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Geologic Assessment of Undiscovered Oil and Gas Resources—Lower Cretaceous Albian to Upper Cretaceous Cenomanian Carbonate Rocks of the Fredericksburg and Washita Groups, United States Gulf of Mexico Coastal Plain and State Waters

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All depths given in report refer to depths below the surface.

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Abstract

In 2010, the U.S. Geological Survey (USGS) assessed Lower Cretaceous Albian to Upper Cretaceous Cenomanian carbonate rocks of the Fredericksburg and Washita Groups and their equivalent units for technically recoverable, undiscovered hydrocarbon resources underlying onshore lands and State Waters of the Gulf Coast region of the United States. This assessment was based on a geologic model that incorporates the Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System (TPS) of the Gulf of Mexico basin; the TPS was defined previously by the USGS assessment team in the assessment of undiscovered hydrocarbon resources in Tertiary strata of the Gulf Coast region in 2007. One conventional assessment unit (AU), which extends from south Texas to the Florida panhandle, was defined: the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU. The assessed stratigraphic interval includes the Edwards Limestone of the Fredericksburg Group and the Georgetown and Buda Limestones of the Washita Group. The following factors were evaluated to define the AU and estimate oil and gas resources: potential source rocks, hydrocarbon migration, reservoir porosity and permeability, traps and seals, structural features, paleoenvironments (back-reef lagoon, reef, and fore-reef environments), and the potential for water washing of hydrocarbons near outcrop areas.

In Texas and Louisiana, the downdip boundary of the AU was defined as a line that extends 10 miles downdip of the Lower Cretaceous shelf margin to include potential reef-talus hydrocarbon reservoirs. In Mississippi, Alabama, and the panhandle area of Florida, where the Lower Cretaceous shelf margin extends offshore, the downdip boundary was defined by the offshore boundary of State Waters. Updip boundaries of the AU were drawn based on the updip extent of carbonate rocks within the assessed interval, the presence of basin-margin fault zones, and the presence of producing wells. Other factors evaluated were the middle Cenomanian sea-level fall and erosion that removed large portions of platform and platform-margin carbonate sediments in the Washita Group of central Louisiana. The production history of discovered reservoirs and well data within the AU were examined to estimate the number and size of undiscovered oil and gas reservoirs within the AU. Using the USGS National Oil and Gas Assessment resource assessment methodology, mean volumes of 40 million barrels of oil, 622 billion cubic feet of gas, and 14 million barrels of natural gas liquids are the estimated technically recoverable undiscovered resources for the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU.

Introduction

In 2010, the U.S. Geological Survey (USGS) completed an assessment of hydrocarbon resources for Jurassic and Cretaceous strata in the onshore and State Waters of the U.S. Gulf Coast (Dubiel and others, 2010, 2011) (fig. 1, table 1). The assessment was based on geologic elements of a total petroleum system (TPS), which included investigations of hydrocarbon source rocks (thermal maturation, hydrocarbon migration patterns), the character of reservoir rocks, and the presence or absence of hydrocarbon traps and seals. The Upper Jurassic-Cretaceous-Tertiary Composite TPS defined previously in the 2007 assessment of hydrocarbon resources in Tertiary strata of the U.S. Gulf Coast (Dubiel and others, 2007) was used in the 2010 assessment of hydrocarbons in Jurassic and Cretaceous strata (Dubiel and others, 2010) (fig. 2). The assessment of Jurassic and Cretaceous strata in 2010 updated portions of the 1995 USGS assessment of stratigraphic intervals in the Gulf Coast region (Schenk and Viger, 1996). “Gulf Coast region” in this paper refers to onshore and State Water areas of the northern U.S. Gulf of Mexico basin, spanning the area from south Texas to the Florida panhandle.

The purpose of this study was to assess the oil and gas resource potential of the carbonate rocks of the Lower Cretaceous (Albian) to Upper Cretaceous (Cenomanian) Fredericksburg and Washita Groups and equivalent units (fig. 3) for conventional undiscovered hydrocarbons (Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU; Dubiel and others, 2011; Swanson and others, 2013). Siliciclastic rocks were assessed separately in the Albian Clastic AU and in the Updip Albian Clastic AU (Dubiel and others, 2011). The interval assessed herein included productive reservoirs in the Edwards, Georgetown, and Buda Limestones. Numerous equivalent carbonate rocks of the Fredericksburg and Washita Groups were also examined, spanning the area from southern Texas to the western panhandle of Florida (fig. 3).

One conventional assessment unit was defined for the stratigraphic interval, which was assessed on the basis of a geologic model incorporating depositional systems, source-rock potential, potential migration pathways, structural features (faults, salt domes), porosity and permeability of reservoir rocks, the potential for water washing of hydrocarbons, and the presence of hydrocarbon producing wells and reservoirs (based on data from Nehring Associates, Inc., 2009; IHS Energy Group, 2009). Continuous accumulations were not assessed within the stratigraphic intervals defined above. The geologic model and assessment process are described in this report.

Assessment Methods

Two proprietary, commercially available databases were used in the assessment. One database (Nehring Associates, Inc., 2009) contained reserves, cumulative production, and other types of information for most oil and gas fields of the United States larger than 0.5 million barrels of oil equivalent (MMBOE). The data used were current as of December 31, 2007. The second database (IHS Energy Group, 2009) contained drilling, well completion, and hydrocarbon production data. Assessments were conducted using USGS methodology (Klett and others, 2003, 2005; Charpentier and Klett, 2004).

Stratigraphy of the Fredericksburg and Washita Groups

Introduction

The stratigraphic units described in this report were originally included in the “Comanche series,” a term first used by Hill (1887) to indicate Lower Cretaceous rocks in the area of Comanche, Texas. Hill (1891) provided some of the earliest descriptions of the Lower Cretaceous based on outcrops in north-central Texas. Hill (1887) identified three distinct divisions within the Comanche series in Texas: the Trinity, Fredericksburg, and Washita Groups (fig. 3). Early studies determined that sediments of the Comanche series were nearshore or of epicontinental, shallow-water origin (Adkins, 1932). Later studies described this series of sediments as the Comanche platform, a shallow-water, medium- to high-energy marine platform containing carbonate grainstone, and rudist bioherms and biostromes (Fisher and Rodda, 1969; fig. 4). More recently, the Comanche platform was found to be composed of about seven platforms that developed during separate progradational events (Scott, 1990), with successive shelves separated by deeper water facies (Scott, 1993).

Fossil groups have been used to correlate the Lower Cretaceous section. Imlay (1945) used ammonites to trace outcropping strata into the subsurface and correlate with microfossil zones in well cuttings. Additional studies of ammonite zonations of Lower Cretaceous sediments, such as Young (1978), provided a basis for improved correlations in Texas and Mexico.

Boundaries and Subdivisions of the Lower and Upper Cretaceous Section

The base and top of the Lower Cretaceous section in the Gulf of Mexico basin do not always coincide with lithostratigraphic boundaries, regional unconformities, or hiatuses (McFarlan and Menes, 1991). Along the northern flank of the Gulf of Mexico basin, a regional unconformity of middle Cenomanian age marks the end of widespread carbonate deposition and the beginning of a cycle in which terrigenous clastic sediment was more dominant (McFarlan and Menes, 1991). The boundary between the Lower and Upper Cretaceous was commonly placed at this unconformity in earlier studies, even though the uppermost beds below it were of Late Cretaceous (early Cenomanian) age (McFarlan and Menes, 1991).

Fredericksburg Group and Equivalent Units of the Western Gulf Coast

Nomenclature and Subdivisions

Across the northern rim of the Gulf of Mexico basin, the Glen Rose Limestone is unconformably overlain by the Fredericksburg Group or equivalent formations, which are composed of limestones of continental shelf origin with a transgressive onlapping pattern (McFarlan and Menes, 1991) (fig. 3). In south Texas, the Fredericksburg Group is subdivided into the West Nueces Formation (limestones) and McKnight Formation (evaporites and limestones) in the Maverick basin (Rose, 1972; McFarlan and Menes, 1991) (fig. 5*A*). The Edwards Limestone is composed of the Kainer Formation (massive dolomitic micrites) (Edwards Limestone B of Fisher and Rodda, 1969; fig. 5*B*) and Person Formation (limestone and dolomite collapse breccias) (Edwards Limestone A of Fisher and Rodda, 1969; Rose, 1972) on the San Marcos arch (Rose, 1972; McFarlan and Menes, 1991) (fig. 3). The Edwards Limestone has been placed within the Fredericksburg Group in many previous studies (Lozo and Smith, 1964; Rose, 1972; Zahm and others, 1995; Mancini and others, 2008). Other studies have suggested that the Edwards Limestone extends throughout both the Fredericksburg and Washita Groups, in the San Marcos platform area (Chenault and Lambert, 2006).

In Texas, the Edwards Limestone is a wedge that thickens southward from 400 feet (ft) in west-central Texas to more than 650 ft in areas approaching the Devils River platform (fig. 4*B*) (Rose, 1972). Udden (1907) first introduced the name Devils River Formation in southwest Texas as an equivalent of the Edwards Limestone in central and northern Texas. Lozo and Smith (1964) refined the area suggested by Udden (1907) for the Devils River Formation, restricting it to the northern rim of the Maverick basin, where Fredericksburg and Washita Groups were not separable. Kerans (2002) provided an interpretative map of the paleogeography of the Comanche shelf in southwest Texas for late Albian time, showing the location of the Devils River platform (fig. 4*B*). In this report, we use USGS nomenclature “Devils River Limestone” for the Devils River Formation defined previously (Udden, 1907; Lozo and Smith, 1964; Kerans, 2002). The evaporites and limestones of the McKnight Formation (McKnight lagoon of Fisher and Rodda, 1969) interfinger with the caprinid mounds and miliolid limestones of the Devils River Limestone (Smith, 1981) (fig. 3). The Kainer and Person Formations grade into the cyclic platform-margin accumulations mapped as the Devils River Limestone.

Lower Cretaceous shelf margin carbonate rocks of Aptian, Albian, and Cenomanian age accumulated in a nearly continuous belt that encircled the entire Gulf of Mexico basin (Bebout and Loucks, 1974). The shelf margin carbonate rocks in the subsurface of south Texas, extending for more than 250 miles (mi) across south Texas, have been commonly referred to as the Stuart City reef trend; these shelf margin rocks are equivalent to the Stuart City Formation (fig. 3) (Bebout and Loucks, 1974). Winter (1961) defined the Stuart City Formation as reef rocks that were equivalent to the Edwards and Glen Rose Limestones in south Texas; this terminology was later followed by Bebout and Loucks (1974). Galloway (2008) used the term “Stuart City reef” to indicate the reef shelf margin of the Fredericksburg Group that extended across the entire Gulf Coast region. In this report, we use “Stuart City Formation” to indicate Fredericksburg Group or Trinity Group (Glen Rose Limestone) shelf margin rocks that extend across the entire Gulf Coast region (fig. 3). We also refer to the “Edwards Limestone of the Stuart City Formation.”

The Edwards Limestone of the Stuart City Formation started to develop at about 107 mega-annum (Ma); drowning of the shelf margin occurred at about 104.3 Ma (Scott, 1993). By middle Albian time, the Edwards Limestone of the Stuart City Formation accumulated up to about 3,900 ft thick and extended around the entire Gulf of Mexico basin (Scott, 1993).

Regional Dense Marker Bed, Edwards Limestone

In earlier studies, the Kiamichi Formation of north Texas was interpreted to be equivalent to the stratigraphic middle of the Edwards Limestone in central Texas, where it was referred to as the Dr. Burt zone of Fisher and Rodda (1969) or the Regional Dense Marker Bed (RDMB) (Tucker, 1962; Fisher and Rodda, 1969; Rose, 1972) (figs. 3, 5*A*). The upper, oil-producing part of the Edwards Limestone on the San Marcos arch, known as the “Edwards Limestone A” as used by Fisher and Rodda (1969), was later referred to as the Person Formation (Rose, 1972) (fig. 3). The lower “Edwards Limestone B” as used by Fisher and Rodda (1969) was later referred to as the Kainer Formation (Rose, 1972), which consists of a lower dolomitic unit and upper grainstone unit (Rose, 1972). Studies in south Texas and northern Mexico correlated the RDMB (or Dr. Burt zone) with the lowest part of the Washita Group (Chenault and Lambert, 2005; Osleger and others, 2004) (fig. 3), suggesting that it is correlative with the Kiamichi Formation. In contrast, Waite and others (2007) used wireline log signatures to correlate an algal boundstone unit within the Edwards Limestone of the Stuart City reef to the RDMB of the San Marcos platform interior; these results suggested that the RDMB is in the middle part of the Fredericksburg Group and that it is not correlative to the Kiamichi Formation of north Texas (Waite and others, 2007). The correlations of Chenault and Lambert (2005) and Osleger and others (2004) were used to place the RDMB in figure 3.

Fredericksburg Group and Equivalent Units of the Central and Eastern Gulf Coast

Nomenclature and Subdivisions

From eastern Texas to west-central Mississippi, the Fredericksburg Group is divided, in ascending order, into the Paluxy Formation and Goodland Limestone (fig. 3). Hill (1891) gave the name “Paluxy” to the sediments located in the upper part of what was then referred to as the Trinity sand. The Paluxy Formation is composed of nonfossiliferous sandstones and shales (Hill, 1894) and is overlain by the white chalky limestones and pelletal marls of the Goodland Limestone (Hill, 1891; Adkins, 1932; McFarlan and Menes, 1991). The Fredericksburg Group grades updip into mudstones, shales, and sandstones. Downdip, the Fredericksburg Group interfingers with the Stuart City Formation along the shelf margin. Figure 6 is a cross section of the Fredericksburg and Washita Groups and equivalent strata in eastern Texas.

Washita Group of the Gulf Coast

Nomenclature and Subdivisions

The deposition of the Fredericksburg Group across the northern rim of the Gulf of Mexico basin ended because of gradual inland uplift and shoreline regression, as indicated by evidence of exposure and erosion of Fredericksburg deposits (Rose, 1972; McFarlan and Menes, 1991). As the uplift and regression ceased, sediments of the Washita Group were deposited. The Washita Group includes, from oldest to youngest, the Kiamichi Formation, Georgetown Limestone, Grayson Shale (equivalent to the Del Rio Clay in the western Gulf Coast), Buda Limestone, and Maness Shale (fig. 3).

Although earlier studies placed the Kiamichi Formation in the upper part of the Fredericksburg Group (Adkins, 1932), more recent studies place it in the lower part of the Washita Group (Anderson, 1980; Ambrose and others, 2009). The Kiamichi Formation is a dark, calcareous clay interbedded with limestone (Nunnally and Fowler, 1954). Across the northern rim of the Gulf of Mexico basin, the platform and shallow-marine limestones of the Georgetown Limestone grade basinward into the skeletal reef limestones of the Stuart City Formation along the shelf margin (McFarlan and Menes, 1991). The Georgetown Limestone is overlain by the Del Rio Clay, a calcareous shale containing mollusks and foraminifera in central and south Texas (Rose, 1972; McFarlan and Menes, 1991). The equivalent Grayson Shale was deposited from eastern Texas to Mississippi (Adkins, 1932; McFarlan and Menes, 1991). During deposition of the Washita Group sediments, carbonate platforms were locally developed in the Chandeleur Sound area off the coast of Louisiana and Mississippi (fig. 7), the Devils River platform in Texas (fig. 4*B*), and on isolated platforms in Mexico (Scott, 1993) (fig. 4*B*).

In north-central Texas, the contact between the Grayson Shale and the overlying Buda Limestone is conformable, grading upward from calcareous claystone interbedded with nodular wackestone to wackestone (Mancini, 1982). South of this area, the contact between the Del Rio Formation and the Buda Limestone is considered to represent a maximum flooding surface (Lock and others, 2003). The Buda Limestone is the uppermost unit of the Washita Group in the western Gulf Coast region with the exception of the East Texas basin, where the Buda Limestone is conformably overlain by the Maness Shale (Ambrose and others, 2009). The contact between the Buda and the Maness is preserved in the deep central part of the East Texas basin due to syndepositional salt movement that created accommodation space that outpaced the changes in sea level (Salvador, 1991; Ambrose and others, 2009). In southern Mississippi, the Dantzler Formation, which contains shales and sandstones, overlies the Andrew Formation limestone (Mancini and others, 2008).

Middle Cenomanian Unconformity

In the northern Gulf of Mexico basin, an important regional unconformity of middle Cenomanian age marks the end of widespread carbonate deposition and the beginning of a cycle in which terrigenous clastic sediment was more abundant (McFarlan and Menes, 1991). In sequence stratigraphic studies in northeastern and south-central Texas, the top of the Washita Group has been defined by an unconformity at the base of the Woodbine Formation and equivalent units; this unconformity is referred to as the middle Cenomanian unconformity (Mancini and Scott, 2006). Further studies integrating the sequence-stratigraphic and biostratigraphic framework in the central and eastern Gulf Coast (Mancini and others, 2008) have referred to the contact between (1) the Washita Group and Tuscaloosa Formation or (2) the Washita Group and Woodbine Formation as the middle Cenomanian or middle Cretaceous sequence boundary (MCSB). This contact is considered by Mancini and others (2008) to be the same as the middle Cenomanian or MCSB of Buffler (1991) or the informal middle Cretaceous unconformity (MCU) of Buffler and Sawyer (1985). The MCSB has been correlated with a middle Cenomanian drop in sea level (Buffler, 1991).

In this report, we use the term MCU to designate the middle Cenomanian unconformity in onshore areas of the Gulf Coast of the United States. The MCU marks the base of Upper Cretaceous transgressive-regressive sequences in the central and eastern Gulf Coast (Mancini and others, 2008). In northern Louisiana, central Mississippi, and western Alabama, the MCU occurs at the top of the Washita Group, and thus at the top of the assessed interval.

The MCU is discussed in more detail in the “Depositional Framework” section of this report. Several Upper Cretaceous units overlie the MCU: the Boquillas Formation in the Devils River uplift; the Eagle Ford Group in the Maverick basin and on the San Marcos arch; the Woodbine Formation in the East Texas basin; and the Tuscaloosa Formation in Louisiana, southwestern Mississippi, southern Alabama, and the Florida panhandle (Mancini and Puckett, 2002; Lock and Peschier, 2006; Mancini and Scott, 2006; Ambrose and others, 2009) (figs. 3 and 7).

Buda Limestone

In the western Gulf Coast region, the Buda Limestone extends in the subsurface from the Rio Grande to the Mexia and Talco fault zones (fig. 7) that bounds the northern extent of the East Texas basin. The Buda Limestone extends eastward at least to the Cretaceous reef front along the south Texas Gulf Coast. Except for the East Texas basin, where it is overlain by the Maness Shale, the Buda Limestone lies at the top of the Washita Group, where it is unconformably overlain by the Eagle Ford Group and Woodbine Formation (Ambrose and others, 2009).

