The Greater Gulf Basin Lower Cretaceous Shale Gas AU consists of Lower Cretaceous Aptian and Albian formations and lower Cenomanian formations of the Comanchean Series, starting with the Aptian Sligo Formation at the base of the series and terminated upwards by the regional mid-Cenomanian unconformity recognized at the top of the Washita Group ([Figures 2](#) and [3](#)). During the Albian and Aptian, distinct depositional cycles comprised of carbonate shelf ([Figure 6A](#)) and clastic material ([Figure 6B](#)) were separated by maximum flooding surfaces and disconformities. The cycles are represented by the following major lithostratigraphic units: the Sligo Formation, and the Trinity, Fredericksburg, and Washita groups (Galloway, 2008; Scott, 2010) ([Figures 2](#) and [3](#)). Ages of these rocks have been correlated by biostratigraphy to global cycles of marine transgression and regression (Mancini and Puckett, 2002) and to local subsidence and tectonic uplift during the Laramide orogeny (Galloway, 2008). Although the Lower Cretaceous in the Texas Gulf of Mexico coastal plain is dominated by carbonate units ([Figure 7](#)), clastics are more prevalent to the north and east in updip areas of Louisiana, Mississippi, Alabama,

and northern Florida (Figure 8) because of proximity to terrigenous source terranes (Rainwater, 1971; Raymond, 1995; Mancini et al., 2008).

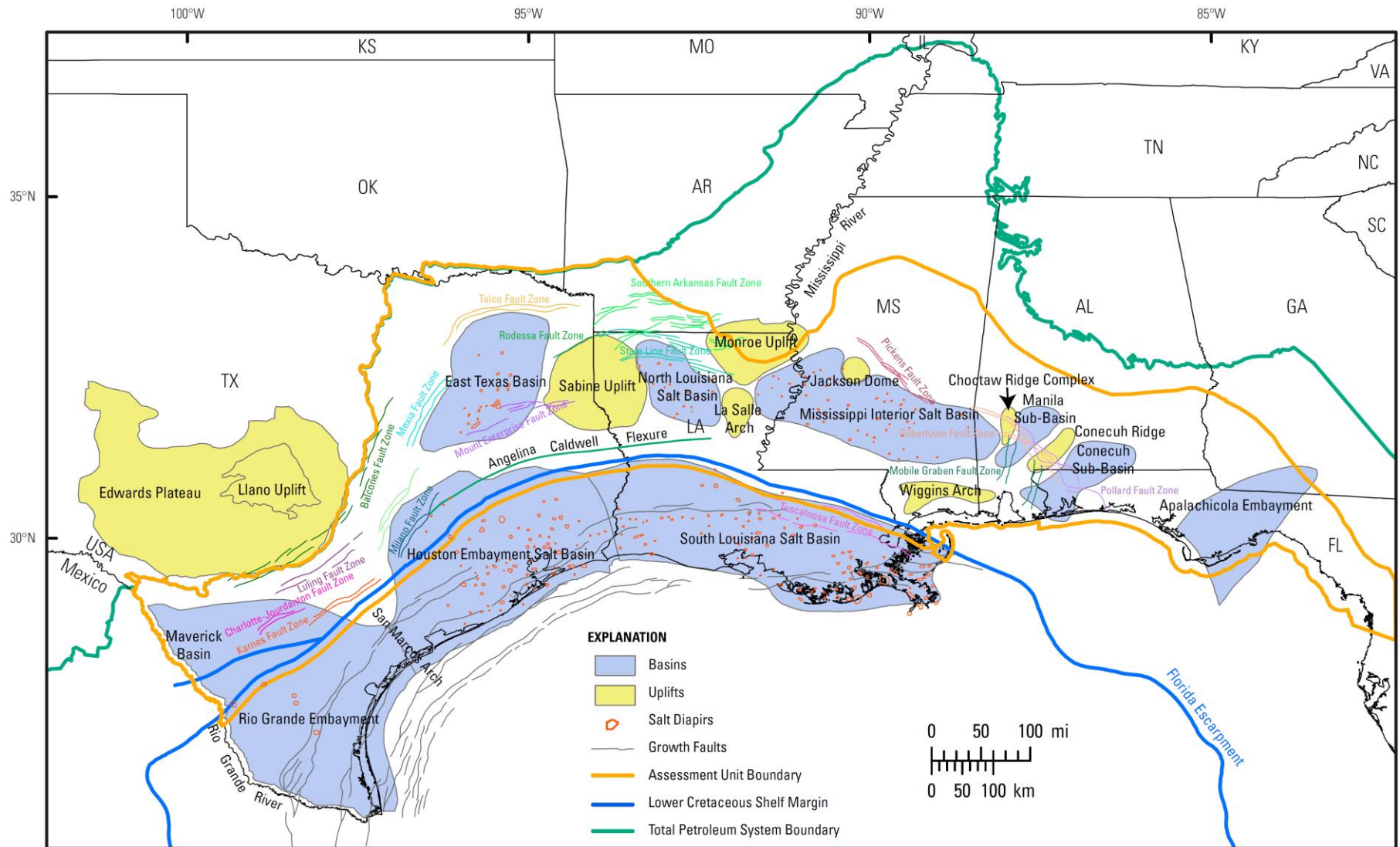


Figure 5. Structure map of northern Gulf of Mexico Basin region showing basins, uplifts and other structural features in the Gulf Coast region that influenced deposition. Modified from Ewing and Lopez (1991) and Li (2006).