The Buda Limestone is mapped on the surface from northern Mexico northward to the Ouachita fold belt and westward into New Mexico (Hill, 1901; Freeman, 1964; Proctor and others, 1970; Brown and others, 1974; Lovejoy, 1976; Waechter and Barnes, 1977; Brown and others, 1979). The Buda Limestone ranges in thickness from less than 3 ft thick in northeast Texas to over 300 ft thick in the western part of Texas (Reaser and Dawson, 1995). The Buda Limestone crops out in the Balcones fault zone (fig. 7) in south-central Texas where it is folded and faulted (Ferrill and Morris, 2008). The Buda Limestone is up to 200 ft thick in the Maverick basin and approximately 300 ft thick in the East Texas basin (based on data from the IHS Energy Group, 2009). The Buda Limestone is truncated by the Sabine uplift on the eastern side of the East Texas basin (Halbouty and Halbouty, 1982) and is not found in northern Louisiana, where hundreds of feet of the Lower Cretaceous strata were removed by uplift and erosion (Galloway, 2008). The clastic Dantzler Formation is the temporal equivalent of the calcareous Buda Limestone at the top of the Washita Group, in the central and eastern Gulf Coast region (Mancini and others, 2008).

Washita and Fredericksburg Groups Undifferentiated

In southern Arkansas, northern Louisiana, and west-central Mississippi, the equivalents of the Washita Group have been referred to as “Washita undifferentiated” by Salvador and Quezada Muñeton (1991). In southeastern Mississippi, southwestern Alabama, and the western Florida panhandle, the equivalents of the Fredericksburg and Washita Groups have been referred to as the “Fredericksburg-Washita undifferentiated” by Salvador and Quezada Muñeton (1991). More recent studies provide division of the Washita and Fredericksburg Groups in the eastern Gulf coast (Mancini and others, 2008). In sequence stratigraphic studies of southern Mississippi, Mancini and others (2008) indicate that sandstones of the Dantzler Formation overlie limestone of the Andrew Formation in updip areas of the basin, whereas sandstone, siltstone, and shale of the Fredericksburg Group overlie limestone of the Andrew Formation in downdip areas of the basin (Mancini and others, 2008).

Structural Features

Introduction

The major structural features of the Fredericksburg and Washita Groups in the northern Gulf of Mexico basin are shown in figure 7. Because structural features controlled sedimentation in the Gulf of Mexico basin to a large extent, a brief summary of the geologic history of the basin is provided below.

Basement Rock—Influence on Deposition

The Gulf of Mexico basin has been described as a divergent-margin basin formed by extensional rift tectonics and wrench faulting (Winker and Buffler, 1988; Buffler, 1991; Mancini and others, 2012). From the Late Triassic to Middle Jurassic, active rifting resulted in deposition of nonmarine siliciclastic sediments and volcanic rocks in subsiding grabens (Salvador, 1991; Mancini and others, 2012), with the accumulation of thick salt deposits and crustal cooling and subsidence in the Late Jurassic and

Cretaceous (Salvador, 1991; Mancini and others, 2012). The transition from continental crust (which predates the formation of the Gulf of Mexico basin) to thick transitional crust (which was extended or intruded as a result of rifting) is related to a regional hinge zone in the basement and marks the updip limit of Louann Salt deposition (Sawyer and others, 1991; Mancini and others, 2012). The change from thick to thin transitional crust is related to a major hinge zone in the basement, which is represented by the Lower Cretaceous shelf margin (Sawyer and others, 1991; Mancini and others, 2012).

There is a pattern of alternating relict basement highs and lows within the zone of thick transitional crust (Winker and Buffler, 1988). The paleotopographic highs are thought to be continental blocks that are relicts of rifting, which have not had much extension or deformation; the lows correspond to depressions in the basement that formed due to greater crustal extension between continental blocks (Sawyer and others, 1991; Mancini and others, 2012). The Wiggins uplift in southern Mississippi is an example of a relict high, whereas the Mississippi Interior salt basin (MISB) and North Louisiana salt basin (NLSB) are examples of basement lows (Mancini and others, 2012). The major negative structural features (East Texas basin, NLSB, and MISB) in the northern Gulf of Mexico basin were actively subsiding depocenters throughout the Mesozoic and into the Cenozoic (Mancini and others, 2012).

Paleotopography—Influence on Sediment Distribution and Heat Flow

Paleotopography had a significant impact on the distribution of sediment, with positive areas providing sources for Mesozoic terrigenous sediments (Mancini and others, 2012). The Sabine uplift and Monroe uplift were major positive basement features that influenced the distribution and nature of Mesozoic deposits in the onshore central Gulf Coast (Mancini and others, 2012). Along the northern rim of the MISB, movement of the Jurassic Louann Salt (fig. 1) produced structures including salt ridges, pillows, and anticlines (Hughes, 1968).

The NLSB experienced elevated heat flow during the Cretaceous due to the reactivation of upward movement, igneous activity, and erosion associated with the Monroe and Sabine uplifts (Mancini and others, 2012). The MISB also experienced elevated heat flow associated with the igneous intrusion that formed the Jackson Dome, which affected a smaller geographic area than that of the Monroe and Sabine uplifts (Mancini and others, 2012). The difference in elevated heat flows in each of these areas resulted in thermogenic gas generation that was initiated at a depth of 12,000 ft for the NLSB and 16,500 ft for the MISB (Mancini and others, 2012).

Deposition on the broad and shallow Lower Cretaceous platform in central Louisiana and southern Mississippi was affected by local tectonic features, including the Sabine uplift, Louisiana and Mississippi salt basins, Monroe uplift, Jackson dome, and Wiggins uplift; most of these features were broad, subtle topographic highs at the time of deposition of Lower Cretaceous sediments (Yurewicz and others, 1993). Mesozoic and Cenozoic strata in the Gulf of Mexico basin were deposited as part of a seaward-dipping wedge of sediment that accumulated in differentially subsiding basins, such as the NLSB, MISB, Manila subbasin, and Conecuh subbasin (fig. 7) (Mancini and Goddard, 2004).

Depositional Framework

Fredericksburg Group and Equivalent Strata

Introduction

The Paluxy Formation (in Texas) and Dantzler Formation (in Mississippi and Alabama) are thought to represent sediments in prograding deltas and shore-zone systems that were deposited on the shelf of the East Texas basin and northeastern Gulf of Mexico during the early stages of the deposition of the Fredericksburg Group (McFarlan and Menes, 1991; Galloway, 2008) (fig. 8). Shelf limestone and dolomite of the Edwards Limestone and its equivalents accumulated on the outer shelf and transgressed landward over the shelf, deltaic, and shore-zone sediments of the Paluxy Formation later in this depositional episode (Galloway, 2008).

The deposition of the Fredericksburg Group ended with widespread accumulation of dark, calcareous claystone and interbedded lime mudstone of the Kiamichi Formation and its equivalents, suggesting that a regional deepening of the northern Gulf of Mexico shelf occurred (Galloway, 2008). Epeirogenic uplift and tilting of the landward basin margin created a minor unconformity at the base of overlying Washita Group strata (Galloway, 2008).

In the following sections, depositional systems for the Fredericksburg Group are discussed generally from west to east in the Gulf of Mexico region.

Comanche Platform—Texas and Northern Mexico

Fisher and Rodda (1969) provided an early interpretation of the paleogeography of the Edwards Limestone in Texas and northern Mexico, suggesting that carbonate grainstone and rudist bioherms, carbonate mudstone, and evaporites of the Edwards Limestone were deposited on the shallow-water, marine Comanche platform in Texas (fig. 4*A*). In their model, two areas of periodically restricted deposition developed on the Comanche platform: the Kirschberg lagoon in central Texas and the McKnight lagoon of south Texas and northern Mexico. Evaporites and shallow-water carbonate mudstone and grainstone were deposited in the Kirschberg lagoon; thin-bedded, ammonite-bearing, black shale, carbonate mudstone, and evaporites were deposited in the McKnight lagoon (Lozo and Smith, 1964; Fisher and Rodda, 1969). Rudist bioherms were thought to have developed along platform edges that were peripheral to the evaporitic lagoons. In their interpretation (Fisher and Rodda, 1969), primary dolomite deposits developed in a belt that was marginal to a lagoonal facies, perhaps as the result of the metasomatic replacement of calcium carbonate from contact with magnesium-enriched brines. Although, Fisher and Rodda (1969) indicated the presence of an extensive North Texas-Tyler basin in north Texas (fig. 4), sequence stratigraphic studies in central and north Texas (Talbert and Atchley, 2000) and maps of the paleogeography of Lower Cretaceous carbonates and depositional facies in the Gulf Coast region (Burgess and others, 1997) suggest that the North Texas-Tyler basin was actually restricted to the area covered by the East Texas basin (fig. 7).

Stuart City Reef in Texas

The Stuart City reef aggraded on the foundation of the Sligo Formation shelf-margin reef on the San Marcos arch and in the northeastern part of the Gulf of Mexico basin (Galloway, 2008). In the Rio Grande embayment, the Stuart City reef diverted westward and inland around the Maverick basin (a subsiding intrashelf basin), resulting in the formation of the Devils River trough (Winker and Buffler, 1988; Galloway, 2008). The restricted shelf in the Maverick basin has been referred to as the "McKnight salina" (Galloway, 2008; fig. 8), which is equivalent to the McKnight lagoon of Fisher and Rodda (1969). In south Texas, Waite (2009) noted that the Stuart City reef is subdivided into two portions by the Regional Dense Marker Bed (RDMB), (1) the lower Edwards ("B"), composed of a high-relief, barrier-type reef margin, possibly analogous to the modern Belize barrier reef, and (2) the upper Edwards ("A"), composed of low-relief bioherms, which may be analogous to the modern Bahamas reef-shoal reef.

Fredericksburg Group in Louisiana and Mississippi

In Louisiana and Mississippi, the Paluxy and Fredericksburg stratigraphic sequence of Yurewicz and others (1993) includes (1) a lowstand fan complex and widespread transgressive platform siliciclastic strata (Paluxy Formation) on the shelf, and (2) highstand platform siliciclastic and carbonate strata (Fredericksburg Group). Three major facies can be identified in the Fredericksburg Group highstand strata: (1) a narrow band of rudist-coral reefs and skeletal-oolitic shoals; (2) a platform-interior lagoonal facies that consists of muddy shelf carbonates that grade updip into shallow-marine and coastal-plain siliciclastic strata in Mississippi and eastern Louisiana; and (3) a slope and basin facies that consists of muddy carbonate strata (Yurewicz and others, 1993). A cross section showing Fredericksburg and Washita Group facies in north-central Louisiana is illustrated in figure 9.

During the late middle Albian, deposition of the transgressive fossiliferous limestone beds of the Andrew Formation occurred in downdip areas of the MISB (Mancini and Puckett, 2002) (fig. 10). Fluvial sandstones and shales of the Dantzler Formation overlie this middle to late Albian cycle and signal a major base-level (relative sea level) fall that is represented by the middle Cenomanian unconformity (Mancini and Puckett, 2002; 2005).

Washita Group

Introduction

The deposition of the Fredericksburg Group was terminated along the northern rim of the Gulf of Mexico basin by inland uplift and shoreline regression in the late Albian, as indicated by updip exposure during the middle to late Albian (McFarlan and Menes, 1991). Flooding of the northern rim was recorded by deposition of the shelf micritic limestones and marls of the Georgetown Limestone of the Washita Group, which grade basinward into the skeletal limestones of the Stuart City reef (McFarlan and Menes, 1991). The Washita Group depositional episode was characterized by aggradational growth of the Stuart City reef and the widespread accumulation of shallow-shelf lime mud, bioclastic sand, marl, and calcareous mud on the northern Gulf platform of Galloway (2008).

Inland uplift resulted in the deposition of marine shales (including the Del Rio Clay and Grayson Shale of the Washita Group) across the northern rim of the Gulf of Mexico basin in the early Cenomanian (McFarlan and Menes, 1991). The youngest deposits of the Washita Group episode are dominantly marine to restricted marine shale, representing partial drowning of the carbonate platform (Galloway, 2008). The shales are overlain across the northern rim of the Gulf of Mexico basin by the onlapping Buda Limestone, which resulted from flooding during the middle Cenomanian (McFarlan and Menes, 1991). The Buda Limestone is discussed in more detail below.

Buda Limestone

The Buda Limestone of the Washita Group was deposited slowly in well-oxygenated seawater in a shallow shelf area roughly parallel to the Stuart City reef (Adkins, 1932; Reaser and Dawson, 1995). Adkins (1932) divided the Buda Limestone into four facies that parallel the Stuart City reef: (1) a coral-bearing marginal facies, (2) a crystalline submarginal facies, (3) a porcelaneous facies, and (4) a rudistid-bearing facies. Martin (1967) divided the Buda outcrop of south-central Texas into a lower glauconitic, biomicrite member and an upper brittle, fossiliferous micrite member; the upper member represented a higher energy environment of deposition than that of the lower member.

Erdogan and Perkins (1970) described the northern and southern lithofacies of the Buda Limestone as being separated by a transitional zone in west and Trans-Pecos Texas. In the north, carbonate grainstone and packstone lithofacies represent a shallow (0 to 30 ft deep) nearshore-marine environment. The transitional zone is dominated by wackestone and packstone lithofacies and represents a deep (20 to 100 ft) open-shelf environment. In the south, carbonate mudstone and wackestone lithofacies represent a relatively quiet deep-water (100 to 300 ft) environment with patch reefs on structurally high areas. In northeast Texas, the Buda Limestone was deposited in an open seaway; its lithology varies from very fine grained limestone to marl (Dawson and Reaser, 1991).

Middle Cenomanian (Post-Comanchean) Erosion in Northern and Central Louisiana

Cullom and others (1962) observed that from 700 to 1,200 ft of section of the platform limestones deposited in northern and central Louisiana during deposition of the Fredericksburg and Washita Groups were removed through erosion as a result of post-Comanchean uplift on the southern flank of the Southern Arkansas uplift (fig. 7). Berryhill and others (1968) noted that the Fredericksburg and Washita Groups in all of northern Louisiana and most of central Louisiana were exposed to erosion as a result of uplift from the eastern part of the East Texas basin to west-central Mississippi. Projecting from subsurface data in west-central Louisiana, Berryhill and others (1968) suggested that from 1,250 to 2,500 ft of section were removed from the Sabine uplift during this event. Mancini and Goddard (2004) demonstrated that the Fredericksburg and Washita strata are completely absent in northern Louisiana and partially removed in central Louisiana. Mancini and others (2012) suggested that the Comanchean/Sub-Gulfian (Middle-Cenomanian) erosional unconformity removed parts of the Trinity, Fredericksburg, and Washita Groups in the northern part of the NLSB, perhaps as the result of the reactivation of upward movement of the Sabine and Monroe uplifts, as well as uplift on the northern flank of the Gulf of Mexico basin.

The middle Cenomanian unconformity (MCU) previously has been attributed to a middle Cenomanian fall in sea level (Buffler, 1991; Yurewicz and others, 1993; Reaser and Dawson, 1995). Galloway (2008), however, suggested that global sea-level change played a minor role in the formation of the MCU and that uplift and tilting of the San Marcos arch, Sabine uplift, and Monroe uplift resulted in the removal of much of the Lower Cretaceous section, which in turn resulted in an angular discordance across the MCU. In this model (Galloway, 2008), the uplift was coincident with and followed by an influx of sandy sediments from fluvial systems that drained eastern continental uplands over a period of 8 million years (m.y.).

Carbonate and Siliciclastic Deposition in the Eastern and Central Gulf Coast Region

Sequence stratigraphic studies indicate that sediment accumulation in the eastern and central Gulf Coast region during the Early Cretaceous included a mix of carbonate and siliciclastic sediments in continental-shelf to slope settings (Mancini and others, 2008). Siliciclastic sediments were deposited in proximity to the source terranes that were typical of the eastern Gulf Coast region, whereas carbonate sediments characterized the western Gulf Coast region (Mancini and others, 2008). The MISB experienced greater accommodation and siliciclastic sediment supply during the late Albian and early Cenomanian than areas in Texas or Louisiana (Mancini and Puckett, 2002). In the MISB, a rise in base level and an increase in shelf accommodation in the late middle Albian resulted in deposition of the fossiliferous limestone beds of the Andrew Formation in downdip areas (Mancini and Puckett, 2002). In southern Mississippi and the near offshore area, the Washita Group includes calcareous shale, limestone, and sandy shale (Mancini and others, 2008). Mancini and Goddard (2004) indicated that Lower Cretaceous sediments are predominantly siliciclastic in the Conecuh and Manila subbasins.

Hydrocarbon Source Rocks

Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System

Introduction

The assessment was based on geologic elements of the Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System (TPS) as defined in the 2007 USGS assessment of Tertiary strata (Dubiel and others, 2007). This composite TPS includes source rocks of Late Jurassic (Oxfordian and Tithonian), Early Cretaceous (Aptian), Late Cretaceous (Turonian), and Tertiary (Paleocene and Eocene) ages (McDade and others, 1993; Wenger and others, 1994).

Source Rocks

The hydrocarbons that have been produced from onshore Lower Cretaceous reservoirs were probably sourced from: (1) Jurassic rocks of Tithonian age (Wenger and others, 1994) and Oxfordian age (Smackover Formation) (Sassen, 1989; Wenger and others, 1994); (2) Lower Cretaceous rocks of Aptian age (Illich and others, 1999); and (3) Upper Cretaceous rocks of Turonian age (Wenger and others, 1994; Illich and others, 1999; Illich and others, 2009). Illich and others also mentioned the possibility of Tertiary (Paleogene) formations as a potential source rock (Illich and others, 2009). The USGS Assessment Team previously suggested that oil produced from Lower Cretaceous reservoirs onshore was sourced from Jurassic source rocks and upper Cretaceous source rocks (Eagle Ford Formation) (M.D. Lewan, USGS, written commun., 2009). Basin modeling indicated that the timing of gas generation from the cracking of Smackover Formation Oxfordian oil was appropriate to charge Lower Cretaceous reservoirs across the Gulf Coast with gas (Lewan, 2002). Figure 11 is a map showing an interpretation of the extent of source-rock intervals based on the geochemistry of produced oils (modified from Wenger and others, 1994; Hood and others, 2002). A study of the bulk chemistry and stable-carbon and hydrogen-isotope compositions of gases from shelf-margin Stuart City Formation reservoirs by Illich and others (2009) suggested that several gas families may be represented in the shelf-margin trend and are possibly sourced from (1) a basinal facies of the Stuart City reef, a seaward facies of the Eagle Ford Group; and (2) a combination of the Edwards Limestone and younger sources, including a Paleogene source.

Studies of oil characterization and thermal-maturation history modeling in the NLSB and MISB (Claypool and Mancini, 1989; Mancini and others, 1999) suggested that Paleocene to Eocene shale and lignite beds were not subjected to favorable burial and thermal maturation histories that are required for petroleum generation (Mancini and others, 2012). Shale beds in the Upper Cretaceous Tuscaloosa Formation have been found to be an effective local petroleum source rock in part of the MISB, but not in the NLSB (Mancini and others, 2012). Upper Jurassic strata and Lower Cretaceous lime mudstone and shale beds are possible source beds in parts of the NLSB and MISB (Mancini and others, 2012). The organic-rich and laminated lime mudstone beds of the Smackover Formation are the source rocks for most of the oils in these areas (Claypool and Mancini, 1989; Mancini and others, 2003).

Vitrinite-reflectance and pyrolysis (Rock-Eval) data of potential source rocks for Lower Cretaceous reservoirs are available in a variety of publications. Dennen and others (2010) compiled thermal maturity data for more than 1,900 samples of Mesozoic and Tertiary rock core and coal samples in the Gulf of Mexico area. Thermal maturity data for Jurassic and (or) Cretaceous rock samples (not including coal samples) are found in the following reports: Mancini and others (2006), for Smackover Formation samples in Alabama, Mississippi, and Louisiana; Price and Clayton (1990), for Jurassic and Cretaceous samples in south Texas; Price (1982), for Cretaceous samples in Texas; Price (1989), for Cretaceous and Eocene samples in Louisiana; and Wagner and others (1994), for Cretaceous and Paleogene samples from offshore areas of Mississippi. McDade (1992) provided extensive thermal maturity data for Cretaceous, Paleocene, and Eocene samples in Louisiana.

Hydrocarbon Migration Pathways

Hydrocarbons generated in Jurassic-age source rocks apparently migrated along major fault systems and salt structures (fig. 7) into overlying traps, filling the Lower Cretaceous reservoirs (Fritz and others, 2000; Hood and others, 2002). Figure 12 shows a general model (modified from Sassen, 1990; M.D. Lewan, USGS, written commun., 2006) for migration pathways from source-rock formations in Louisiana.

In the NLSB, hydrocarbon expulsion and migration from Smackover Formation source rocks started in the Early Cretaceous and continued into the Tertiary (Mancini and others, 2012). Modeling studies suggested that Smackover hydrocarbons were first generated and expelled in the Early Cretaceous (from the southern part of the NLSB) followed by migration of these hydrocarbons updip into the Sabine uplift, Monroe uplift, and northern parts of the Gulf of Mexico basin (Mancini and others,

2012) (fig. 7). The migration of Smackover hydrocarbons into overlying strata may have been facilitated by vertical migration along faults (Mancini and others, 2012).

The faults that define the northern and eastern boundaries of the southern part of the MISB are thought to result from downslope movement of the Late Jurassic Louann Salt and thus coincide with the updip limit of the salt unit (Evans, 1987). Stacked reservoirs in more than one formation in the southern part of the MISB probably resulted from vertical migration associated with the faulting caused by growth or withdrawal of the Louann Salt (Evans, 1987). Evans (1987) suggested that oil in the sandstone reservoirs of the Fredericksburg and Washita Groups on the flank of the Monroe uplift in the southern part of the MISB may be the result of horizontal or intrastratal migration from shales of the Tuscaloosa Formation. In a study of the Word field within the Edwards Limestone of the Stuart City Formation shelf margin in Texas, Fritz and others (2000) suggested that subsurface fluids moving along faults associated with the underlying Sligo Formation shelf margin were important mechanisms for porosity enhancement as well as hydrocarbon emplacement.

Reservoir Rocks

Introduction

Hydrocarbon production in the carbonate rocks of the Fredericksburg and Washita Groups has occurred primarily in the western Gulf Coast region. In south Texas, hydrocarbon production from the Edwards Limestone can be divided into two general categories: (1) updip oil production from three major fault zones (fig. 13) and (2) deep gas production in the Stuart City reef (shelf margin) (Galloway and others, 1983) (fig. 14). Secondary dissolution porosity and reservoir heterogeneity, resulting from porous units that interfinger with nonporous wackestone, are important in the evaluation of reservoir potential. Hydrocarbon discoveries primarily in the Edwards Limestone and equivalent units have occurred in the (1) Luling fault zone, (2) Charlotte-Jourdanton fault zone, (3) Karnes fault zone, (4) Lower Cretaceous shelf margin (Stuart City reef), and (5) Sabine uplift (fig. 7). Each of these areas is discussed below. Reservoirs in the Georgetown and Buda Limestones are also discussed. Finally, general characteristics of reservoirs in the Edwards, Georgetown, and Buda Limestones are listed in table 2 (based on data from Nehring Associates, Inc., 2009).

Fault Zones

Luling Fault Zone

The first discovery in the Luling fault zone (fig. 7) was in 1922; discoveries in the Larremore, Salt Flat, and Darst Creek fields (fig. 13) were made by 1929, in areas where the top of the Lower Cretaceous Edwards Limestone is less than 2,600 ft deep (Cook, 1979). The Darst Creek field is typical of the Luling trend, with oil in reservoirs of the Edwards Limestone trapped on the upthrown side of down-to-the-basin faults of middle Tertiary age (Cook, 1979). The dense Georgetown Limestone (fig. 3) serves as the top seal for the reservoir in the Edwards, and shales of the Upper Cretaceous Taylor Group (fig. 1) form the lateral seal across the fault (Cook, 1979). The upper 50 ft of the Edwards Limestone is the primary reservoir, but reservoirs in the overlying Upper Cretaceous Buda Limestone, Austin Group, and Taylor Group also have been productive at Darst Creek (Cook, 1979) (figs. 1 and 3). The Edwards Limestone in the Luling trend is a leached, porous dolomite and dolomitic limestone that was deposited in tidal-flat and shallow-marine environments (Cook, 1979). Because of the complex diagenetic history of the limestone and the occurrence of chert, reservoir quality is variable.

Charlotte-Jourdanton Fault Zone

The Charlotte-Jourdanton fault zone (fig. 7) also has been referred to as the Atascosa trough (Cook, 1979; Galloway and others, 1983) and Charlotte fault zone (Kosters and others, 1989). The fault zone is composed of a series of en echelon grabens, which are interpreted to have been subsiding during deposition of Lower Cretaceous rocks (Rose, 1972; Cook, 1979). Shallow-marine and tidal-flat carbonate rocks of the Edwards Limestone are predominant in this area (Cook, 1979). Production in the Charlotte-Jourdanton fault zone began with the Imogene field discovery in 1942 (fig. 13), and most fields in the Charlotte-Jourdanton trend are characterized by the overlap of two major en echelon faults (Cook, 1979). The Jourdanton field is typical of those associated with the Charlotte-Jourdanton fault zone (fig. 15); in this field, Edwards Limestone reservoirs are trapped against up-to-the-basin faults, with a maximum throw of 600 ft at depths of 7,300 ft (Cook, 1979). Most reservoirs in the Charlotte-Jourdanton fault zone are composed of dolomitized mudstone on the upthrown side of up-to-the-basin faults; reservoirs in structural traps have about 13 percent porosity and 10 millidarcys (mD) permeability (Kosters and others, 1989).

Karnes Fault Zone

Production in the Karnes fault zone started with the Fashing field discovery in 1956 (Cook, 1979) (fig. 13). Like the Charlotte-Jourdanton fault zone, the Karnes fault zone is characterized by en echelon grabens, and shallow-marine and tidal-flat carbonate rocks of the Edwards Limestone are predominant (Cook, 1979). The Person field, discovered in 1959, is typical of the Karnes fault zone and covers an extensive area (about 12,600 acres) for 23 mi along strike (Cook, 1979). Production in the Person field is from six zones that apparently perform as a single reservoir in the Edwards Limestone at an average depth of 11,000 ft (Cook, 1979). Reservoirs in the Person field average about 14 percent porosity and 2 mD permeability (Cook, 1979). There is also some production from the underlying Lower Cretaceous Kainer Formation (fig. 3). Dolomites form the most productive reservoirs, as the result of collapse features from the solution of evaporites that led to increased porosity (Cook, 1979).

Stuart City Reef Trend

Introduction

Although the earliest drilling in the Stuart City reef trend (shelf margin) took place from 1942 to 1951, the first discovery in the reef trend was not until 1953 (Cook, 1979). Complex interbedding of porous grainstone and boundstone with nonporous wackestone has contributed to reservoir heterogeneity in the reef trend (Kosters and others, 1989). Algae-encrusted miliolid-coral-caprinid-bearing packstone, mollusk-bearing grainstone, rudist grainstone, and coral-bearing stromatoporoid boundstone are the only facies within the trend having porosities greater than 5 percent and permeabilities greater than 5 mD (Kosters and others, 1989). High primary porosities in grainstone and boundstone of the reef trend have been diagenetically reduced through cementation (Kosters and others, 1989).

Numerous fields of dry gas in the Edwards Limestone of the Stuart City Formation were discovered in the 1960s at depths of 11,000 to 14,000 ft (fig. 14). Horizontal drilling revitalized the shelf margin play in the 1990s (Waite, 2009). Reservoirs occur in combination traps along the shelf margin and have an average porosity of about 5 percent (Waite, 2009). Rudist bivalves were some of the main reef builders. Multiple geologic models may be needed to accurately characterize the entire Stuart City shelf margin, and the geologic heterogeneity may be controlled to some degree by the basement configuration, faulting, and salt-related tectonics (Waite, 2009).

Stuart City Field

The Stuart City field (discovered in 1954) is typical of those associated with the Stuart City shelf margin (fig. 14; Kosters and others, 1989), having abrupt and pronounced facies changes across the reef (Cook, 1979). The reef trend is a narrow band, and units stratigraphically higher in the section (Georgetown Limestone, Del Rio Clay, and Buda Limestone) are commonly missing over the crest of the reef (Cook, 1979). Reef facies plunge toward the platform under shallow-marine rocks that were deposited in a back-reef environment as a result of the progradation of the reef in a basinward (Gulf of Mexico) direction (Cook, 1979). Toward the basin interior, the Stuart City reef commonly contains fore-reef debris followed by calcareous mudstones deposited in deeper waters (Cook, 1979).

Washburn Ranch Field

Recognition and correlation of the RDMB (figs. 3, 5*A*), which separates Edwards "A" from Edwards "B," has been important for understanding changes and potential for production within the Stuart City shelf margin (Waite, 2009). In the Washburn Ranch field (fig. 14) of the Rio Grande embayment, the Edwards Limestone is relatively shallow (10,000 to 12,000 ft), and the pay section for gas is restricted to the upper portion of the Edwards above the RDMB (Edwards "A") (Waite, 2009). Reservoir rocks in this field consist of small bioherms with grainstone or packstone cycles, and porosity and permeability are high (Waite, 2009). Porosity includes both interparticle and vuggy porosity; vuggy porosity is formed through dissolution (Waite, 2009). Production in the Washburn Ranch field appears to be best in wells on salt-related structural highs (Waite, 2009).

Pawnee Field

The Pawnee field, discovered in 1961, covers 9,000 acres at the depths of Edwards Limestone reservoirs (Cook, 1979) (fig. 14). Shale of the Upper Cretaceous Eagle Ford Group lies directly on the Stuart City reef trend in this field; the Buda Limestone, Del Rio Clay, and Georgetown Limestone are absent (Cook, 1979). The upper part of the reef complex contains large rudists and rudist fragments in a muddy matrix, whereas the lower part of the reef consists of coral, algal boundstone with fewer rudistids (Cook, 1979). On the reef trend, individual beds are difficult to correlate, even between wells within the same field (Cook, 1979).

Word Field

The Edwards Limestone is relatively deep (13,500 to 14,100 ft) in the Word field (fig. 14). As with the Washburn Ranch Field, the RDMB is an important indicator of reservoir potential (Waite, 2009). In this field, Edwards Limestone “A” is landward of the main shelf-edge fault and contains thick, dry gas columns, whereas Edwards Limestone “B” is mostly wet gas (Waite, 2009). Production from the Edwards Limestone in the Word field is likely associated with microporous lime grainstones and packstones of the open-platform facies and beach subfacies (Baker and Scott, 1985). Intermittent, syndepositional, subaerial exposure may have been responsible for porosity development in the Word field, particularly in areas where karstic upland subfacies interfinger with tidal-flat subfacies (Baker and Scott, 1985). Sequence stratigraphic studies of the Word field suggested that the Edwards Limestone shelf margin prograded several miles seaward (southeastward) of the Sligo Formation shelf margin (Fritz and others, 2000) (fig. 16). These findings may indicate that reservoir facies (grainstone and reef facies) exist basinward of fields currently producing on the reef trend.

Sabine Uplift

Waskom Field

Oil and gas were discovered in 1924 at the Waskom field on the Sabine uplift (fig. 7) in several Cretaceous rock units, including the Lower Cretaceous Barlow Formation, which is equivalent to the Goodland Limestone (Loetterle, 1950) (fig. 3). The reservoirs of the Barlow Formation are dense limestones with calcite veinlets, which have slight porosity developed by secondary leaching at an unconformable contact with the overlying Austin Group (Loetterle, 1950). The accumulation in the Sabine uplift reservoirs is primarily the result of a structural trap. The field is on a nearly circular dome on the Sabine uplift, and because the flanks of the dome are gently dipping, the productive area is large (Loetterle, 1950). In the Talco field of eastern Texas (fig. 7), the Goodland Limestone is not a reservoir, serving instead as a seal for reservoirs of the Paluxy Formation (Wendlandt and Shelby, 1948; Shelby, 1949).

Mississippi Interior Salt Basin

As described previously, limestones of the Andrew Formation are present in the downdip areas of the MISB (Mancini and Puckett, 2000) (fig. 3). Although production in the MISB has traditionally been assigned to sandstone reservoirs of the Dantzler Formation or the “Fredericksburg-Washita undifferentiated” of Salvador and Quezada Muñeton (1991) (referred to as “Fredericksburg and Washita Groups, undivided” in fig. 3), part of this production may be from limestone reservoirs in the Andrew Formation (Mancini and Puckett, 2000). In the south-central portion of the MISB, potential exists for oil production from carbonate shoal and reef lithofacies of the Andrew Formation’s depositional sequences (Mancini and Puckett, 2000; Mancini and others, 2008). In the Waveland field of southern Mississippi (fig. 7), there are productive reservoirs for gas and condensate in the lower Albian Mooringsport Formation, and to a lesser extent, in the “Fredericksburg-Washita undifferentiated” of Salvador and Quezada Muñeton (1991) and Paluxy Formation (Baria, 1981). Some wells in Mississippi were reported to produce oil and gas from limestone reservoirs within the Fredericksburg and Washita Groups.

Washita Group Reservoirs

Georgetown Limestone Reservoirs

According to Nehring Associates, Inc. (2009), all of the fields that produce from the Georgetown Limestone of the Washita Group are productive from carbonate reservoirs deposited in back-reef or carbonate platform depositional settings. The reservoirs are 3 to 175 ft thick, at depths ranging from 1,900 to 12,000 ft, and have porosities that average from 3 to 12 percent

(Nehring Associates, Inc., 2009). The Georgetown Limestone is more than 200 ft thick in the East Texas basin and thins to less than 100 ft in some areas over the San Marcos arch in central Texas (Rodda and others, 1966; Rose, 1968). In the Maverick basin (fig. 7), the Georgetown Limestone thickens to more than 300 ft. Recent development drilling in Georgetown reservoirs has made use of horizontal drilling to intersect natural fracture systems, and hydraulic fracturing technology has been used to enhance productivity. Three-dimensional seismic data and amplitude-versus-offset technology have been used in central Texas to delineate naturally-occurring, heavily fractured areas of the Georgetown Limestone for improved production rates (Pearson and others, 2003).

Buda Limestone Reservoirs

Production from reservoirs in the Buda Limestone is primarily associated with production from the Upper Cretaceous Austin Group (fig. 3). The Buda Limestone and Austin Group are open-marine foraminifer micrites and coccolith-bearing lime micrites (Scholle, 1977). Oil production occurs in a broad trend that extends from south to east Texas (Galloway and others, 1983). Production is from fractures that connect sparse matrix pores with permeable fracture systems. The Austin Group has been the major producer; in many cases, Buda Limestone wells have been recompletions or extensions of Austin Group wells. In the Luling fault zone, fields in the Austin Group and Buda Limestone that overlie reservoirs in the Edwards Limestone are essentially depleted by production because the fields are at relatively shallow depths (Galloway and others, 1983). Stapp (1977) described the Buda Limestone as an excellent target, particularly in south Texas where the Buda is only 150 to 200 ft below the base of the Austin Group, and the upper limestone layer of the Buda (5 to 20 ft thick) is commonly porous or fractured. There is also potential for production in Buda reservoirs that are characterized by natural fracture porosity in downdip areas.

Historically, completion years in Buda Limestone wells range from 1929 to 1998 and most wells have produced oil and gas (based on data in Nehring Associates, Inc., 2009). The Buda Limestone is very dense and has a matrix permeability averaging less than 0.1 mD (Snyder and Craft, 1977). The Buda produces from areas where secondary fracturing has improved permeability and reservoir capacity (Scholle, 1977). Oil occurs in the Buda Limestone where there is fault-zone brecciation or where there are fractures caused by stress and compaction over buried structures (Stapp, 1977). In the East Texas basin, Buda Limestone production may come from fractures associated with ring faults around salt domes (Maione, 2000). Production is enhanced and stabilized by acid fracturing (Stapp, 1977).

The Buda Limestone was assessed previously by the USGS in 1995 (Schenk and Viger, 1996). Assessment units consisted of the Buda Fault Zone Oil Play and the Buda Downdip Oil Play. The Buda Fault Zone Oil Play was not assessed quantitatively because it only contained two fields in the Buda Limestone, the Salt Flat and Darst Creek fields (fig. 13), which were discovered in 1928 and 1929, respectively (Dawson, 1986). There have been no new discoveries in the Buda Fault Zone Oil Play in more than 65 years. The Buda Downdip Oil Play was assessed quantitatively for conventional oil and gas and included nine reservoirs discovered from 1950 to 1981 (Schenk and Viger, 1996). The latest production from the Buda Limestone was established in the Sand Branch Creek field in 1998 (Railroad Commission of Texas, 1998). The Sand Branch Creek field is the only addition to the previously assessed fields.

Seals and Traps

Seals

Shales, mudstones, and nonporous carbonate rocks serve as seals to hydrocarbon migration in the Fredericksburg and Washita reservoirs. The clay-rich deposits of the Del Rio Clay and (or) Grayson Shale (fig. 3) that were widely dispersed across the shallow-marine shelf in the northwest Gulf Coast (Galloway, 2008) likely form seals to hydrocarbon migration. The Del Rio Clay, Buda Limestone, and Eagle Ford Group (fig. 3) are known to be the upper confining units to the Edwards aquifer in central Texas, which indicates that these formations perform a hydrogeologic function by trapping fresh water in the carbonate rocks of the Georgetown and Edwards Limestones (Clark and others, 2007). The Del Rio Clay has negligible effective porosity and permeability in south-central Texas, and it is the primary confining unit of the Edwards aquifer (Stein and Ozuna, 1995). Because the Del Rio Clay, Buda Limestone, and Eagle Ford Group are confining units, they may function as hydrocarbon seals. It is also possible that the calcareous claystones and interbedded lime mudstones of the Kiamichi Formation provide seals to hydrocarbon migration.

A few specific examples of hydrocarbon seals in reservoirs in the Fredericksburg or Washita Groups follow. In the Stuart City reef trend, seals are provided by carbonate rocks of the Georgetown Limestone, shales of the Taylor Group, and tight carbonates within the Edwards Limestone (Nehring, 1991). Nonporous wackestone provides an effective seal for grainstone and boundstone reservoir facies of the reef trend in the Pawnee field (fig. 14) (Kosters and others, 1989). In the Luling fault trend, dense Georgetown Limestone serves as the top seal, and Upper Cretaceous Taylor Group shales form the lateral seal across the fault (Cook, 1979). In the Waveland field, located on the western plunge of the Wiggins arch in Mississippi (fig. 7), impermeable lime mudstones serve as seals by capping the porous and permeable limestones of the Fredericksburg and Washita Groups (Warner, 1992).