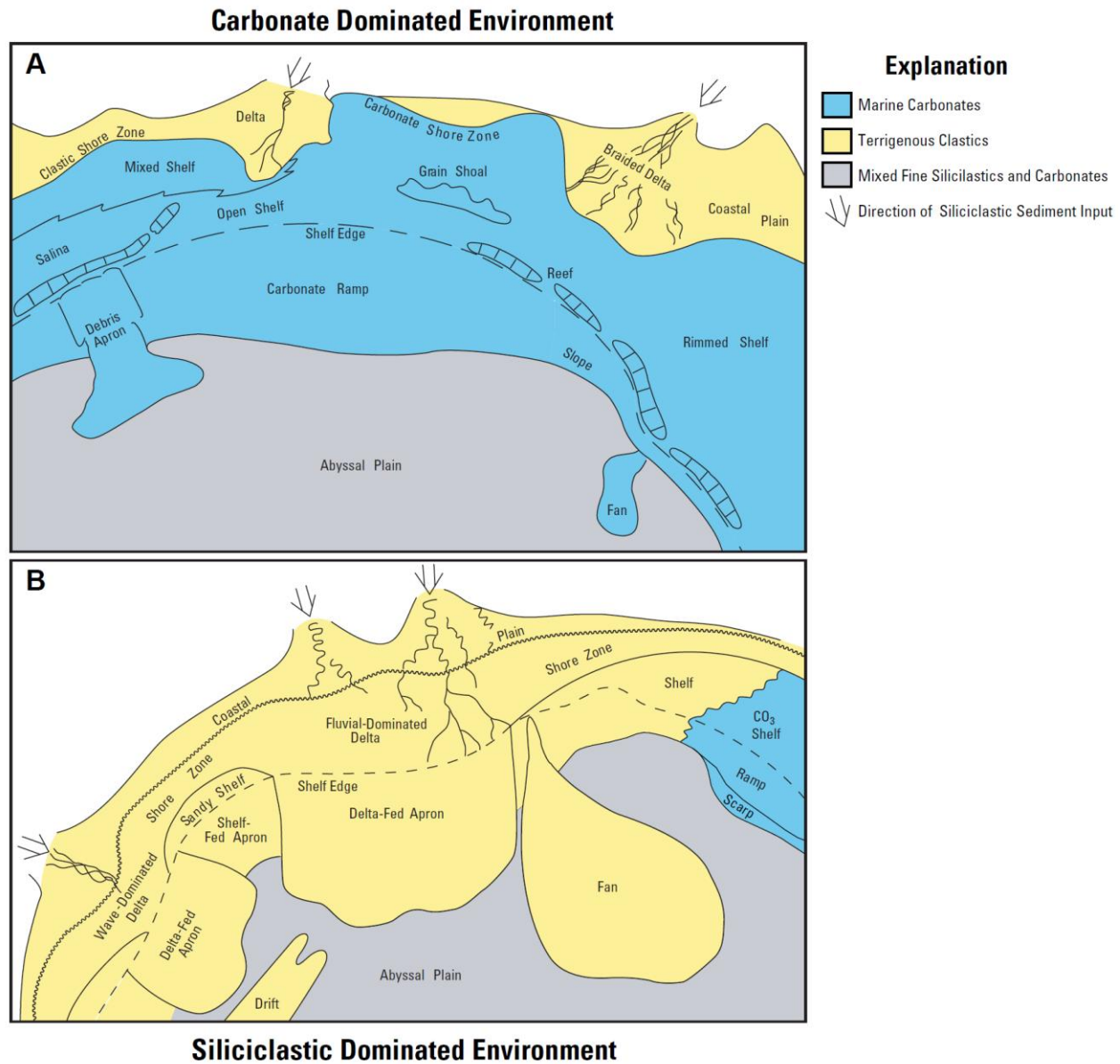
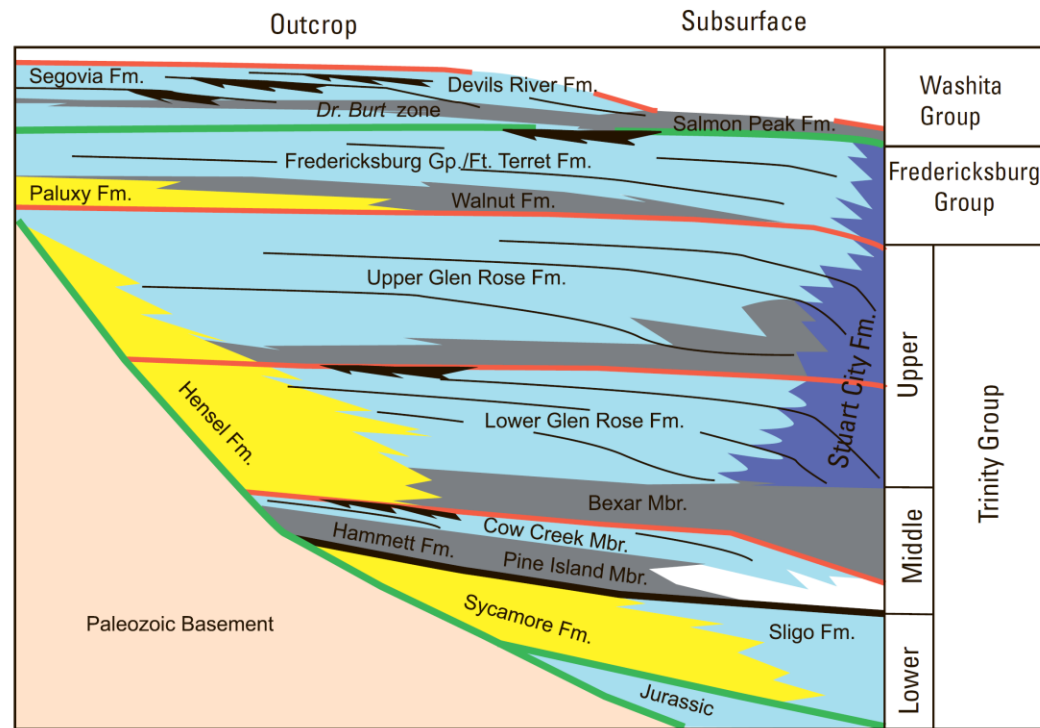


Figure 6. Cretaceous depositional regimes of the Gulf of Mexico region: A) marine, carbonate-dominated environment, and B) siliciclastic, fluvial-deltaic environment (from Galloway, 2008).



Explanation

- Second order sequence boundary
- Third order sequence boundary
- High-frequency sequence boundary or approximate time line
- Transgressive systems tract terrigenous deposits reworked from the precursor lowstand
- Highstand carbonate platforms
- Shaly or marly peak transgressive facies
- Reef margin
- Foreshore areas



Locations of outcrops from which generalized cross section was constructed

Figure 7. Depositional model for the western Gulf Coast region during the Cretaceous, showing dominance of carbonate sediments (from Kerans and Loucks, 2002).

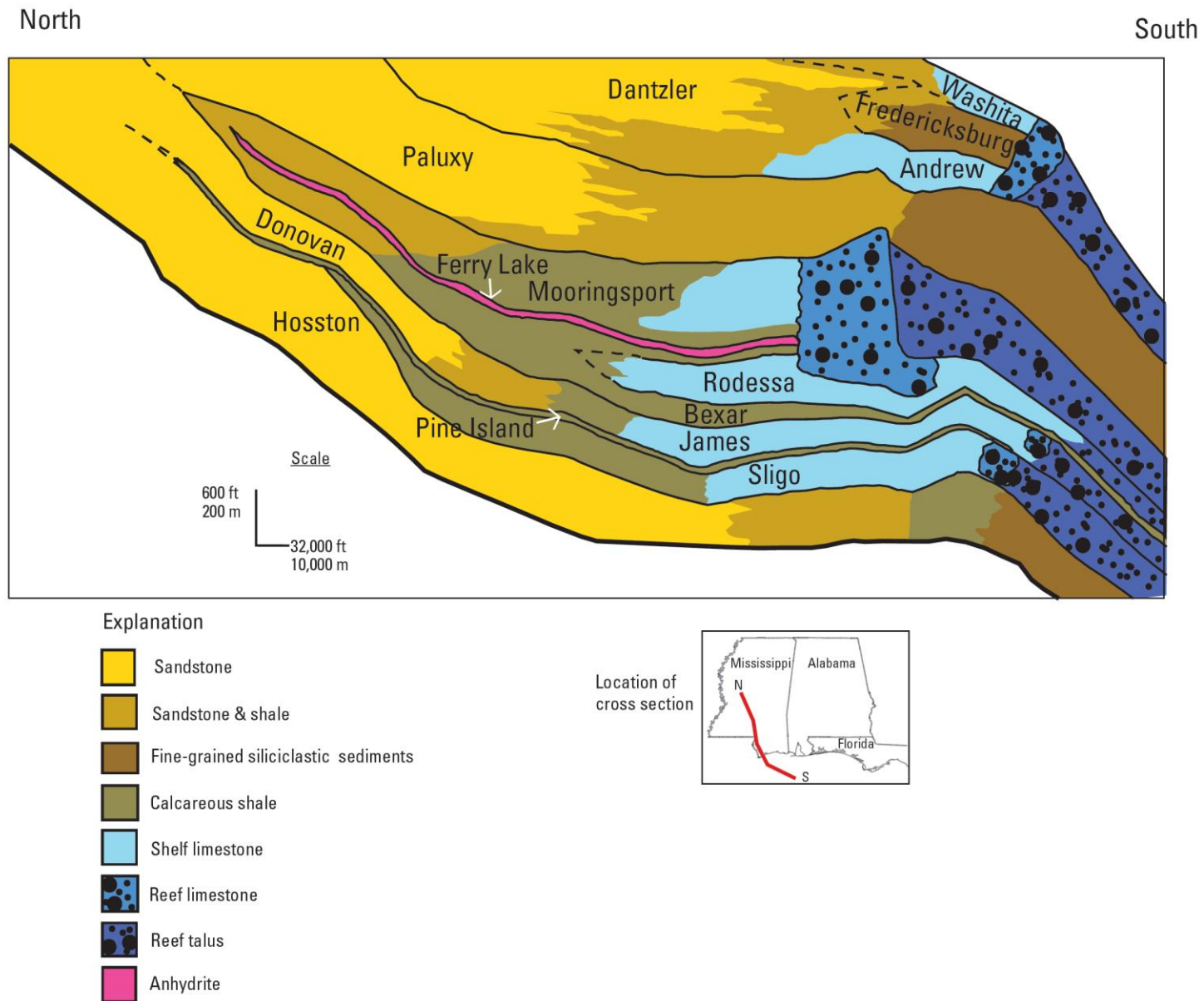


Figure 8. Depositional model for the eastern Gulf Coast region during the Cretaceous and early Cenomanian, showing dominance of clastic sediments (from Mancini and Puckett, 2002; Yurewicz et al., 1993).

Stratigraphy

Sligo Formation

The lower Aptian Sligo Formation is an argillaceous and fossiliferous aggrading and prograding limestone formation that is recognized in the subsurface from Texas to Florida (McFarlan and Menes, 1991; Mancini and Puckett, 2002). The Sligo Formation interfingers with terrigenous clastic sediments of the underlying Hosston Formation and becomes oolitic in east Texas and western Louisiana where it is known as the Pettet Limestone (McFarlan and Menes, 1991). The Sligo is not recognized in Mississippi (Raymond, 1995). Conventional hydrocarbon accumulations in the Hosston (Dyman and Condon, 2006) and Sligo and Pettet formations were assessed separately (Dubiel et al., 2010, 2011; Doolan and Karlsen, 2011; Karlsen and Hackley, 2011) from the unconventional AU described herein.