Traps

Examples of the types of traps for reservoirs in the Edwards, Georgetown, and Buda Limestones (Nehring Associates, Inc., 2009) are in table 3. In reservoirs of the Edwards Limestone in the Word North field (located in the northeastern part of the Word field, fig. 14), which is in the reef trend, traps are formed by reef-related facies changes, diagenetic modifications, and faults (Kosters and others, 1989). In reservoirs in the Georgetown Limestone, the primary traps and seals are formed by facies changes in reefs, faults, and extensional faults on anticlinal noses (Nehring Associates, Inc., 2009). In reservoirs in the Buda Limestone, fractures on anticlinal noses and other structures, such as faults associated with salt diaper flanks, form the primary trap (Nehring Associates, Inc., 2009).

Geologic Model for Assessment of Undiscovered Hydrocarbons

Model Definition

The geologic model developed by the USGS Assessment Team for estimating undiscovered hydrocarbons in carbonate rocks of the Fredericksburg and Washita Groups is based on the following factors: (1) the thickness and depth of the assessed stratigraphic intervals; (2) the distribution of mature hydrocarbon source rocks; (3) potential migration pathways from source rocks to reservoirs: (4) the depositional framework, porosity, and permeability of potential reservoirs; and (5) the presence of traps and seals. Because only the carbonates of the Fredericksburg and Washita Groups were assessed, the ratio of carbonate to siliciclastic sediments was also part of the geologic model used in this study. An events chart for the geologic model is shown in fig. 17.

Thickness and Depth of the Assessed Strata

An isopach map (fig. 18) showing the apparent thicknesses (in feet) of the assessed stratigraphic interval (carbonate rocks of the Fredericksburg and Washita Groups and equivalent units) was created on the basis of published data from Cullom and others (1962), Mosteller (1970), Bebout and Schatzinger (1977), McFarlan (1977), Wood and Guevara (1981), Badali (2002), Mancini and Goddard (2004), Mancini and others (2008), Stoudt, Hutchinson, and Gordon (1990), and Stoudt, McCulloh, and Eversull (1990). In figure 18, the updip boundary of the isopach map in northern Louisiana and western Mississippi represents the eroded boundary of the assessed intervals. In updip areas of central and western Mississippi, thickness data for carbonate facies within Fredericksburg and Washita Groups were not available, and well data suggesting the presence of limestone facies (IHS Energy Group, 2009) in these areas were used to estimate isopach contours. A structure-contour map showing the depth to the top of the assessed stratigraphic interval (fig. 19) was created on the basis of well data from the IHS Energy Group (2009).

Shelf Margin

Facies, Environments, and Reservoirs

Figure 20 is a schematic cross section that illustrates the depositional model used to define the assessment unit for the Fredericksburg and Washita Groups and equivalent units. Figure 21 is a block diagram that illustrates the various lithologic facies and interpreted environments of the Stuart City reef trend. In this model (based on Bebout and Loucks, 1974, 1983; Waite, 2009), the shelf margin consists of a progradational carbonate rock package of requieniid boundstones and caprinid-algal packstones; the presence of skeletal grainstones shows evidence of brief subaerial exposure. Patch reefs are present on the upper slope.

Producing reservoirs, composed of the grainstones and packstones that were deposited in back-reef and shelf-margin depositional environments, benefit from preserved primary and secondary porosity. Secondary porosity probably developed as a result of (1) solution fluids that travelled along fault planes, (2) fluids associated with natural fractures, and (3) subaerial exposure and karstification. The block diagram (fig. 21) is used here as a model for the reef trend that extended across the entire northern Gulf of Mexico basin during the period of time when the Fredericksburg and Washita Groups were deposited (McFarlan and Menes, 1991; Yurewicz and others, 1993; Galloway, 2008).

Progradation of the Edwards Limestone Margin

Although the Edwards Limestone shelf margin has been mapped in numerous reports as coincident with the Sligo Formation shelf margin (Fisher and Rodda, 1969; Bebout and Loucks, 1974), Fritz and others (2000) suggested that in east-central Texas (proximal to the San Marcos arch) the Edwards Limestone shelf margin prograded seaward (southeastward) beyond the Sligo Formation shelf margin, potentially forming undiscovered reservoirs (fig. 16). The highly progradational nature of the Edwards margin places prospective back-reef and reef grainstones seaward of the recognized margin in central Texas; Fritz and others (2000) stated that these areas are virtually unprospected and that they have significant potential for new gas reserves. Scott (2010) described a potential new play, the fore-reef-margin carbonate wedge, which has rarely been drilled and tested. Contemporaneous sediment wedges that are downslope of the shelf margins of the Sligo and Stuart City Formations are thought to be thick, wide, and laterally extensive, and they may have potential as new reservoirs (Bebout and Loucks, 1974; Tyrrell and Scott, 1987; Scott, 1993; Fritz and others, 2000). Sequence stratigraphic studies also suggested that there is potential for hydrocarbons in areas where sediment wedges may consist of reef debris eroded from shelf margins (Fritz and others, 2000; Scott, 2010).

Carbonate Versus Siliciclastic Sediments

In eastern Louisiana, Mississippi, Alabama, and northwestern Florida, the Fredericksburg and Washita Groups consist of both carbonate and siliciclastic sediments (fig. 22). Because siliciclastic sediments were assessed separately (Dubiel and others, 2011), the percentage of the Fredericksburg and Washita Groups that are composed of carbonate rocks was estimated on the basis of data obtained from cross sections (Yurewicz and others, 1993; Mancini and Goddard, 2004) and information from sequence stratigraphic studies (Badali, 2002; Mancini and others, 2008). This estimate is explained in more detail in the "Boundaries Used to Define Assessment Units" section below.

Boundaries Used to Define Assessment Units

Introduction

The following geologic controls, hydrocarbon production data, and political boundaries were used to delimit the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU (figs. 23, 24, 25): (1) producing wells and reservoirs of the Fredericksburg and Washita Groups; (2) the total petroleum system (TPS) boundary; (3) late Quaternary water washing of potential reservoir intervals; (4) the updip extent of carbonate rocks within the Fredericksburg and Washita Groups; (5) the extent of erosion of rock units within the assessed stratigraphic interval; (6) the predominance of siliciclastic deposits and extent of carbonate rocks in the eastern Gulf Coast; (7) the Lower Cretaceous shelf margin; and (8) the boundaries of State and Federal Waters. Each of these factors is discussed below.

Distribution of Reservoirs and Wells in Assessed Strata

The Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU was constructed to include all producing wells and reservoirs of carbonate rocks within the Fredericksburg and Washita Groups. Fields with reservoirs in the Fredericksburg and Washita Groups and equivalent units span the area from southwest Texas to the border area of Texas and Louisiana based on data from Nehring Associates, Inc. (2009) (fig. 24). Reservoirs are the most abundant in central and southwest Texas.

Producing wells within the Fredericksburg and Washita stratigraphic intervals (based on data from IHS Energy, 2009) are present from southwest Texas to Alabama (fig. 25), but are the most abundant in central Texas, southwest Texas, and the Sabine uplift. A large number of wells that produce hydrocarbons from carbonate rocks in the Fredericksburg and Washita stratigraphic intervals are also present in the East Texas basin and MISB. Although numerous wells show production from carbonate rocks of the Fredericksburg and Washita Groups in eastern Louisiana, Mississippi, and Alabama, this production is reported as being from "Washita-Fredericksburg" sandstone reservoirs in the reservoir data from Nehring Associates, Inc. (2009). In Mississippi and Alabama, producing wells indicating the presence of limestone facies were included in the AU. In south Texas, both the presence of producing wells and water washing in the area were used to define the updip limit of the AU (see "Water Washing of Hydrocarbons in South-Central Texas" section below).

Total Petroleum System Boundary in Texas and Southern Oklahoma

Carbonate rocks are a major component of the Fredericksburg and Washita Groups and equivalents in Texas and southern Oklahoma. In these areas, the updip (subsurface) extent of the carbonate rocks coincides with the TPS boundary. In Texas and southern Oklahoma, the AU was constructed to include all of the subsurface rocks of the Fredericksburg and Washita Groups, with the exception of one area in south Texas that has the potential for water washing (see next section).

Water Washing of Hydrocarbons in South-Central Texas

Water washing is the dissolution of light molecular species from oil and gas into water (Lafargue and Barker, 1988). Because processes that alter the composition of a crude oil can have a direct impact on the commercial value of an oil field, there is interest in understanding the potential for occurrence of water washing and biodegradation; biodegradation commonly occurs with water washing (Palmer, 1991). The AU boundary coincides with the TPS boundary in most of Texas and in southern Oklahoma. In south-central Texas, recharge zones of the Edwards aquifer are adjacent to (updip of) the TPS boundary. Maclay (1995) determined the approximate downdip limit of the freshwater zone of the Edwards aquifer in this area. The AU boundary was constructed to (1) exclude most of the freshwater zone, to decrease the potential for water washing of hydrocarbons, and (2) include productive wells within carbonate rocks of the Fredericksburg and Washita Groups. The resulting AU boundary (fig. 26) is downdip of the TPS boundary, and slightly updip of the downdip limit of the Edwards aquifer freshwater zone defined by Maclay (1995).

Updip Extent of Carbonate Rocks in Fredericksburg and Washita Groups in the Central and Eastern Gulf Coast Region

Previous researchers (Murray, 1952; Cullom and others, 1962; Rainwater, 1971) constructed lines indicating the updip limit (subsurface) of the Fredericksburg and Washita Groups in Arkansas, Louisiana, Mississippi, and Alabama (fig. 23). In this report, the updip boundary of the AU is based on the lines from these previous studies, the presence of producing wells within the Fredericksburg and Washita Groups and equivalent units, and a determination of whether the assessed stratigraphic interval had been eroded (see following section). Although Murray (1952) indicated the presence of limestone facies in downdip areas of the Fredericksburg and Washita Groups (fig. 23), data from IHS Energy Group (2009) confirmed the presence of limestone facies in areas farther updip of the boundary of Murray (1952).

Eroded Strata in Louisiana, Arkansas, and Mississippi

As discussed earlier, erosion of the Fredericksburg and Washita Groups and equivalent units occurred in what is now southern Arkansas, northern Louisiana, and west-central Mississippi, as a result of uplift during the middle Cenomanian (Cullom and others, 1962; Rainwater, 1971; Yurewicz and others, 1993). Post-Comanchean uplift on the south flank of the Southern Arkansas uplift (fig. 7) has been associated with this erosion (Cullom and others, 1962). To define the updip boundary of the AU in these areas, data was compiled from published cross sections (Mancini and Goddard, 2004; Stoudt, Hutchinson, and Gordon, 1990; Stoudt, McCulloh, and Eversull, 1990; McFarlan, 1977) and a “line of erosion” indicating the absence of Fredericksburg Group, Washita Group, and equivalent rocks was constructed (fig. 27). The AU boundary in these areas is similar to the updip extent of the Fredericksburg and Washita Groups described in earlier studies (Murray, 1952; Rainwater, 1971). In northern Louisiana, central Mississippi, and central Alabama, a combination of the line of erosion and the presence of producing wells in the Fredericksburg and Washita Groups was used to define the updip boundary of the AU.

Predominance of Siliciclastic Deposits in the Eastern Gulf Coast Region

Siliciclastic rocks were the dominant lithology deposited in the back-reef paleoenvironmental setting in northeastern Louisiana, Mississippi, Alabama, and the Florida panhandle during Albian time (fig. 22) (McFarlan and Menes, 1991; Mancini and Goddard, 2004; Galloway, 2008). In these areas, of the sediments deposited during the time of Fredericksburg and Washita deposition, two thirds were estimated to be siliciclastic rocks and one third was estimated to be carbonate rocks. This estimate was based on published cross sections by Mancini and Goddard (2004).

Extent of Carbonate Rocks in the Eastern Gulf Coast Region

Previous studies suggest that carbonate rocks of the Fredericksburg and Washita Groups are predominant in downdip areas of the eastern Gulf Coast region (fig. 23) (Murray, 1952; Mancini and Puckett, 2002). In the MISB, limestones of the Andrew Formation are more developed downdip along the southern margin of the MISB, and sandstones of the Dantzler Formation are more dominant updip (Mancini and Puckett, 2002). Maps by Murray (1952) and Yurewicz and others (1993) indicate that carbonate rocks of the Fredericksburg and Washita Groups are limited to areas near the reef margin. For these reasons, the updip boundary of the AU in Alabama was constructed to be slightly downdip of the updip extent of the Fredericksburg and Washita Groups indicated by Murray (1952) (fig. 23). The presence of carbonate rocks, as indicated by wells (IHS Energy Group, 2009) that penetrated the Fredericksburg and Washita Groups, was also used to determine the eastern extent of the AU boundary in southern Alabama and the western panhandle of Florida.

Downdip Limit of Assessment Unit—The Lower Cretaceous Shelf Margin

The boundary of the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU was constructed to be 10 mi downdip of the recognized Lower Cretaceous shelf margin (Ewing and Lopez, 1991) in order to include potential reservoirs. Progradation of the shelf margin and the potential deposition of reef debris were important in determining this downdip limit. As described in the "Geologic Model for Assessment of Undiscovered Hydrocarbons" section (fig. 20), because the Edwards Limestone shelf margin prograded basinward of the Sligo Formation shelf margin over a distance of several miles in some areas, there is potential for shelf-margin reservoirs basinward of currently producing fields (Fritz and others, 2000). As discussed earlier, sediment wedges are thought to exist downslope of the Stuart City reef trend (Bebout and Loucks, 1974; Fritz and others, 2000). A detailed sequence stratigraphic study based on seismic, lithologic, and biostratigraphic data in east-central Texas (Fritz and others, 2000) suggested that the delineation of the Edwards Limestone shelf margin could be moved seaward more than 3 mi from the previously published position of the margin (Word field, as shown in fig. 16). Reef and grainstone deposits have been found to be located seaward of the currently recognized margin (Fritz and others, 2000). There is also potential for reef debris in an apron basinward of the margin because it would have been eroded from the shelf margin (Fritz and others, 2000; Scott, 2010). The AU was constructed to include these possible reservoirs.

State and Federal Water Boundaries

The offshore State and Federal Water boundary was used to define the downdip boundary of the AU in southeastern Louisiana, Mississippi, Alabama, and the western Florida panhandle. State and Federal boundaries are from Thormahlen (1999).

Estimates of the Numbers and Sizes of Undiscovered Reservoirs

Introduction

To make estimates of technically recoverable undiscovered hydrocarbon resources, the geologic model that was developed for the Fredericksburg and Washita Groups was used and the production history for oil and gas reservoirs within these intervals was examined. To examine production history, the discovered oil accumulations for the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU were divided into "thirds," with each third containing the same (or close to the same) number of reservoirs (fig. 28*A*, 28*B*). Estimates of undiscovered oil, gas, and natural gas liquid resources for the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU are in table 4. Appendix 1 contains the input data form for the AU.

Oil Reservoirs

First Third of Discoveries

Several trends in oil production are identified on the basis of data from Nehring Associates, Inc. (2009) (figs. 28*A,* 28*B*). In figure 28, the geologic area (fault zones, embayments, or basins) of selected reservoirs also are identified, with a focus on the largest and most recent reservoirs (smaller reservoirs are generally not identified). In the first third of the discoveries (from 1917 to 1947; fig. 28*A*), the largest reservoir discoveries were made in the Luling fault zone. Several discoveries were made in the

Charlotte-Jourdanton fault zone in the late 1940s (not identified on plot). Most reservoirs in the first third of discoveries are in the Edwards Limestone; however, reservoirs in the Goodland Limestone, Fredericksburg Group, Buda Limestone, and Georgetown Limestone are also present.

The largest oil reservoirs (from about 1920 to 1930, fig. 28*A*) were in the deeper intervals of the Luling fault zone on the San Marcos arch, at depths of about 2,000 to 2,500 ft (fig. 28*B*). These reservoirs are in limestone and dolomite, with porosity ranging from 21 to 50 percent (based on Nehring Associates, Inc., 2009). Grown oil accumulation (defined as the known petroleum volume adjusted upward to account for future reserve growth; Klett and others, 2005) sizes range from 84 to 187 million barrels of oil (MMBO). In the Luling fault zone, the Edwards Limestone has been described as a leached, porous dolomite and dolomitic limestone deposited in tidal-flat and shallow-marine environments (Cook, 1979). Leaching and dolomitization in this area enhanced porosity to a great extent. Because reservoirs in the Luling fault zone are shallow, further discoveries of this size are not likely.

Second Third of Discoveries

In the second third of discoveries (1950 to 1977, figs. 28*A*, 28*B*), discoveries were made in the Charlotte-Jourdanton fault zone, Karnes fault zone, Houston embayment, Angelina-Caldwell flexure area, and Maverick basin at depths down to 11,000 ft. Reservoirs are in the Edwards, Buda, and Georgetown Limestones. The largest discovery was in a Buda Limestone reservoir (33.5 MMBO) in the Houston embayment and Angelina-Caldwell flexure area.

Third Third of Discoveries

In the last third of discoveries (1980 to 1998, figs. 28*A*, 28*B*), discoveries were made in the Houston embayment and Angelina-Caldwell flexure area, Charlotte-Jourdanton fault zone, Sabine uplift, and the East Texas basin. Accumulations are primarily in the Buda and Georgetown Limestones, but reservoirs in the Edwards Limestone are also present. Depths for the reservoirs range from 3,000 to 10,000 ft. The largest reservoir is in the Buda Limestone in the East Texas basin (10.4 MMBO). Several reservoirs in the Georgetown Limestone are located on the updip side of the Angelina-Caldwell flexure.

Sizes of Discovered Reservoirs

With the exception of the early discoveries in the Luling fault zone, the largest reservoirs are less than 40 MMBO; these reservoirs were discovered in the Karnes fault zone in the late 1950s (Edwards Limestone reservoir) and in the Houston embayment and Angelina-Caldwell flexure area in the late 1970s (Buda Limestone reservoirs). From 1980 to the present, there has been a decrease in the maximum size of oil reservoirs. Only one reservoir (a Buda Limestone reservoir in the Angelina-Caldwell flexure area) was discovered during the period from 1990 to 2009, and it had an oil accumulation size of slightly less than 1 MMBO. Cumulative grown oil volumes for the AU indicate that there has not been a significant increase in oil volumes since the late 1970s (fig. 28*C*).

Estimates of Numbers and Sizes of Undiscovered Reservoirs

Because reservoirs in the Luling fault zone are at shallow depths, undiscovered reservoirs are not expected to be as large as those found in the 1920s, which were roughly 80 to 200 MMBO (fig. 28*A*). However, to allow for the possibility of new oil reservoirs being discovered in fault zones or areas such as the Angelina-Caldwell flexure, a maximum oil accumulation size of 60 MMBO is estimated for this AU (refer to data entry form, appendix 1). This accumulation size is larger than the largest found in the past 40 years (about 35 MMBO). The median oil accumulation size was estimated to be 1.5 MMBO because it is slightly higher than that of the only discovery in the last 20 years (close to 1 MMBO). A maximum of 30 and a mode of 12 for the number of undiscovered oil accumulations is estimated because only 12 oil reservoirs have been discovered from 1980 to 2009 (based on data from Nehring Associates, Inc., 2009)

Gas Reservoirs

First Third of Discoveries

The following trends are identified for gas reservoirs of the Fredericksburg and Washita Groups and their equivalents (as determined by data from Nehring Associates, Inc., 2009). As with oil accumulations, gas accumulation discoveries for the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU were divided into ”thirds,” with each third containing an equal number of reservoirs (figs. 29*A*, 29*B*). In figures 29*A* and 29*B*, the geologic area (fault zones, embayments, or basins) of selected reservoirs also are identified, with a focus on the largest and most recent reservoirs (smaller reservoirs are generally not identified). In the first third of discoveries (1924 to 1960), the earliest gas discovery was in 1924 of a reservoir in the Barlow Limestone in the Sabine uplift at a depth of less than 3,000 ft. All other discoveries in the first third of discoveries were of reservoirs in the Edwards Limestone. The largest gas reservoirs were in the Charlotte-Jourdanton fault zone at a depth of about 7,000 ft and in the Karnes fault zone at a depth of about 10,000 ft. Several reservoirs in the first third of discoveries are in dolomite and limestone. Production from the reef margin started in the mid-1950s, predominantly at depths of about 10,000 ft in the San Marcos arch and Rio Grande embayment areas. Two reservoirs on the reef margin are at depths of about 13,000 to 14,000 ft.

Second Third of Discoveries

In the second third of discoveries (1961 to 1977, figs. 29*A*, 29*B*), the largest reservoirs are in the Edwards Limestone on or near the reef margin and range in size from about 450 to 500 billion cubic feet of gas (BCFG). Although most of the reservoirs in the second third were discovered in the Edwards Limestone, a few smaller reservoirs (not labeled in figs. 29*A*, 29*B*) were discovered in the Buda and Georgetown Limestones as well as in the McKnight and Kiamichi Formations (limestone and dolomite) in the Maverick basin. More than half of the discoveries in the second third were on the reef margin. Discoveries were made in the Karnes and Charlotte-Jourdanton fault zones in the 1960s (not all examples are labeled in figs. 29*A*, 29*B*). A few discoveries were also made in the Houston embayment (not labeled in figs. 29*A*, 29*B*).

Third Third of Discoveries

In the last third of discoveries (1978 to 2006, figs. 29*A*, 29*B*), the largest accumulations were discovered in the Houston embayment (reservoirs in the Edwards Limestone ranging from about 150 to 200 BCFG) and in the Angelina-Caldwell flexure area (a reservoir in the Buda Limestone of about 160 BCFG). The deepest reservoir was in the Edwards Limestone on the reef margin at a depth of about 16,000 ft. The most recent discoveries in the plot (1991 to 2006), were in the Angelina-Caldwell flexure area (reservoirs in the Edwards and Buda Limestones), the Maverick basin (a reservoir in the Georgetown Limestone), and in areas on or downdip of the reef margin. The most recent discovery in the plot (2006) is of a reservoir in the Edwards Limestone downdip of the reef trend at a depth of about 14,000 ft and with an accumulation size of about 45 BCFG.

From about 1978 to 2006, depths of discovered reservoirs ranged from about 5,770 to 16,200 ft, and the largest gas accumulations were in the Houston embayment and Angelina-Caldwell flexure area (up to about 200 BCFG). A plot of discovery year versus cumulative grown gas volume shows a moderate upward trend in gas volume since the early 1980s (fig. 29*C*).

Estimates of Numbers and Sizes of Undiscovered Reservoirs

As described in the geologic model, there is potential for undiscovered gas reservoirs in reef, back-reef, and fore-reef areas. There is significant potential for undiscovered gas accumulations in sediment wedges consisting of debris eroded from shelf margins. Because these debris zones are at great depths, they have not been intensively developed. There is also potential for undiscovered gas reservoirs in the Angelina-Caldwell flexure, Maverick basin, and other structural trends. For all of these reasons, the maximum gas accumulation size is estimated to be 500 BCFG (refer to data entry form, appendix 1); this gas accumulation size has not been discovered since 1977. The median gas accumulation size is estimated to be 9 BCFG. Because only about 16 reservoirs were discovered from about 1977 to 2009, the maximum and mode of the number of undiscovered gas accumulations is estimated to be 60 and 20, respectively.

Assessment Results

The estimated means for total undiscovered oil and gas resources for the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU in onshore and in State Waters are as follows: 40 million barrels of oil (MMBO), 622 billion cubic feet of gas (BCFG), and 14 million barrels of natural gas liquids (MMBNGL) (tables 1, 4). The estimated mean of 40 MMBO for undiscovered oil resources is about 5.7 percent of the total estimated mean (700 MMBO) for undiscovered conventional oil resources in Jurassic and Cretaceous stratigraphic units assessed by the USGS in 2010 (table 1; Dubiel and others, 2011). The estimated mean of 622 BCFG for undiscovered gas resources is about 3.2 percent of the total estimated mean undiscovered gas resources (19,429 BCFG) in Jurassic and Cretaceous stratigraphic units assessed in 2010 (table 1; Dubiel and others, 2011).

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A

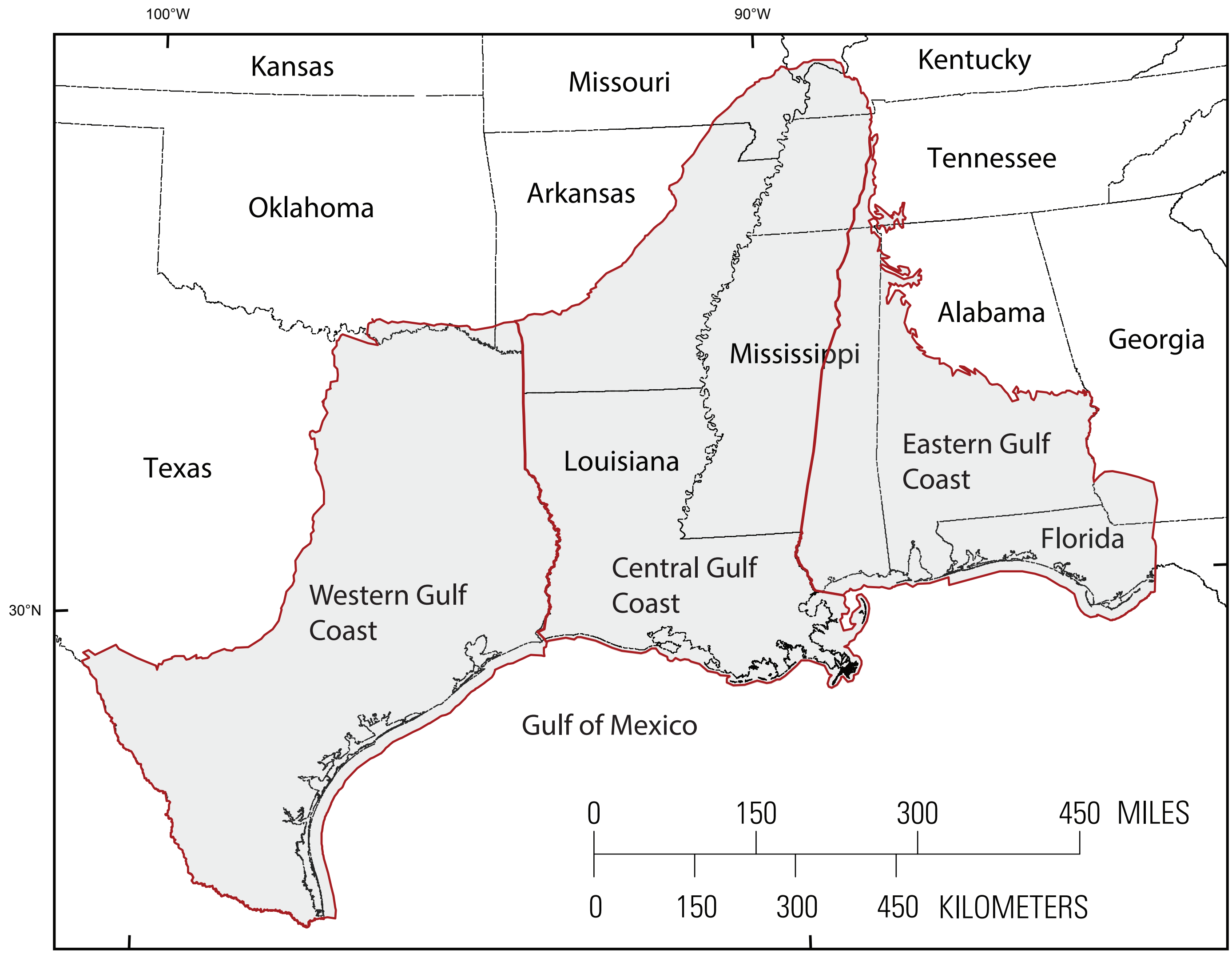


Figure 1 (this page and next page). Map showing the study area and a stratigraphic correlation chart of the Gulf Coast region of the United States. *A*, Map showing the three-part subdivision of the Gulf Coast region into western, central, and eastern parts. *B*, Stratigraphic chart showing the upper part of the Middle Jurassic through Upper Cretaceous strata (modified from Mancini and others, 2008; Dubiel and others, 2010). Assessed carbonate rocks of the Fredericksburg and Washita Groups and equivalent strata are highlighted in yellow. Stratigraphic relations by Dubiel and others (2010) were also based on Salvador and Quezada Muñeton (1991) and Witrock and others (2003). Warwick and others (2007) was also used. Sligo and Hosston Formations were revised based on recent information (J. L. Coleman, U.S. Geological Survey, written commun., 2013; Roberts-Ashby and others, 2014). Abbreviations: Fm., Formation; Gp., Group; Ls., Limestone; Mbr., Member; undiv., undivided.

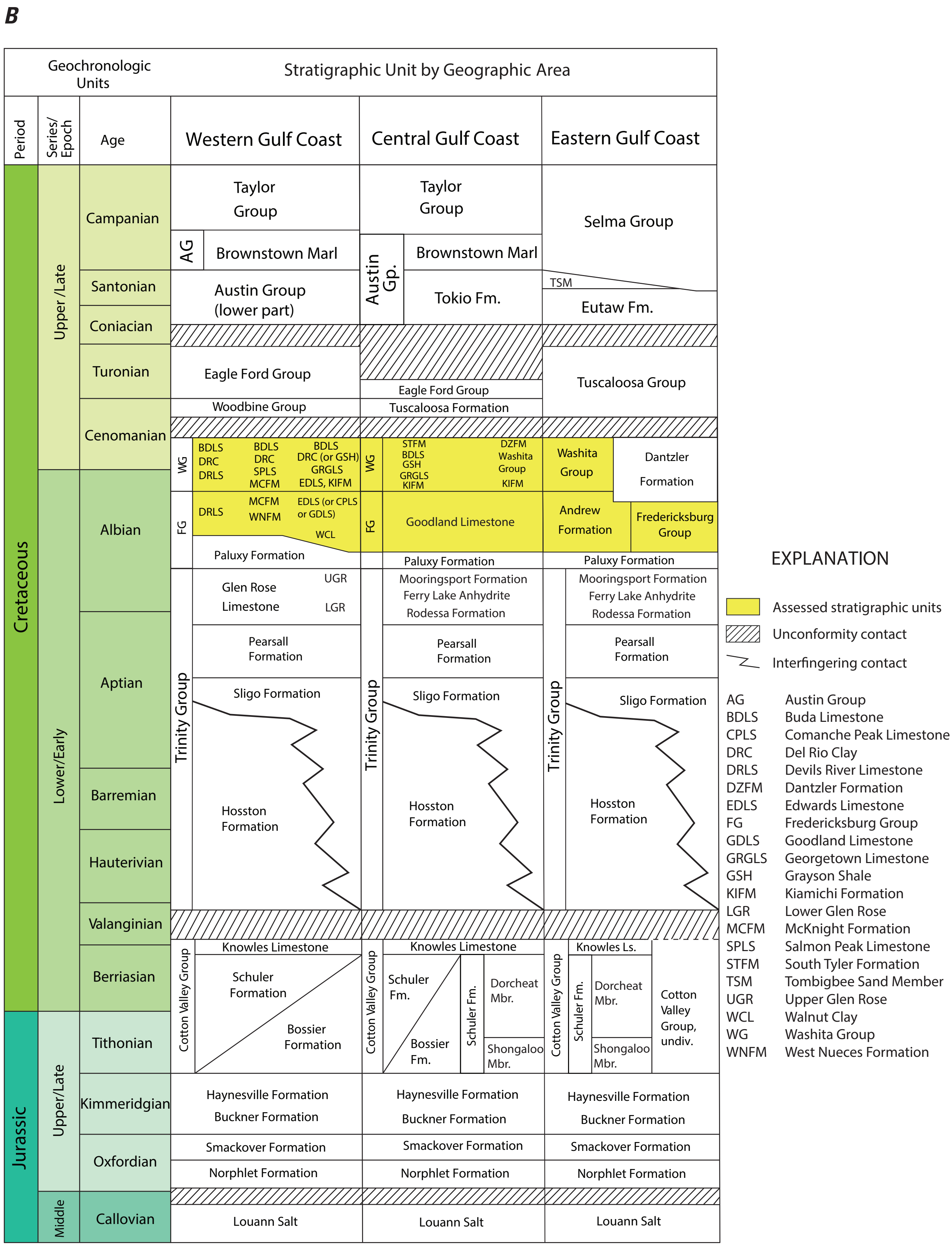


Figure 1. Continued.

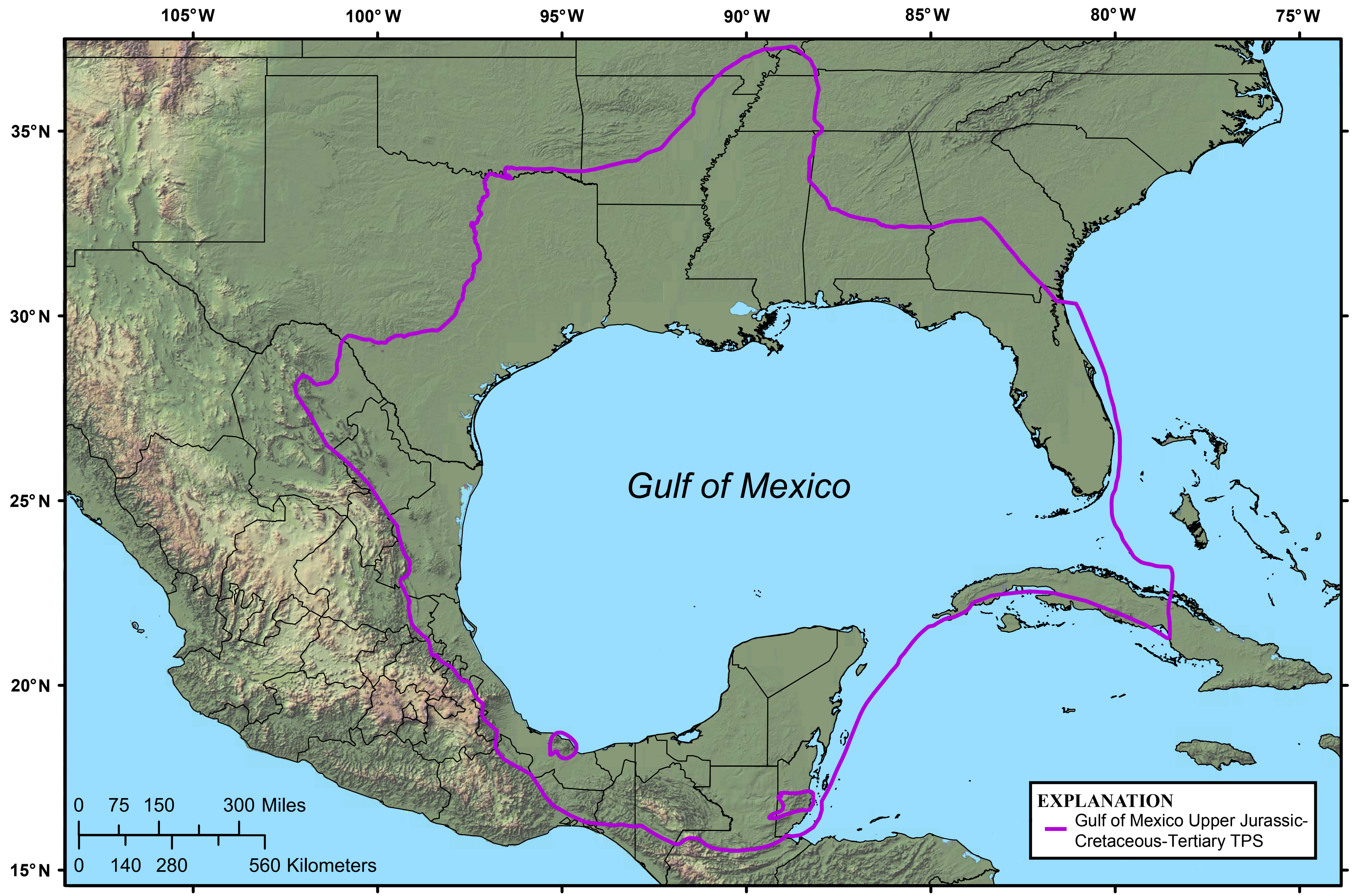


Figure 2. Map showing the Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System (TPS) for the Gulf of Mexico basin (modified from Warwick and others, 2007).