Trinity Group

The Trinity Group has two major divisions, the Pearsall Formation and the Glen Rose Formation. These formations and their equivalents are recognized throughout the study area, from south Texas to the western Florida panhandle ([Figure 3](#)).

Pearsall Formation

The predominantly terrigenous clastic Pearsall Formation overlies Sligo carbonates from south Texas to northern Florida (McFarlan and Menes, 1991). The lowest unit of the Pearsall, the Pine Island Shale, contains dark shales interbedded with thin limestones and is overlain by dense limestones of the James Limestone and the upper unit of the Pearsall Formation, the Bexar Shale (McFarlan and Menes, 1991). Hackley (2012) separately assessed the Pearsall Formation in the Maverick Basin of south Texas for unconventional hydrocarbon accumulations; therefore, the Greater Gulf Basin Lower Cretaceous Shale Gas AU does not include the Pearsall Formation southwest of the San Marcos Arch ([Figure 5](#)).

Glen Rose Formation

In the carbonate shelf areas of the study area, Aptian-Albian Glen Rose limestones transgressed over the Pearsall Formation (McFarlan and Menes, 1991; Mancini and Puckett, 2002). The Glen Rose Formation is recognized as a single discrete unit in south Texas composed of argillaceous dolomite with anhydrite layers (Rose, 1972). Northward and eastward into east Texas and Alabama, the Glen Rose is subdivided into the Rodessa Formation, the Ferry Lake Anhydrite and the Mooringsport Formation, which is a predominantly argillaceous unit that commonly hosts conventional oil and gas accumulations (Baria, 1981; Raymond, 1995). Conventional oil and gas accumulations in the Glen Rose Formation and equivalent strata were assessed separately (Dubiel et al., 2010, 2011).

Fredericksburg and Washita Groups

Units of the Fredericksburg and Washita Groups are recognized and subdivided in most of Texas, but are not differentiated in the northeastern Gulf of Mexico Basin, with the exception of the clastic Paluxy and Dantzler Formations ([Figure 3](#)). Conventional hydrocarbon accumulations in the Fredericksburg and Washita groups were assessed separately (Dubiel et al., 2010, 2011) from the Greater Gulf Basin Lower Cretaceous Shale Gas AU described herein.

Fredericksburg Group

In updip areas of Texas, Louisiana, Mississippi, and Alabama, the top of the Glen Rose Formation interfingers with terrigenous clastics of the Paluxy Formation of the basal Fredericksburg Group, a time-transgressive unit representing a change from fluvial-deltaic clastic facies to purely marine limestone facies of the Edwards and equivalent Goodland Formations (Anderson, 1989). In south and central Texas, the Fredericksburg Group includes the Edwards Limestone, composed of transgressive West Nueces limestones and overlying McKnight evaporites to the south, and the Kainer massive dolomitic micrites and the Person biomicrites and rudist grainstones to the north (Rose, 1972; McFarlan and Menes, 1991). From east Texas to west-central Mississippi, the Fredericksburg Group is divided in ascending order into the Paluxy, Goodland, and Kiamichi Formations (McFarlan and Menes, 1991) ([Figure 3](#)).

Washita Group

The Washita Group overlies the Fredericksburg Group, unconformably in many places (Anderson, 1989). Washita deposition began with the Kiamichi Formation, a regional shale unit described as distal turbidite (Scott et al., 1975). Overlying the Kiamichi is the Georgetown Formation and its equivalents: the Duck Creek Limestone, Fort Worth Formation, Denton Clay, Pawpaw Formation, Weno Limestone, and Main Street Formation of late Albian age, the lower Cenomanian Del Rio and equivalent Grayson formations, and the Buda Formation (McFarlane and Menes, 1991). In the East Texas Basin, the Buda Formation is conformably overlain by the Maness Shale (Ambrose et al., 2009). Elsewhere in Texas, the top of the Buda Formation is considered to be a submarine discontinuity (Mancini and Scott, 2006). The clastic Dantzler Formation is the Buda equivalent at the top of the Washita Group in the central and eastern Gulf of Mexico region (Mancini et al., 2008) ([Figure 3](#)).

Cretaceous Reef Trend Formations

The downdip part of the Greater Gulf Basin Lower Cretaceous Shale Gas AU contains the Sligo, Glen Rose, and Edwards reefs at the Cretaceous shelf edge earlier described. The carbonate-margin trend was summarized by Winker and Buffler (1988) and is briefly reviewed here. Reef facies of the Sligo Formation developed on the shelf margin during the Aptian in Texas and may have continued into the Albian in eastern Texas. Reef facies of the Edwards Formation, also known as the Stuart City trend in Texas, developed slightly landward of the

Sligo margin in Texas and are nearly continuous around the present onshore northern Gulf Coast area before extending seaward as the Florida Escarpment ([Figure 5](#)) (Fritz et al., 2000).

Reef margins in the Greater Gulf Basin Lower Cretaceous Shale Gas AU are composed of transgressive and regressive cycles of framework limestone deposition that interfinger with the landward facies of the Sligo Formation, and the Trinity, Washita and Fredericksburg Groups (McFarlan and Menes, 1991). In central Texas, eight composite sequences containing nearly 50 high-frequency cycles of low- to high-energy regimes, punctuated by mud-dominated to grainstone-dominated cycles, were documented, starting with the Sligo Formation and continuing to the Upper Cretaceous (Phelps et al., 2010).

Mid-Cenomanian Unconformity

The top of the Greater Gulf Basin Lower Cretaceous Shale Gas AU is set at the mid-Cenomanian unconformity. Depositional patterns in the northern Gulf of Mexico Basin were interrupted in the mid-Cenomanian, during a period of global sea level fall and uplift from local igneous activity, resulting in this region-wide unconformity. Maximum erosion of Lower Cretaceous units occurred in the north-central Gulf coastal area (Li, 2006; Galloway, 2008). Both the Maness Formation in east Texas and the Dantzler Formation red beds in west-central Mississippi and southern Alabama represent local deposition in areas not affected by the mid-Cenomanian unconformity (McFarlan and Menes, 1991).

Extent, Thickness, Lithology and Depth of Shales in AU

The Sligo Formation primarily is carbonate in east Texas, Louisiana, and Arkansas and becomes more clastic-rich in Mississippi and eastward (Mitchell-Tapping, 1981). Shallow-marine Sligo Formation shales in Mississippi are dark-red to grey and interbedded with gray to white, fine-grained sandstone from shoreface and marine-shelf environments (Devery, 1982; Mancini and Puckett, 2002). Individual “shale” beds in the Sligo Formation generally are thin, on the order of 10s of ft (e.g., Mancini and Puckett, 2002; Enomoto et al., 2012).

Total shale thickness in the Trinity Group is up to 1500 feet, but unnamed dark gray to black shales occur only in a thin band of approximately 500 ft thickness in Texas and western Louisiana ([Figure 9](#)) (Forgotson, 1956). Regionally extensive shaly units of the Trinity Group include the Pine Island Shale and Bexar Shale of the Pearsall Formation, and the Mooringsport Formation (Forgotson, 1956; Kimmel, 1957; Rainwater, 1971; Scott et al., 1975; Young, 1986; Raymond, 1995; Mancini et al., 2008; Enomoto et al., 2012). The Pearsall Formation is thicker in east Texas, Louisiana, Arkansas, and Mississippi, where it is up to 800 ft; in Alabama and Florida, the Pearsall thins to a maximum of about 300 ft (Enomoto et al., 2012). Regional studies by Forgotson (1957, 1963) indicated Pearsall Formation shale thickness at a maximum of about 400 ft in southern Alabama and thinner elsewhere in the northern Gulf of Mexico Basin. In general, the regional studies by Forgotson (1957, 1963) and Enomoto et al. (2012) indicated Pearsall shales are dark gray to black in downdip areas, green and brown in updip areas in the western and central parts of the basin, and red in updip areas in the eastern part of the basin ([Figure 10](#)).

The Mooringsport Formation is recognized from east Texas to the western panhandle of Florida ([Figure 11](#)) and is up to 300 feet thick in southern Alabama (Raymond, 1995). Some thin Trinity Group shales also are present in the Glen Rose Formation and its equivalents in the eastern part of the study area (Devery, 1982; Warner and Moody, 1992).

The Kiamichi Formation is widespread and mapped at outcrop from Arkansas and Oklahoma southwestward into the Permian Basin of southwestern Texas as well as southeastward into west-central Mississippi, where it is described as dark calcareous clay with thin limestone interbeds (Nunnally and Fowler, 1954). Various workers have proposed placing the Kiamichi as either the uppermost formation in the Fredericksburg Group or lowermost formation in the Washita Group; currently, the USGS assigns the Kiamichi to the Fredericksburg (USGS, 2011). At outcrop, the Kiamichi Shale varies in thickness from 10-150 ft (Hill, 1891; Wilmarth, 1938; Leggat, 1957; Shelburne, 1959; Perkins, 1960; Fox and Hopkins, 1960; Freeman, 1964; Barnes, 1967a,b, 1972; Brown, 1971). In McMullen County, Texas, the Kiamichi Formation is described as 400 ft thick, with alternating beds of black brittle shale, sandstone, and calcareous marls with beds of marine megafossils, such as oysters (Kimmel, 1957). In the Blackfoot field in the western part of the East Texas Basin the Kiamichi Formation is 90 ft thick (Branson, 1950).

In the Washita Group there are numerous thin units described as containing shale, for example: the Duck Creek Limestone, Denton Clay, Pawpaw Formation, Weno Limestone, and the Maness Shale ([Figure 3](#)). Lithofacies include fossiliferous black shales, thin calcareous shales, marls, sandy clays, and sand lenses (Hill, 1891, 1901; Wilmarth, 1938; Smith, 1940; Lozo, 1943; Leggat, 1957; Shelburne, 1959; Fox and Hopkins, 1960; Freeman, 1964; Barnes, 1967a,b, 1972; Rainwater, 1971; Scott et al., 1975; Mancini, 1977; Mancini, 1982). These units are limited to the Texas part of the Greater Gulf Basin Lower Cretaceous Shale Gas AU. The Duck Creek Limestone, Denton Clay, Pawpaw Formation and Weno Limestone each have thicknesses ranging from 3-50 feet (Cuyler, 1929; Brown, 1971). The Maness Shale is up to 50 feet thick in the East Texas Basin (Ambrose et al., 2009). The Del Rio Formation and equivalent Grayson Shale of the Washita Group are more regionally extensive and recognized from the Maverick Basin eastward to central Louisiana (Mancini et al., 2008) ([Figure 3](#)). The Del Rio/Grayson is 80-100 ft thick throughout most of Texas with thicknesses in proximity to the Stuart City reef varying from 50-170 ft and a maximum thickness of 265 ft in the Maverick Basin (Brown, 1971; Mancini, 1977, 1982).

Formation-tops data from IHS Energy Group (2010) were used to construct a depth-below-surface map ([Figure 12](#)) for the upper stratigraphic limit (the mid-Cenomanian unconformity) of the Greater Gulf Basin Lower Cretaceous Shale Gas AU. The depth below surface map reflects the overall basinward dip of Gulf stratigraphic units and clearly reflects the presence of the major structural features of the basin. The deepest parts of the AU upper stratigraphic limit are along the Cretaceous shelf edge where depth below surface is up to 25,000 ft.

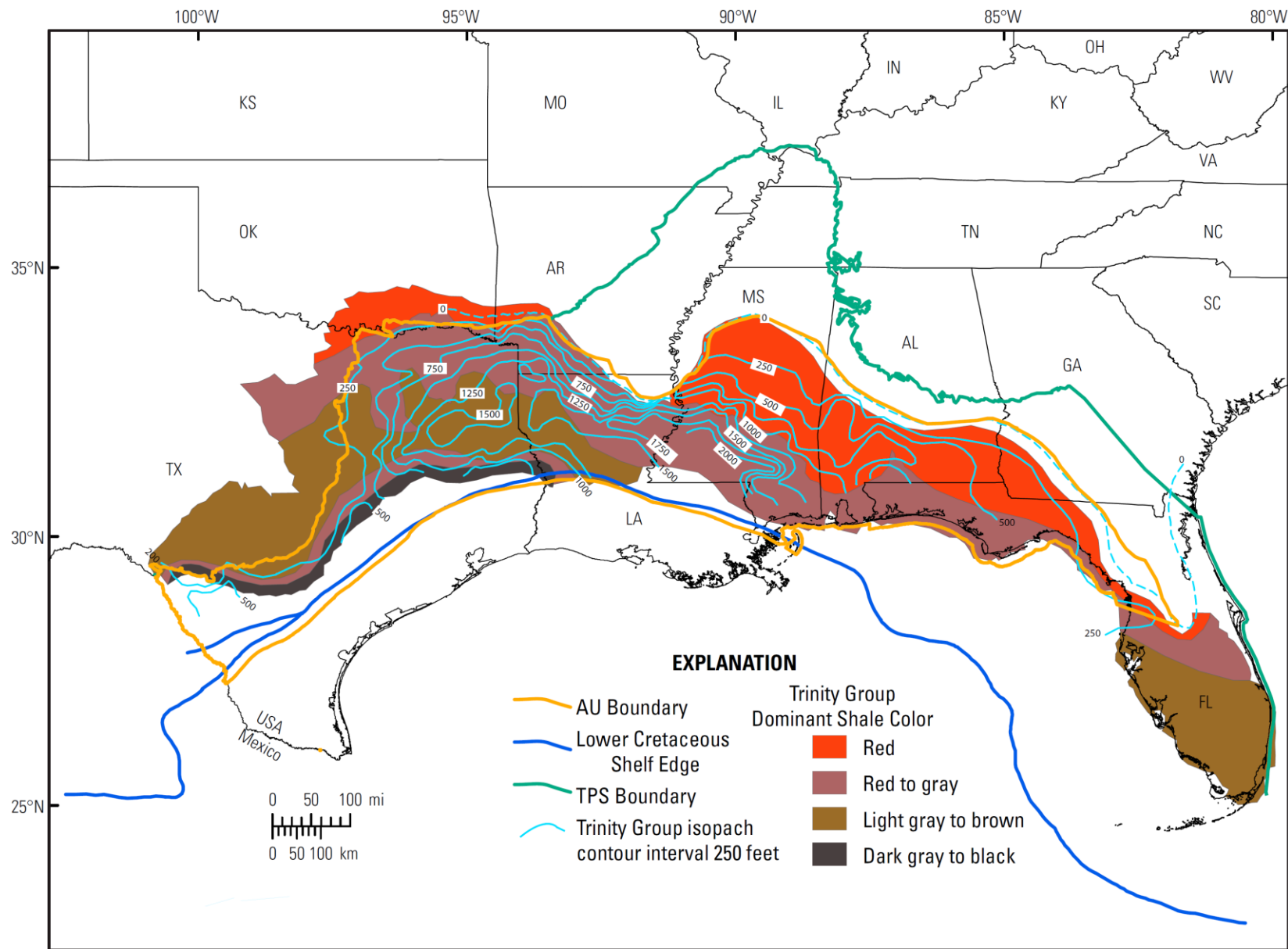


Figure 9. Isopach map of Trinity Group shales, showing dominant shale color by area (from Forgotson, 1956).