A

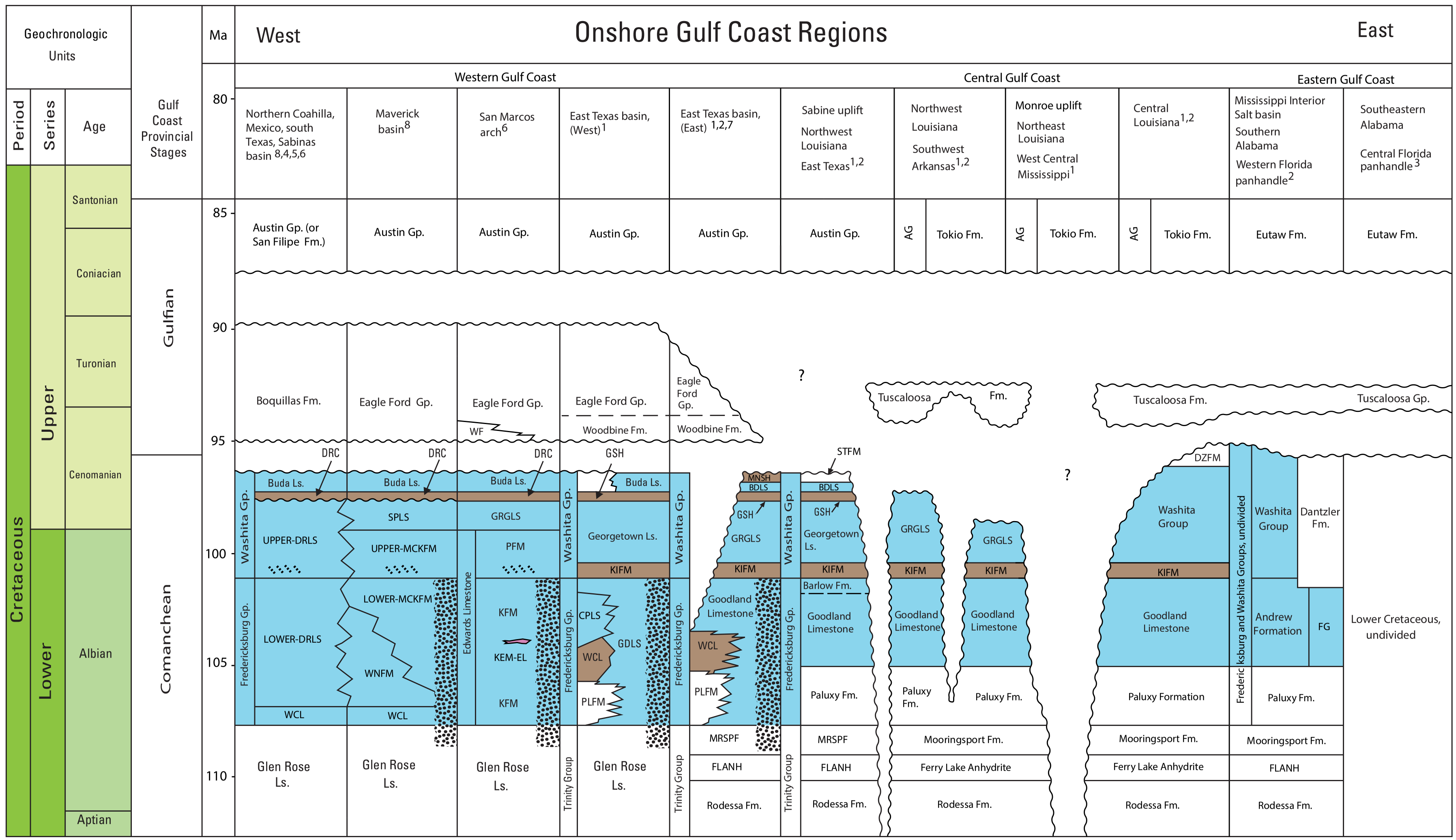


Figure 3 (this page and facing page). *A*, Chart showing the stratigraphic nomenclature of the western, central, and eastern U.S. Gulf Coast region, modified primarily from American Association of Petroleum Geologists (2002) and Mancini and others (2008). Ages are from Mancini and others (2008). Carbonate rocks of the Fredericksburg and Washita Groups and equivalent stratigraphic units that were assessed are highlighted in blue, brown, and magenta. *B*, Explanation and references used in the stratigraphic chart *A*. Abbreviations; Fm., Formation; Gp., Group; Ls., Limestone; Ma, mega-annum (millions of years before present).

B

EXPLANATION

AG	Austin Group
BDLS	Buda Limestone
CPLS	Commanche Peak Limestone
DRC	Del Rio Clay
DRLS	Devils River Limestone
DZFM	Dantzler Formation
FG	Fredericksburg Group
FLANH	Ferry Lake Anhydrite
GDLS	Goodland Limestone
GRGLS	Georgetown Limestone
GSH	Grayson Shale
KEM-EL	Kirschberg Evaporite Member of the Edwards Limestone
KFM	Kainer Formation
KIFM	Kiamichi Formation
MCKFM	McKnight Formation
MNSH	Maness Shale
MRSPF	Mooringsport Formation
PFM	Person Formation
PLFM	Paluxy Formation
SPLS	Salmon Peak Limestone
STFM	South Tyler Formation
WCL	Walnut Clay
WF	Woodbine Formation
WNFM	West Nueces Formation

Dominant lithology of stratigraphic intervals assessed

Carbonate rock

Shale, mudstone, and siltstone

Evaporite

Stuart City Formation

Regional Dense Marker Bed of Tucker (1962)

Inferred contact

Conformable contact

Unconformable contact

Interfingering contact

References

[1]American Association of Petroleum Geologist (2002)
[2]Mancini and others (2008)
[3]Salvador and Quezada Muñeton (1991)
[4]Zahm and others (1995)
[5]Smith (1970)
[6]Chenault and Lambert (2005)
[7]Ambrose and others (2009)
[8]Osleger and others (2004)

Figure 3. Continued.

A

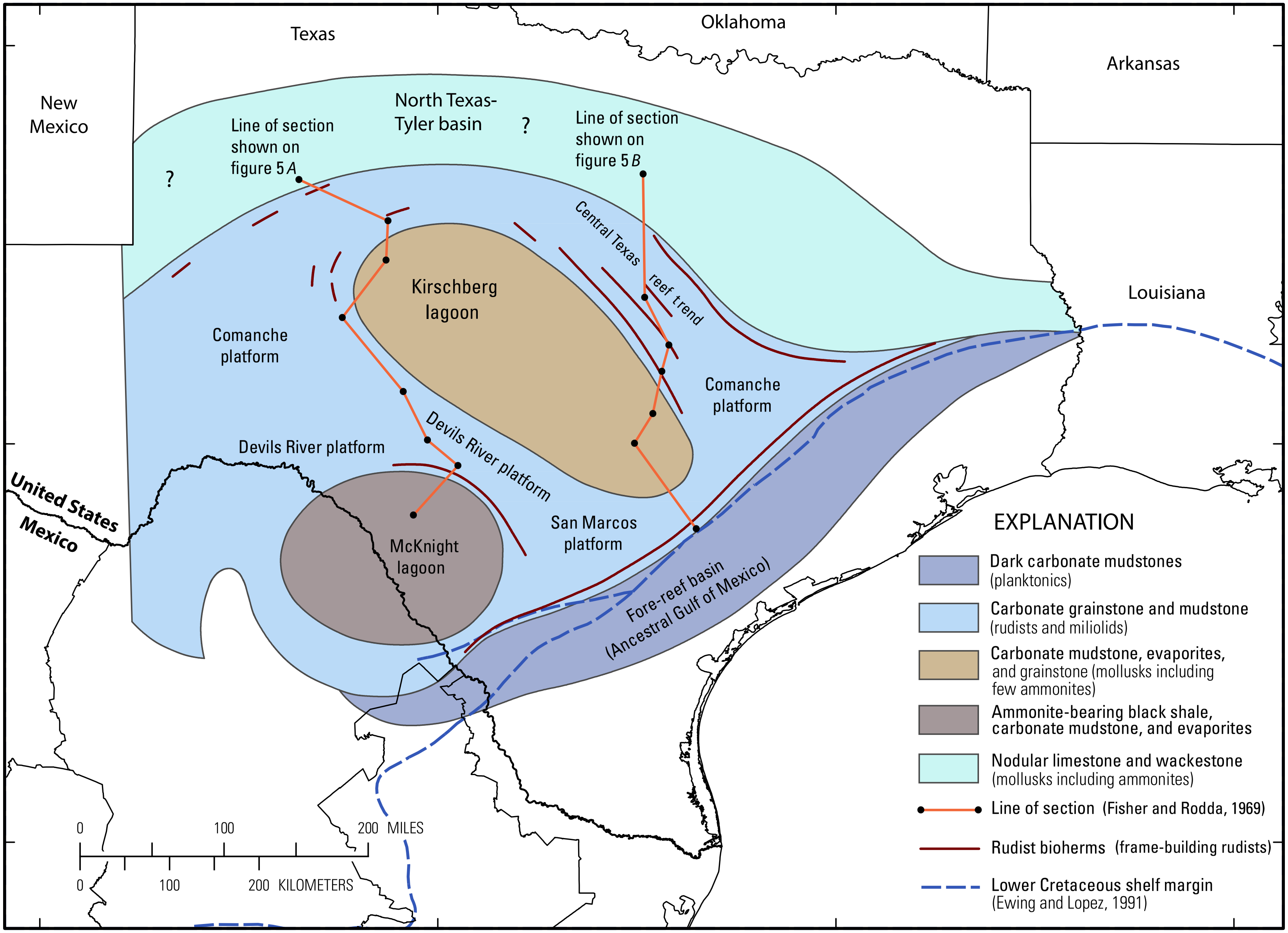
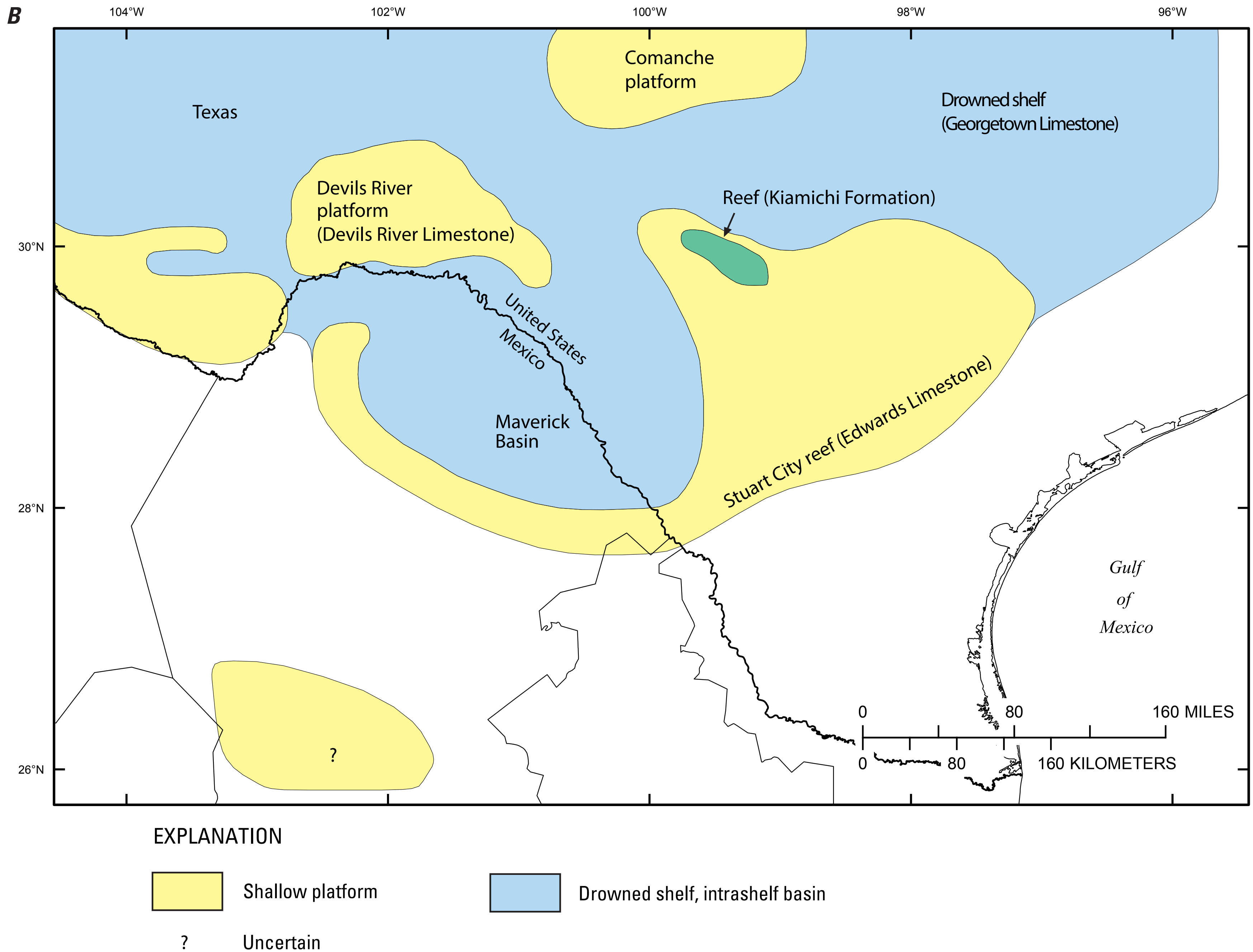


Figure 4 (this page and facing page). Maps showing the paleogeography of the Edwards Limestone and related strata in Texas in Early Cretaceous (Albian) time. *A*, Map showing the paleogeography of the Edwards Limestone in central Texas in Early Cretaceous (Albian) time (modified from Fisher and Rodda, 1969). The Lower Cretaceous shelf margin (Ewing and Lopez, 1991) is also shown on the map. *B*, Map showing the paleogeography of the Comanche shelf in Early Cretaceous (late Albian) time in southwest Texas (modified from Kerans and others, 2002).



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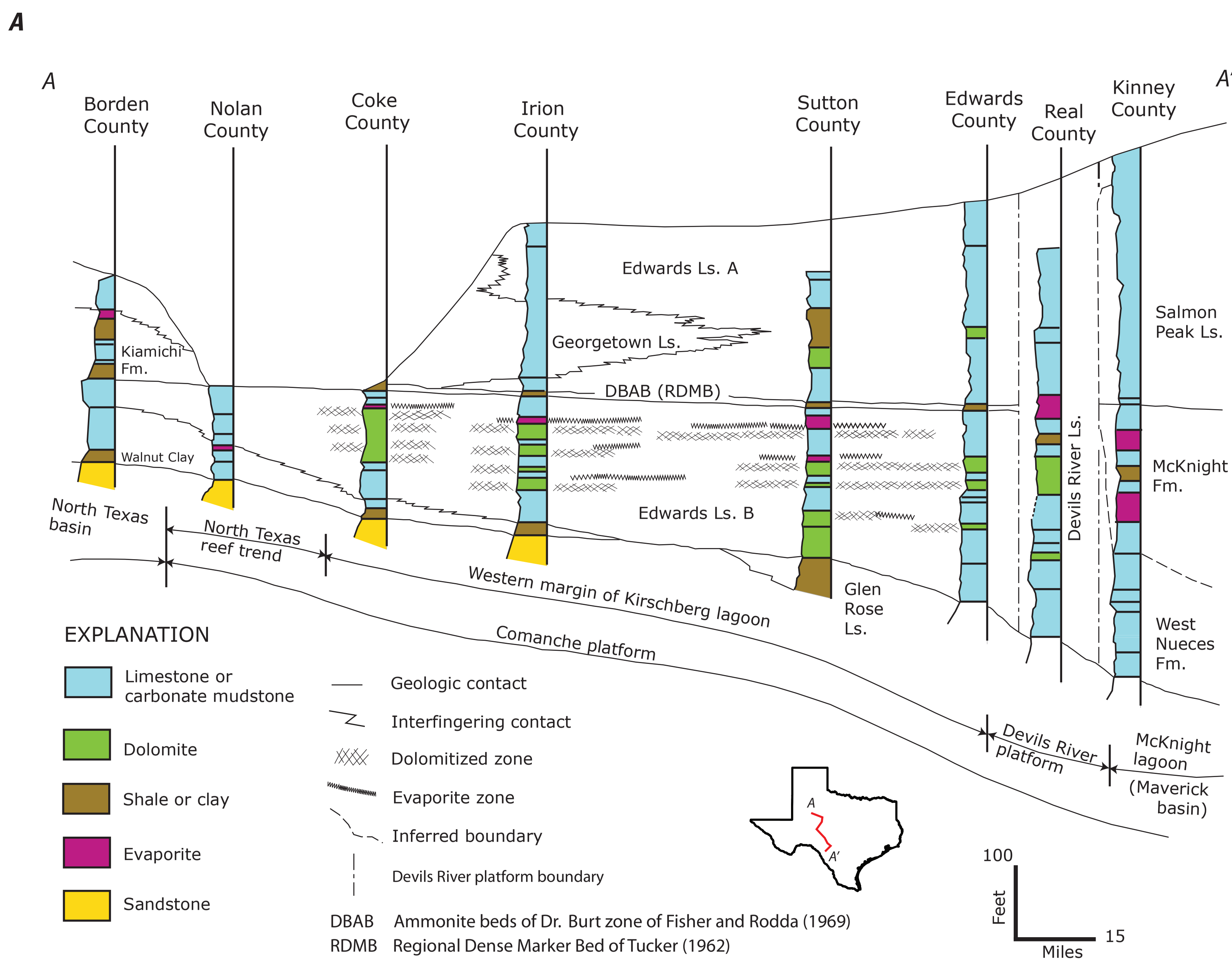
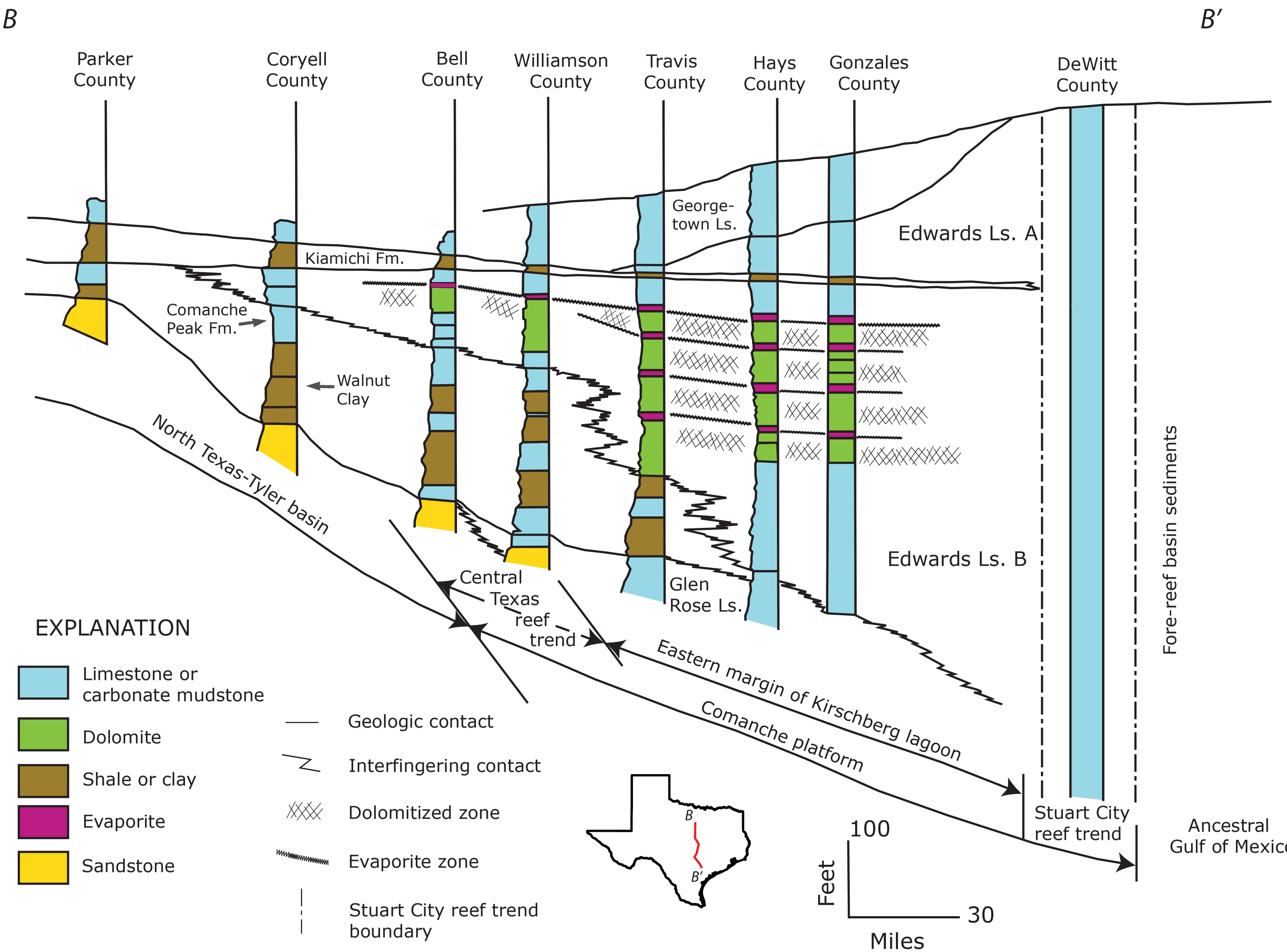


Figure 5 (this page and facing page). Stratigraphic cross sections showing relations between the Fredericksburg Group and equivalent strata (modified from Fisher and Rodda, 1969). *A*, West-central Texas. *B*, East-central Texas. The location of the Comanche platform is shown on the map in figure 4*A*. Abbreviations: Fm., Formation; Ls., Limestone.

B



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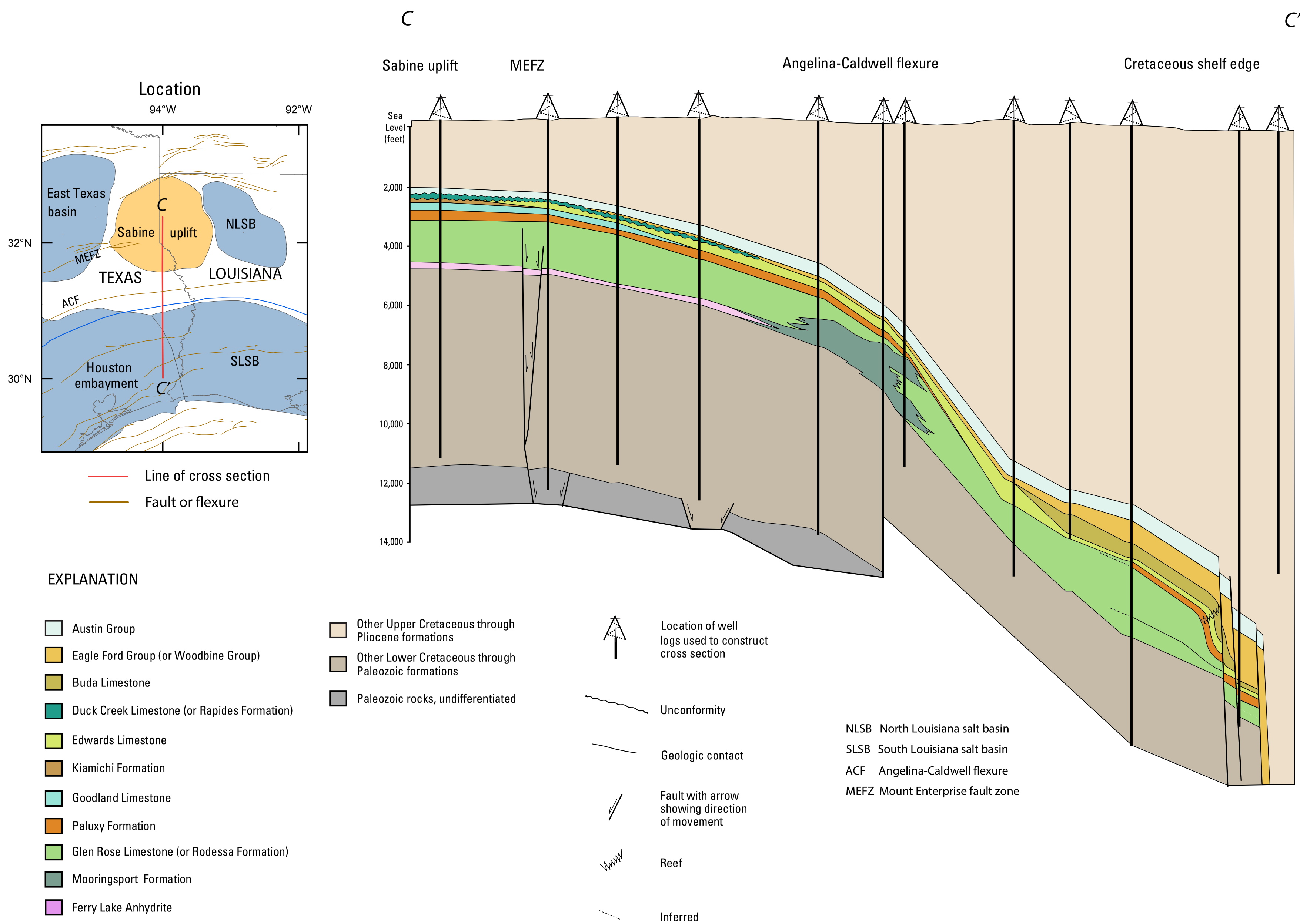


Figure 6. Cross section of the Fredericksburg and Washita Groups and equivalent strata in eastern Texas (modified from Stoudt, Hutchinson, and Gordon, 1990). Abbreviations: Fm., Formation; Gp., Group; Ls., Limestone.

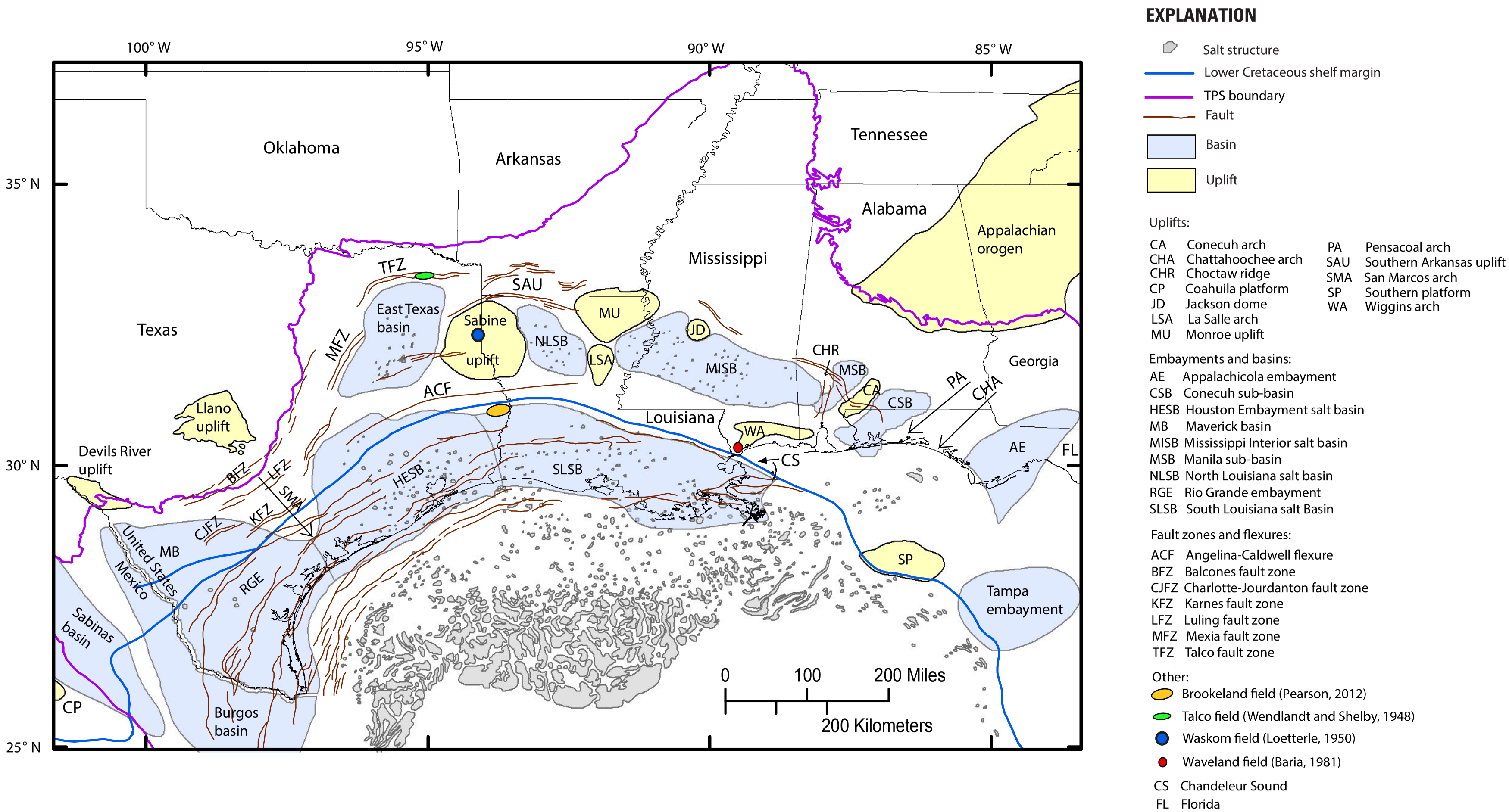
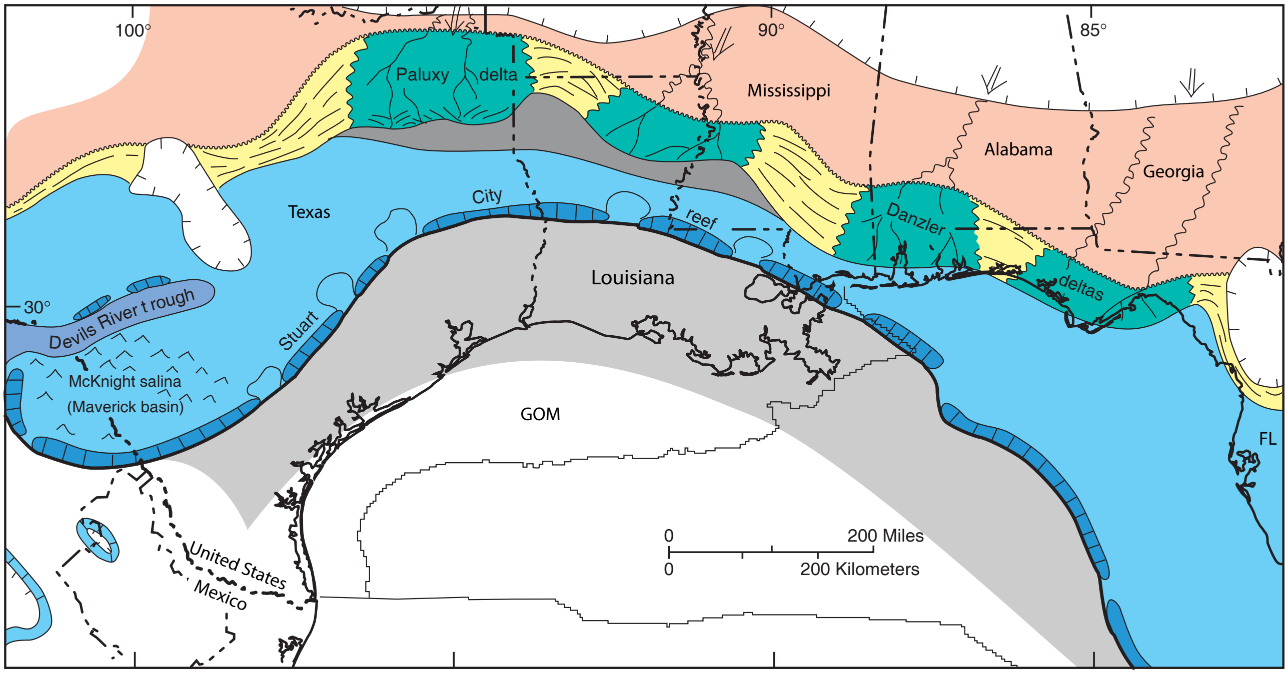


Figure 7. Regional map of the northern part of the Gulf of Mexico basin showing structural features. The Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System (TPS) boundary (Dubiel and others, 2007), the Lower Cretaceous shelf margin (Ewing and Lopez, 1991), and the locations of fields discussed in the report are shown. Structural features were modified from Ewing and Lopez (1991), Laubach (1997), Llinas (2003), Mancini and Goddard (2004), and Mancini and others (2008).



Reprinted from *The sedimentary basins* of the United States and Canada, vol. 5, *of* The sedimentary basins of the world, Galloway, W.E., Depositional evolution of the Gulf of Mexico sedimentary basin, p. 505–549, 2008, with permission from Elsevier.

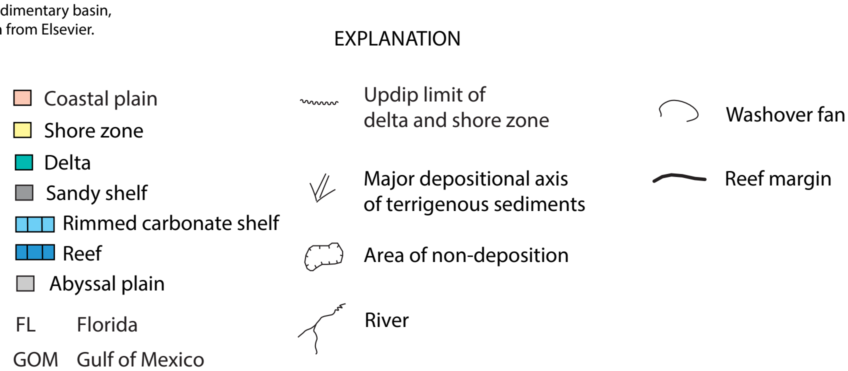


Figure 8. Map showing generalized paleogeography of the U.S. Gulf Coast region during Early Cretaceous (Albian) time, when the Fredericksburg Group strata were deposited (modified from Galloway, 2008).

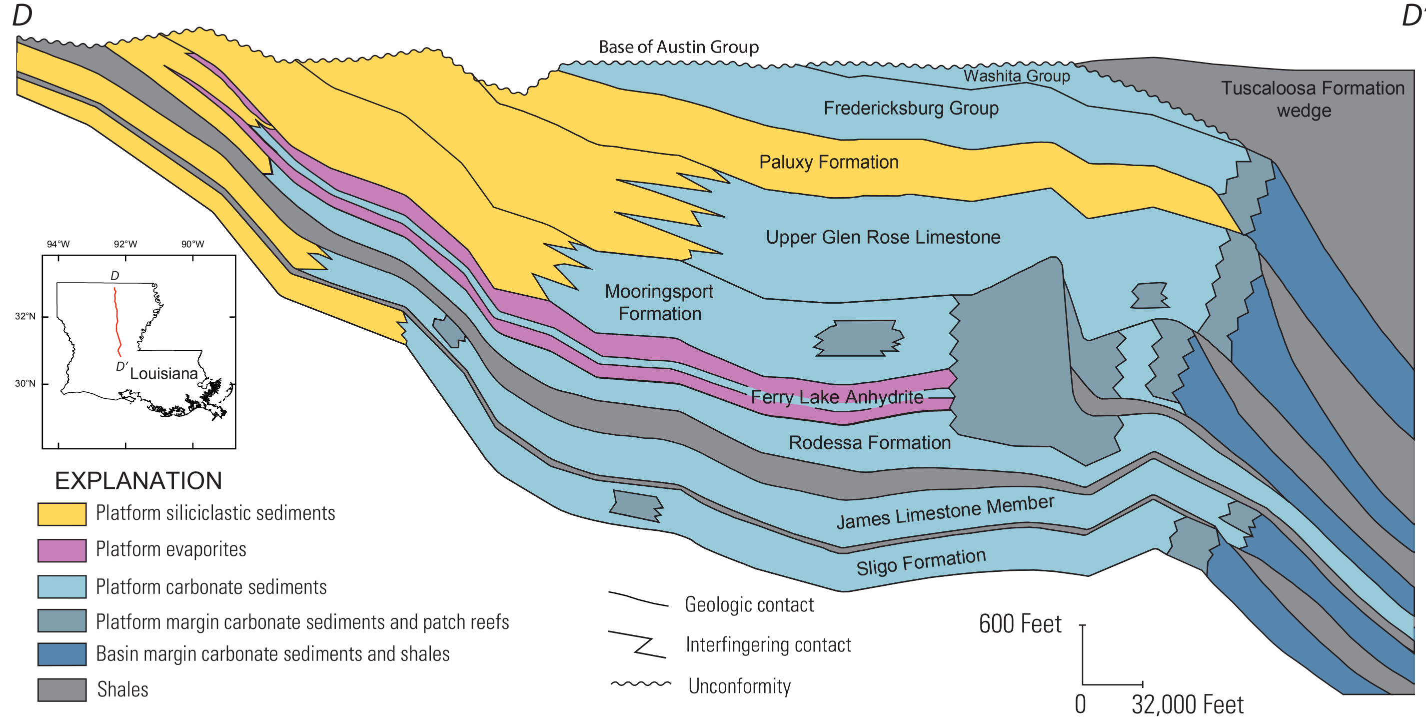
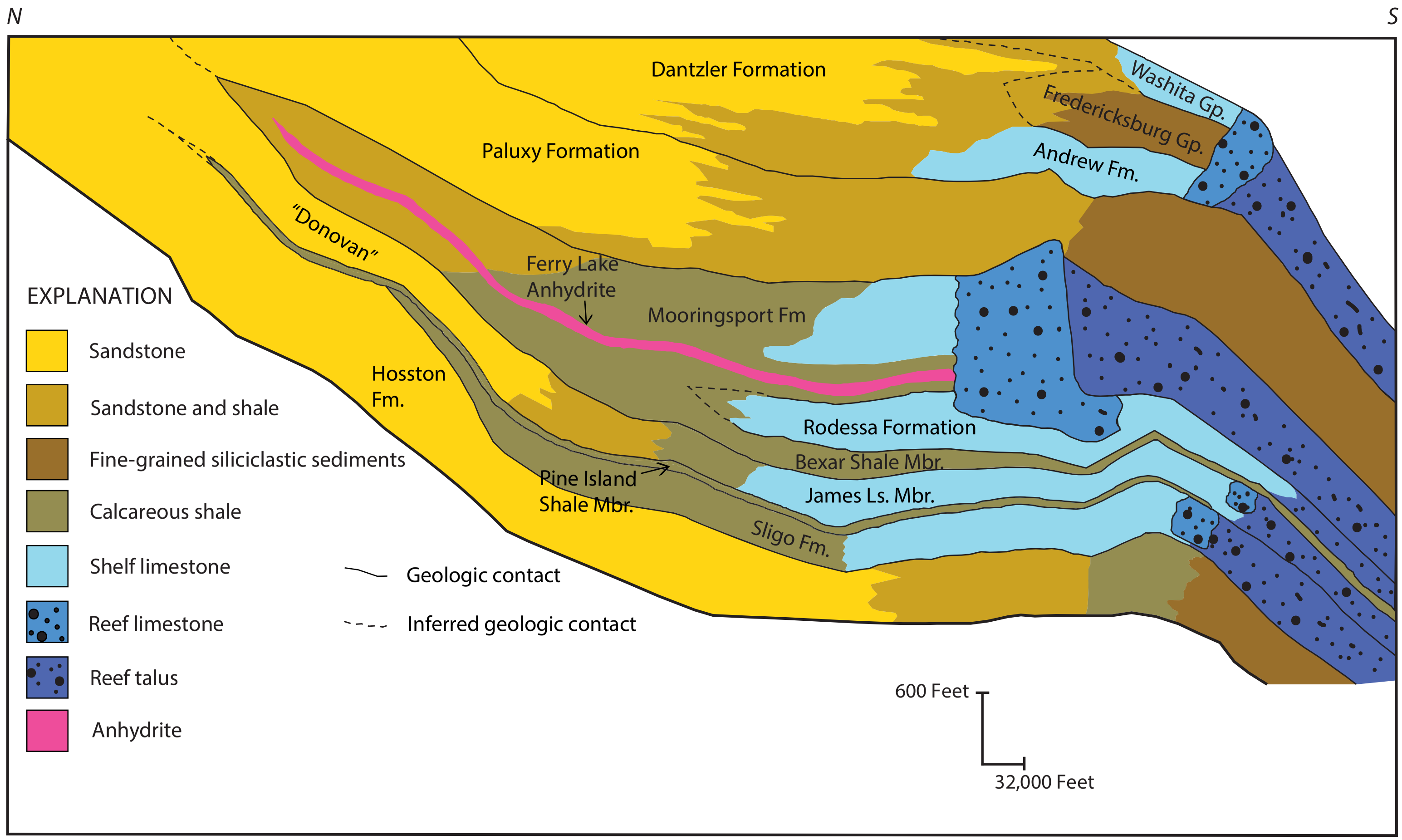
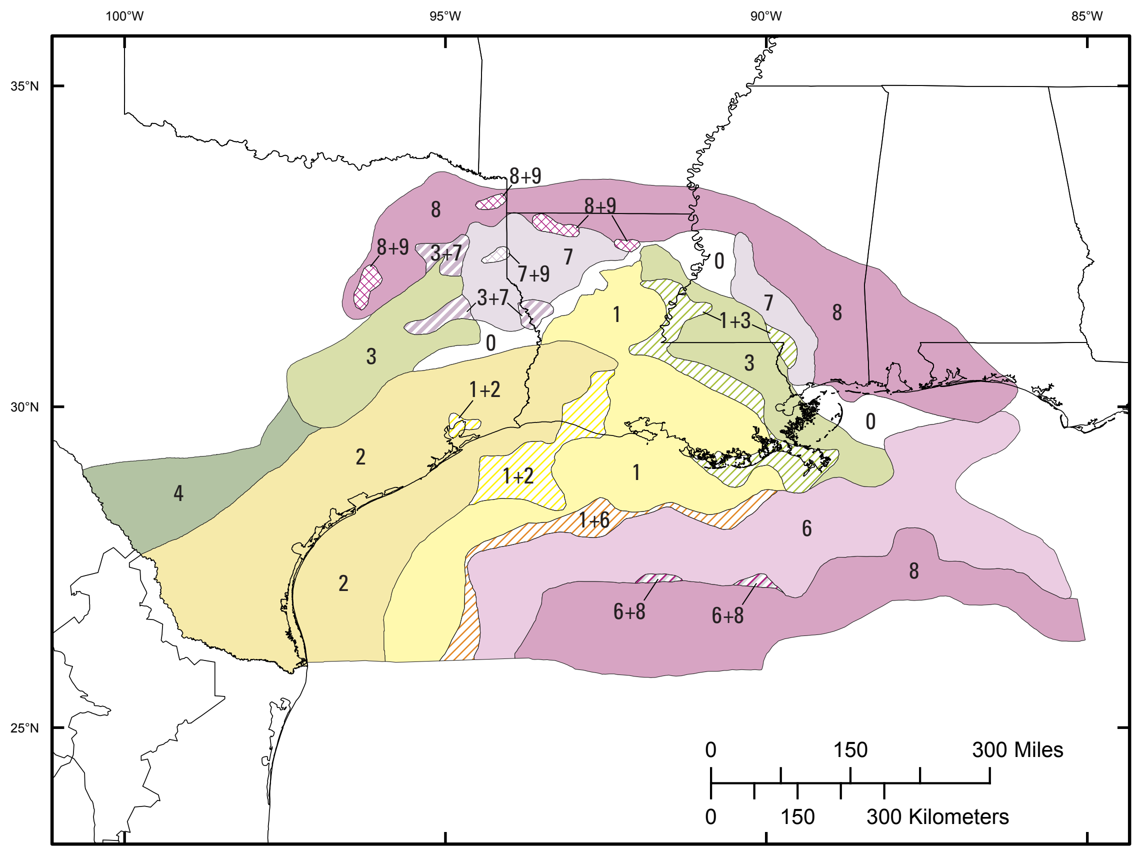