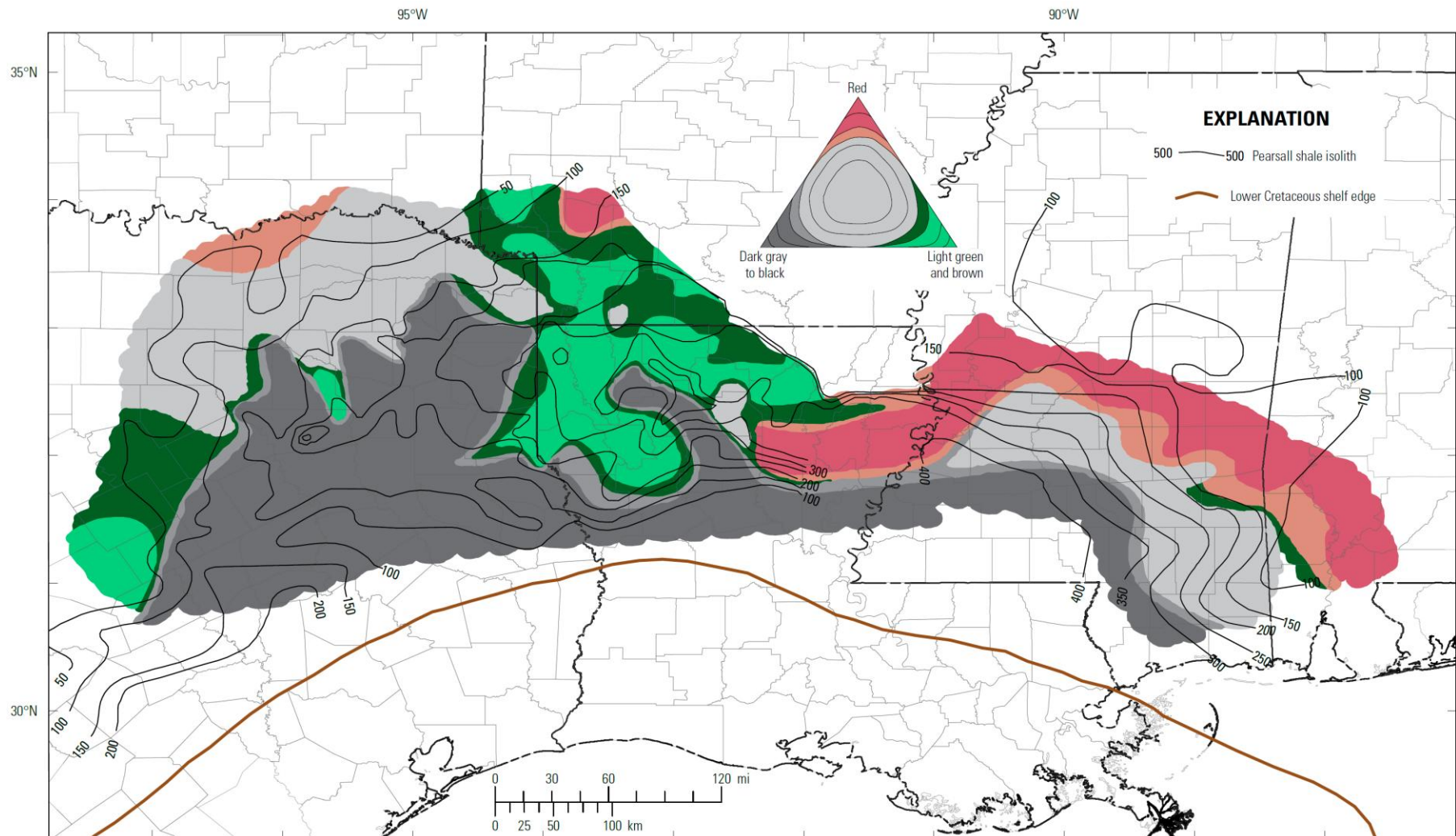


Figure 10. Shale isolith and shale color map of the Pearsall Formation across the northern Gulf of Mexico Basin (from Forgotson, 1963). Location of Lower Cretaceous shelf edge is from Galloway et al. (2000). See Forgotson (1960) for explanation of entropy function lithofacies maps as symbolized in the ternary shale color diagram.

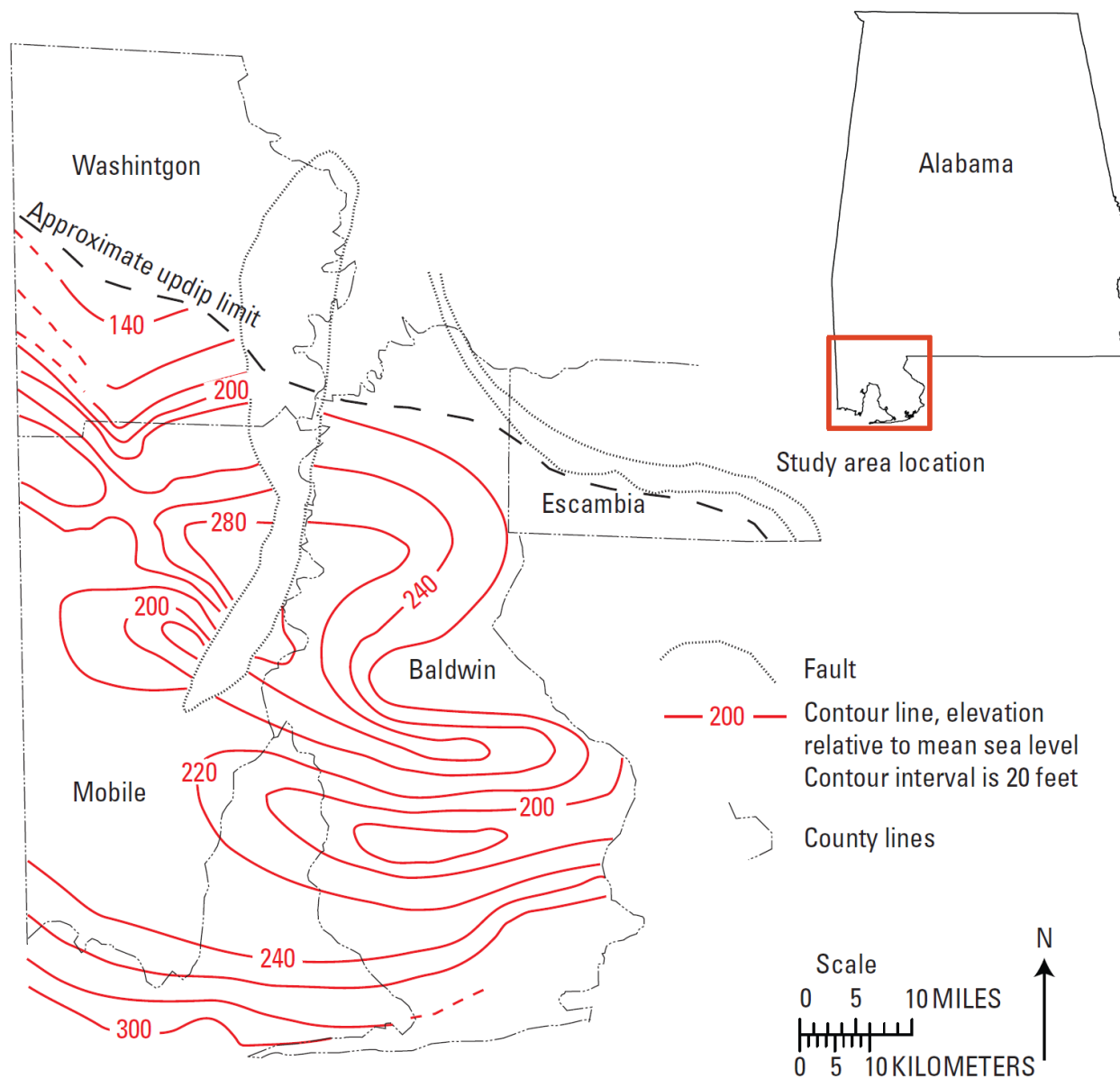


Figure 11. Isopach map of Mooringsport Formation in southern Alabama (from Raymond, 1995).

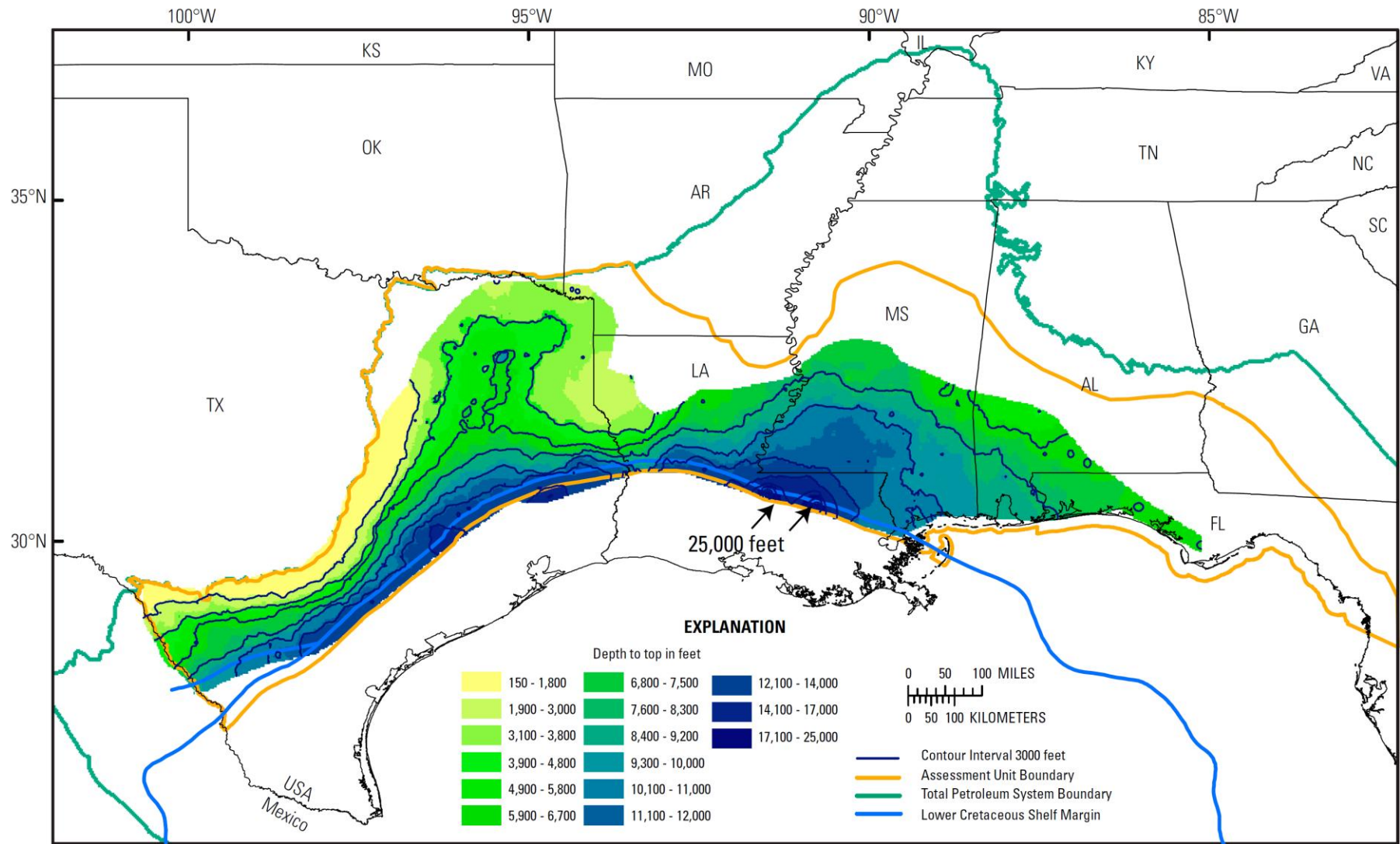


Figure 12. Depth-below-surface map to the top of the Greater Gulf Basin Lower Cretaceous Shale Gas AU, constructed from formation-tops data for the Buda Limestone, Manass Shale, and equivalents (data from IHS Energy Group, 2010).

Thermal Maturity and Organic Geochemistry

Geochemical data available from lithologies in the Greater Gulf Basin Lower Cretaceous Shale Gas AU at the time of this assessment are compiled in [Table 1](#) and spatially located in [Figure 13](#). In general, for a shale to be considered favorable for gas production, it should contain total organic carbon (TOC) content > 2.0 wt.% and vitrinite reflectance (R_o) values > 1.0% (e.g., Wang and Gale, 2009), although each shale play is different. Only one sample in the collection meets the first criterion, the Del Rio Shale sample from Bastrop County, Texas, containing TOC content of 4.63 wt.%, but low calculated R_o value of 0.6%. According to Peters (1986), T_{max} is a crude indicator of thermal maturity, with oil generation indicated by T_{max} of about 435°C. The Del Rio Shale sample has a T_{max} value of 431°C, suggesting that it has not yet reached conditions where oil generation would start (Peters, 1986; Peters and Cassa, 1994). Other samples with R_o values >1.0% do not meet other criteria; for example, the Sligo Formation sample from Natchitoches Parish, Louisiana, with R_o of 1.37%, has a TOC content of only 0.23 wt.%. However, consideration of shale-gas prospectivity as a function of thermal maturity also should consider kerogen type, as Type III kerogen (terrestrial organic matter) can begin to generate gas at R_o as low as 0.5% (Tang et al., 1996). A cross plot of S2, another indicator of hydrocarbon generating capacity, with TOC content (Peters and Cassa, 1994; Edman and Pitman, 2010) indicates the current group of samples from shales in the AU are not good source-rock candidates, with the exception of the one Del Rio Shale sample ([Figure 14](#)). Enomoto et al. (2012) presented Rock-Eval and R_o information for about thirty samples from the Pearsall Formation and upper Sligo Formation from the San Marcos Arch eastward. In general, their data also indicated poor regional prospectivity for shale gas considering the criteria of Wang and Gale (2009), with R_o values mostly <1.0 % and TOC averaging around 0.5 wt.%. However, to make reliable interpretations of shale-gas prospectivity, larger quantities of thermal maturity and organic geochemistry data are needed to augment and refine the reconnaissance-scale regional studies that currently are available.

USGS thermal maturity modelling (Dubiel et al., 2012) of the Eagle Ford Shale, which overlies the Greater Gulf Basin Lower Cretaceous Shale Gas AU, indicated that the Eagle Ford becomes mature for hydrocarbon generation several tens of miles updip from the Lower Cretaceous shelf margin, except in the Maverick Basin and Houston Embayment where it becomes mature significantly updip of the shelf edge ([Figure 15](#)). Considering the modelling data of Dubiel et al. (2012) and taking into account the increased depth to the Lower Cretaceous, as well as consideration of the R_o data from Enomoto et al. (2012), a hypothetical R_o boundary for the gas generation threshold (R_o >1.2%) at the top of the Greater Gulf Basin Lower Cretaceous Shale Gas AU is shown in [Figure 15](#). This estimate of thermal maturity likely indicates that most of the area of the Greater Gulf Basin Lower Cretaceous Shale Gas AU is immature for self-sourced gas with the exception of very close proximity to the Cretaceous shelf edge.

Map Location No.	API No.	Depth (ft)	Group/Formation/ Member	State	County/Parish	TOC	S1	S2	S3	T _{max}	HI	OI	PI	R _o	Source of data
1	23047000020000	-11 190	Washita–Fredericksburg	MI	Harrison	0,39		0,15	0,56	422	38	143			Dennen et al., 2010
1	23047000020000	-10 500	Washita–Fredericksburg	MI	Harrison	0,53	0,01	0,24	1,08	428	45	203	0,04		Dennen et al., 2010
1	23047000020000	-10 810	Washita–Fredericksburg	MI	Harrison	0,5	0,01	0,21	0,89	428	42	178	0,05		Dennen et al., 2010
1	23047000020000	-10 120	Washita–Fredericksburg	MI	Harrison	0,61	0,02	0,67	0,85	452	109	139	0,03		Dennen et al., 2010
2	17079203650000	-12 701	Sligo	LA	Rapides	0,23			0,23	365	43	100	0,5		Mancini et al., 2006
2	17079203650000	-12 738	Sligo	LA	Rapides	0,45			0,35	408	16	78	0		Mancini et al., 2006
3	17069005080000	-11 077	Glen Rose?	LA	Nachitoches	0,1			0,36	288	30	360	0,75		Mancini et al., 2006
4	17069202330000	-9 653	Mooringsport	LA	Natchitoches	1	0,05	0,1	0,13	437	10	13	0,32	1,0	Mancini et al., 2006
4	17069202330000	-15 413	Sligo	LA	Natchitoches	0,23	0,04	0,04	0,07	369	17	30	0,49	1,37	Mancini et al., 2006
5	17061000860000	-3 645	Washita?	LA	Lincoln	0,83	0,11	0,38	0,4	430	46	48	0,22	0,58*	Dennen et al., 2010
6	17013002630000	-7 301	Rodessa	LA	Bienville	0,46	0,04	0,17	0,39	413	37	85	0,19	1,14	Mancini et al., 2006
7	42005301090000	-7 455	Fredericksburg Group	TX	Angelina	0,65	0,32	0,81	0,27	437	125	42	0,28	0,71*	Dennen et al., 2010
8	42073306790000	-7 900	Glen Rose?	TX	Cherokee	0,5	0,1	0,38	0,11	437	76	22	0,21	0,71*	Dennen et al., 2010
9	42021008260000	-6 369	Del Rio	TX	Bastrop	4,63	1,42	23,35	0,68	431	504	15	0,06	0,6*	Dennen et al., 2010
10	42029026910000	-4 133	Bexar	TX	Bexar	0,99				427	178	124			Thompson and Kennicutt, 1992
10	42029026910000	-4 136	Bexar	TX	Bexar	0,71				419	80	146			Thompson and Kennicutt, 1992
10	42029026910000	-4 140	Bexar	TX	Bexar	1,33				431	289	89			Thompson and Kennicutt, 1992
11	42283002040000	-9 852	Georgetown–Austin	TX	La Salle									0,97	Price and Clayton, 1990
12	42325017440000	-3 895	Bexar	TX	Medina	1,66				424	430	36			Thompson and Kennicutt, 1992
13	42323000920000	-1 377	Del Rio	TX	Maverick	0,54	0,24	0,36	0,29	423	67	54	0,4	0,45*	Dennen et al., 2010

Depths in ft below surface; TOC, wt.% total organic carbon; S1, S2, mg hydrocarbons/g rock; S3, mg CO2/g rock; Tmax in °C; HI, hydrogen Index (S2*100/TOC); OI, Oxygen Index (S3*100/TOC); PI, Production Index (S1/(S1+S2)). Ro in %; *Calculated Ro = 0.0180 x Tmax - 7.16 (Jarvie et al., 2001).

Table 1. Rock-Eval and vitrinite reflectance data available for lithologies in the Greater Gulf Basin Lower Cretaceous Shale Gas AU.

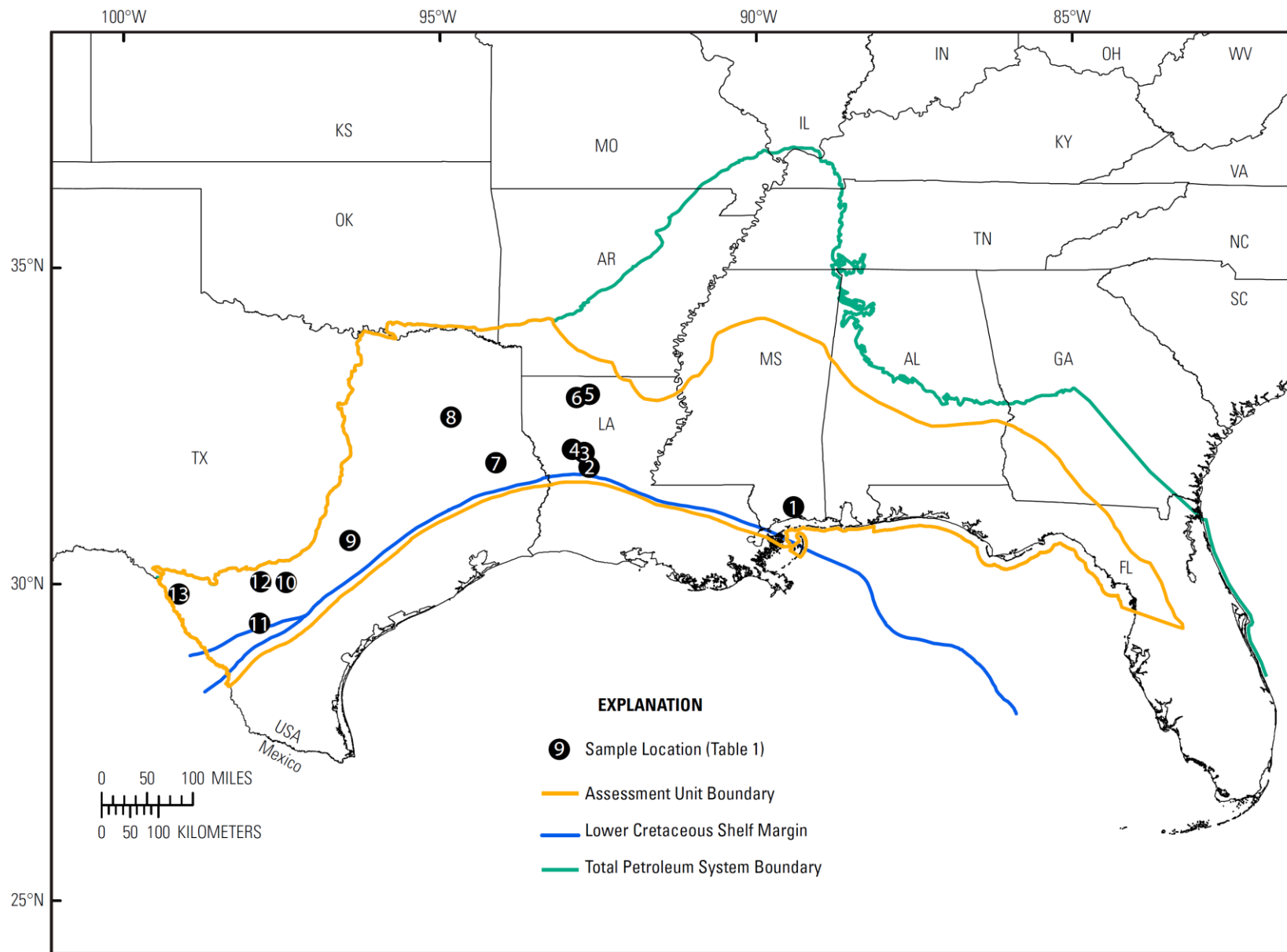


Figure 13. Map showing location of samples from which geochemical data are available.

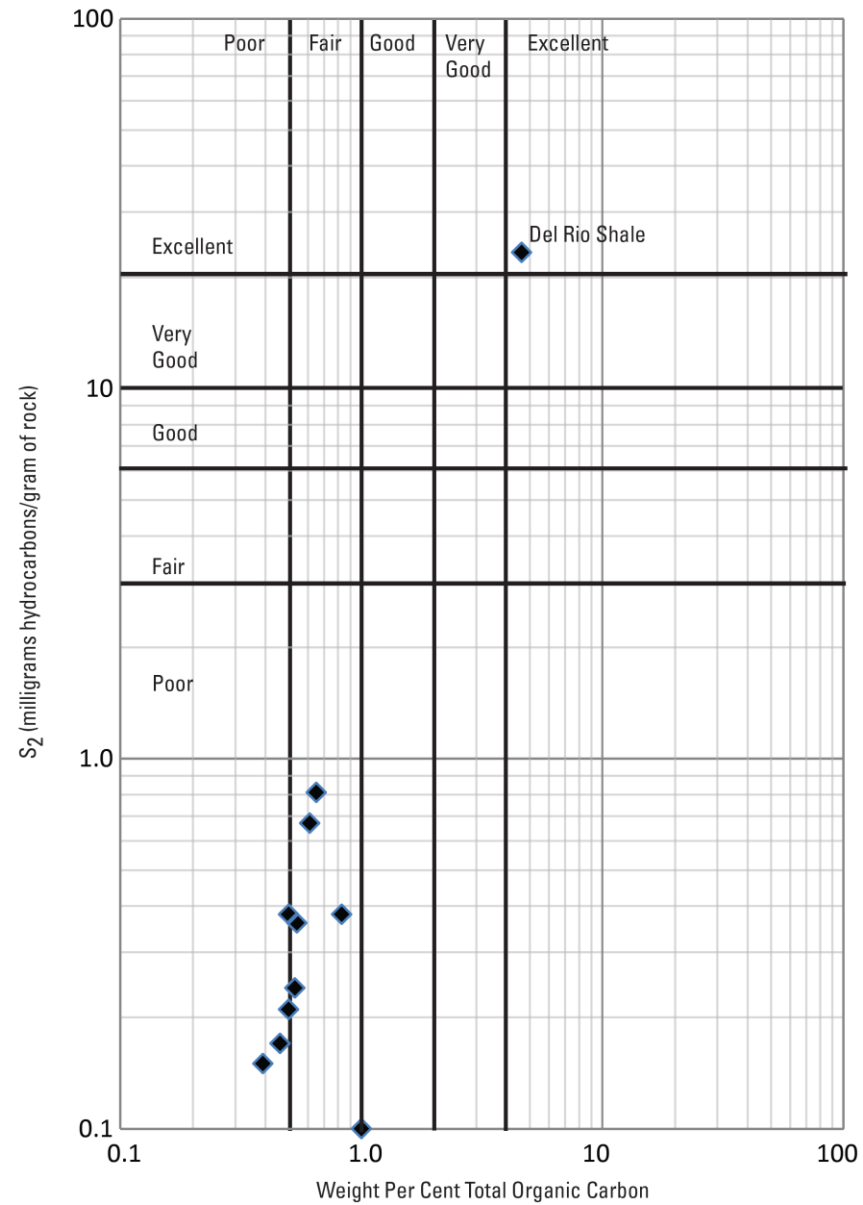


Figure 14. Cross plot of S₂ (milligrams hydrocarbons/gram of rock) versus wt.% total organic carbon content and favorable values for potential source rocks (modified from Peters and Cassa, 1994; Edman and Pitman, 2010).

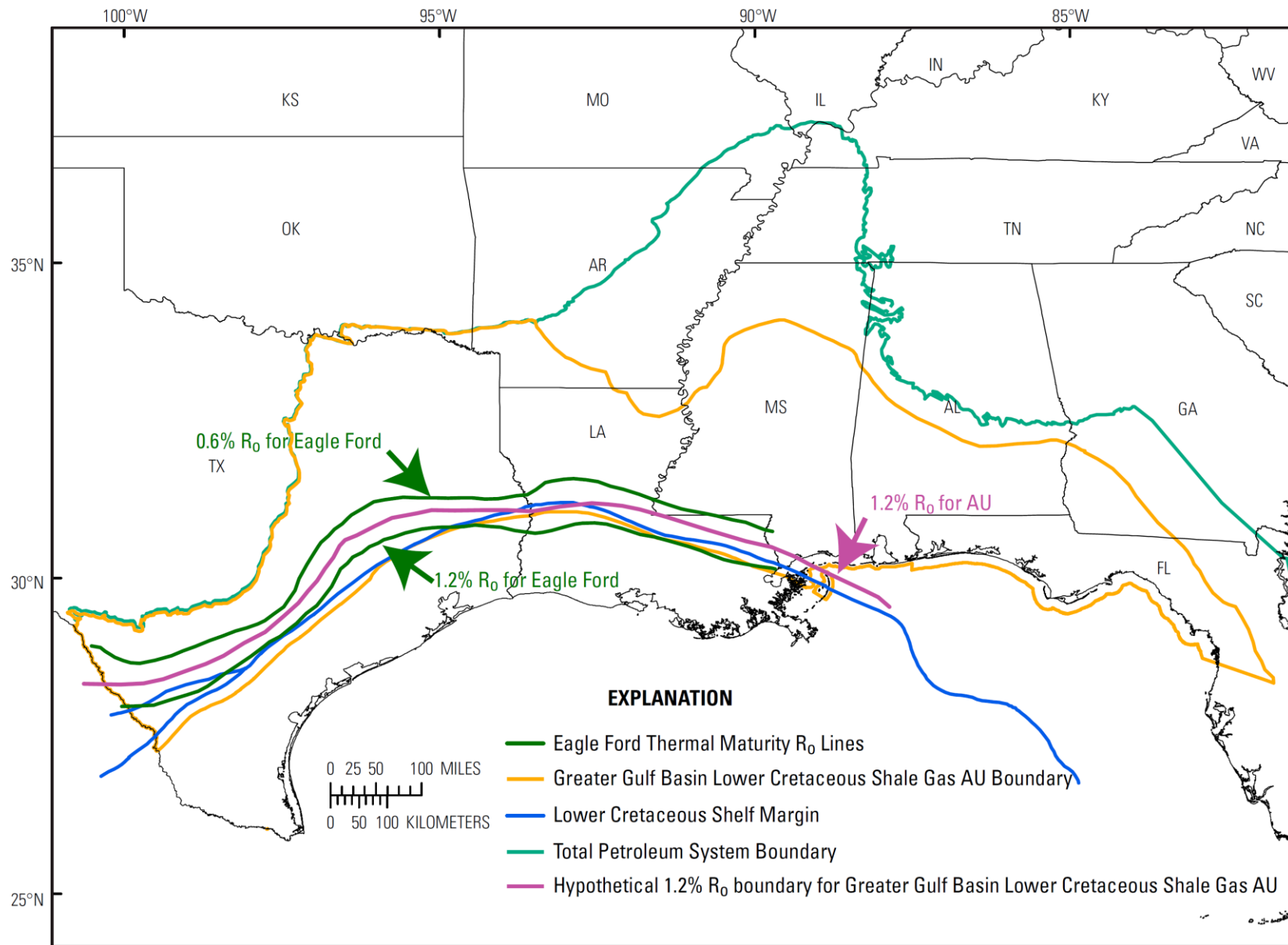


Figure 15. Hypothetical boundary for $R_0 > 1.2\%$ in the Greater Gulf Basin Lower Cretaceous Shale Gas AU, using modelling data from the overlying Eagle Ford Shale (Dubiel et al., 2012). Placement of the $R_0 > 1.2\%$ boundary also considers R_0 data from Enomoto et al. (2012).

Overview of Exploration and Production History

At the time of the 2010 assessment there were no continuous gas production data available for any of the formations in the Greater Gulf Basin Lower Cretaceous Shale Gas AU. However, conventional reservoirs have been productive from the Sligo Formation, and Trinity, Fredericksburg, and Washita groups since the early days of Gulf hydrocarbon exploration (Nehring Associates, 2009). For example, conventional Sligo Formation clastic reservoirs have produced oil and gas in the Mississippi Interior Salt Basin since the 1920s, and conventional Sligo carbonate reservoirs are present throughout the East Texas Basin and eastward into northern Louisiana and southern Arkansas (Nehring Associates, 2009). Oil and gas have been producing from the James Limestone of the Pearsall Formation in the East Texas Basin, northern Louisiana, and from deep reservoirs in southern Mississippi. Conventional production from interbedded transgressive shoreface sands in the Pine Island Shale includes the West Raymond Field in Hinds County, Mississippi (Warner and Moody, 1992), some production in Florida (Applegate and Lloyd, 1985), and production from the Hogg Sand Member in southern Arkansas (Clanton, 1967). Undiscovered conventional hydrocarbon resources from these and other units in the Lower Cretaceous were separately assessed (Dubiel et al., 2010, 2011). At the time of the 2010 assessment, there was no indication of the presence of biogenic gas in the Greater Gulf Basin Lower Cretaceous Shale Gas AU.

Summary and Suggestions for Future Work

As part of a 2010 assessment of undiscovered hydrocarbon resources in the onshore northern Gulf of Mexico Mesozoic section, the USGS defined but did not quantitatively assess a Greater Gulf Basin Lower Cretaceous Shale Gas AU. The AU was defined because of the potential for future continuous “shale” gas production in the Lower Cretaceous section, but was not assessed due to the lack of current hydrocarbon production and the absence of lithologic data necessary for a quantitative assessment. To provide a quantitative assessment of the potential volumes of recoverable hydrocarbons from continuous shale reservoirs, the following information is needed: 1) extent of reservoir; 2) thickness and lithology of reservoir rocks, 3) total organic carbon content of the potential reservoir rocks, 4) depth of the reservoir, 5) thermal maturity of the reservoir rocks, 6) well production data and indication of gas shows, 7) pressure data, and 8) estimated ultimate recoveries per well (Charpentier and Cook, 2010). Accurate prediction of undiscovered continuous hydrocarbon resources in the Greater Gulf Basin Lower Cretaceous Shale Gas AU will require these data sets to be developed and refined through future research efforts and through industry exploration and production. Ongoing research on continuous resources within the stratigraphic limits of the Greater Gulf Basin Lower Cretaceous Shale Gas AU includes investigation of the organic geochemistry and thermal maturity of the Pearsall Formation in the central and eastern Gulf Coast area (Enomoto et al., 2012). The preliminary work of Enomoto et al. (2012) has suggested poor regional prospectivity for shale gas in the Pearsall due to low thermal maturity and low TOC content. However, their work has also suggested potential focus areas for further research, including the deep downdip Pearsall section in the southern Mississippi Interior Salt Basin. Other prospective units that should be investigated in the Greater Gulf Basin Lower Cretaceous Shale Gas AU include the McKnight/Kiamichi Shale and Del Rio Shale in the Maverick Basin where shale units are thicker and thermal maturity is higher. In future work, horizontal drilling, hydraulic fracturing activities and production information from wells confirmed to be producing from “shale” units in the AU should be compiled and monitored. The reservoir character of “shale” units in higher thermal maturity zones close to the

Cretaceous shelf edge also should be investigated. Finally, thermal maturity and organic-richness data are needed from throughout the spatial extent of the AU to determine the viability of “shale” units for commercial production.

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