Figure 9. Simplified north-south stratigraphic cross section showing lithofacies of the Fredericksburg and Washita Groups and other Lower and Upper Cretaceous units in north-central Louisiana (modified from Yurewicz and others, 1993). The cross section is flattened on the base of the overlying Austin Group, as interpreted by Yurewicz and others (1993). Abbreviations: Fm., Formation; Gp., Group; Ls., Limestone; Mbr., Member.



Reprinted from *Cretaceous Research*, vol. 23, no. 3, Mancini, E.A., and Puckett, T.M., Transgressive-regressive cycles in Lower Cretaceous strata, Mississippi Interior salt basin area of the northeastern Gulf of Mexico, USA, p. 409–438, 2002, with permission from Elsevier.

Figure 10. Schematic stratigraphic cross section showing the distribution of Lower Cretaceous lithofacies from the updip area of the Mississippi Interior salt basin (north, *N*) to the Lower Cretaceous shelf margin and slope in the offshore area of the northeastern Gulf of Mexico (south, *S*) (modified from Mancini and Puckett, 2002; based on Yurewicz and others, 1993). Abbreviations: Fm., Formation; Gp., Group; Ls., Limestone; Mbr., Member. "Donovan" is an informal name used to designate the sandstone interval between the Pine Island Shale Member and the base of the shaly interval below the Ferry Lake Anhydrite, as described by Mancini and Puckett (2002).



EXPLANATION

[Source-rock interval age and depositional environment, based on oil geochemistry characteristics.]

0	Not designated
1	Lower Tertiary (centered on Eocene) marine and intermediate
1+2	Lower Tertiary (centered on Eocene) marine and terrestrial
1+3	Lower Tertiary (centered on Eocene) marine and intermediate, and Upper Cretaceous (centered on Turonian) marine (low sulfur)
1+6	Lower Tertiary (centered on Eocene) marine and intermediate, and 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), and Upper Jurassic or Lower Cretaceous (?) calcareous
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) and Upper Jurassic carbonate (elevated salinity)
7	Upper Jurassic or Lower Cretaceous (?) calcareous
7+9	Upper Jurassic or Lower Cretaceous (?), and Triassic (Eagle Mills Formation) lacustrine
8	Upper Jurassic (Oxfordian) carbonate (elevated salinity)
8+9	Upper Jurassic (Oxfordian) carbonate (elevated salinity) and Triassic (Eagle Mills Formation) lacustrine
Intermediate	Intermediate between marine and terrestrial

Figure 11. Map of the U.S. Gulf Coast region showing an interpretation of the extent of source-rock intervals, which are based on geochemical characteristics of produced oils and source-rock samples (modified from Wenger and others, 1994; Hood and others, 2002).

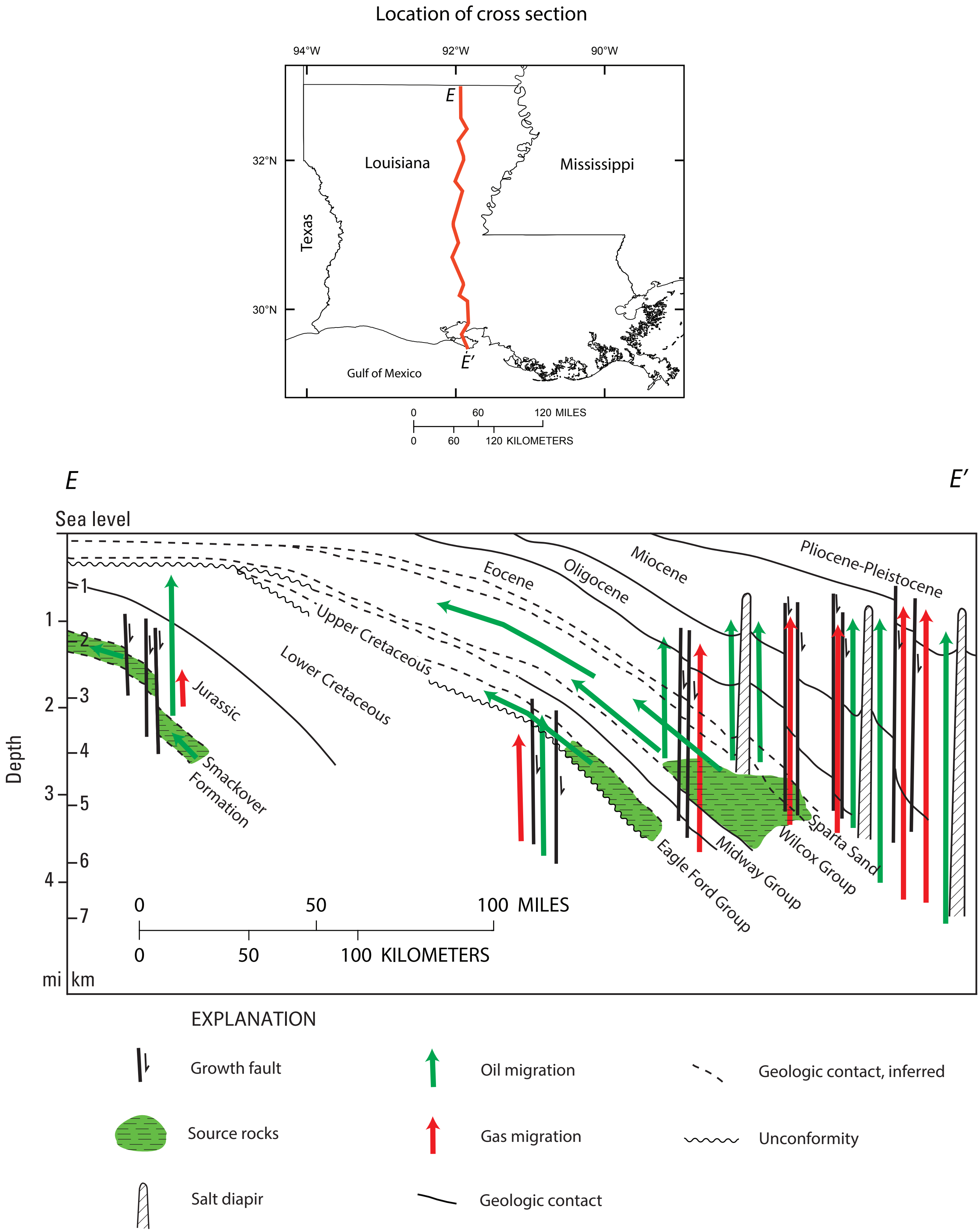


Figure 12. Schematic cross section from northern to southern Louisiana showing a general model for source-rock formations and migration pathways. Abbreviation: mi, miles; km, kilometers (figure modified from M. Lewan, U.S. Geological Survey, written commun., 2006; Sassen, 1990).

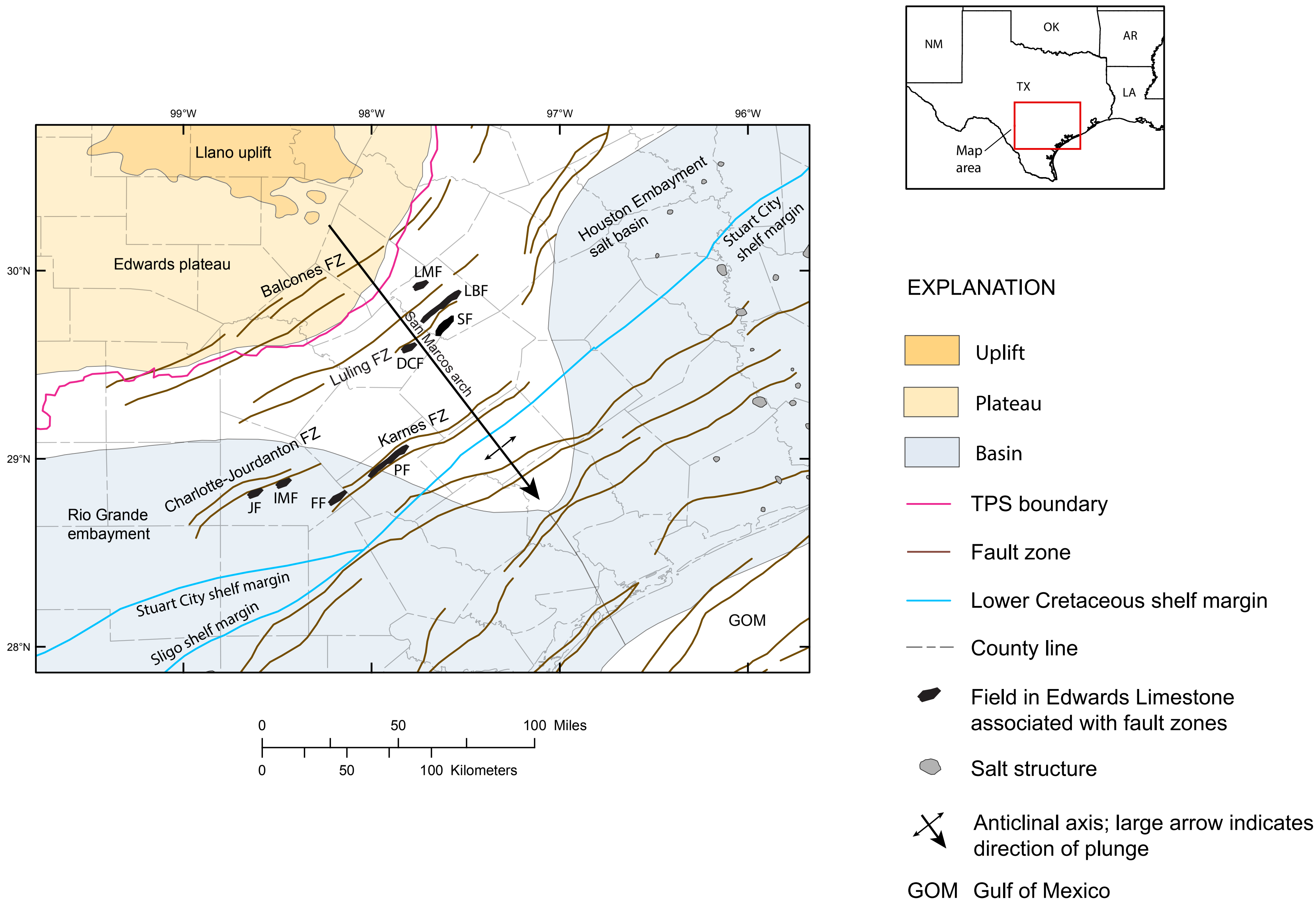


Figure 13. Map of south-central Texas showing the locations of fields in the Edwards Limestone that are associated with fault zones of regional extent in the San Marcos arch area (modified from Galloway and others, 1983). Locations of fields are approximate (based on Cook, 1979; Galloway and others, 1983; and Kosters and others, 1989). Abbreviations: DCF, Darst Creek field; FF, Fashing field; FZ, fault zone; IMF, Imogene field; JF, Jourdanton field; LBF, Luling-Branyon field; LMF, Larremore field; PF, Person field; SF, Salt Flat field; TPS, Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System.

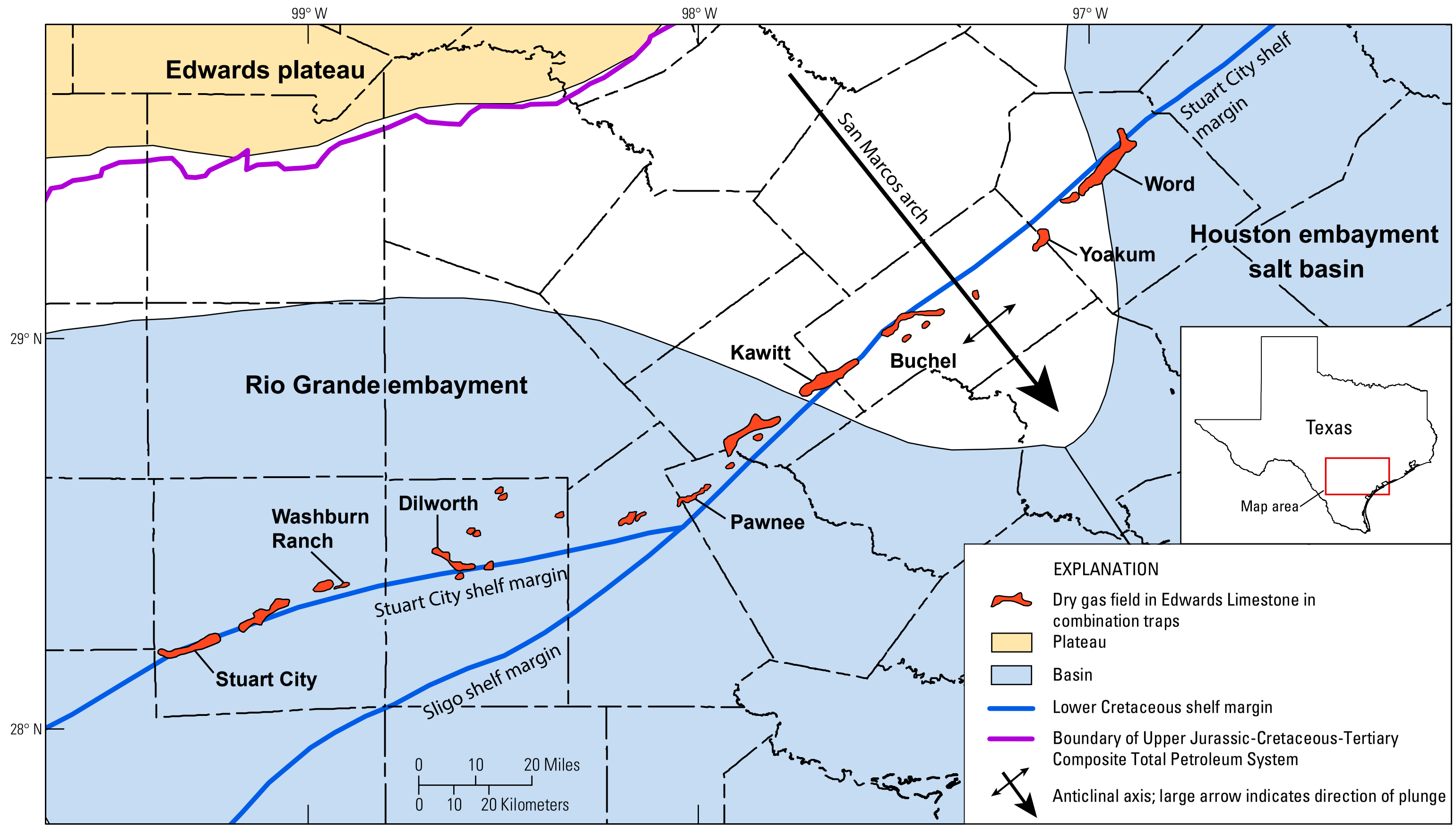


Figure 14. Map of south-central Texas showing fields of dry gas in the Edwards Limestone in combination traps along the Stuart City reef margin (modified from Waite, 2009; names and locations of fields from Waite, 2009). Abbreviation: Ls., Limestone.

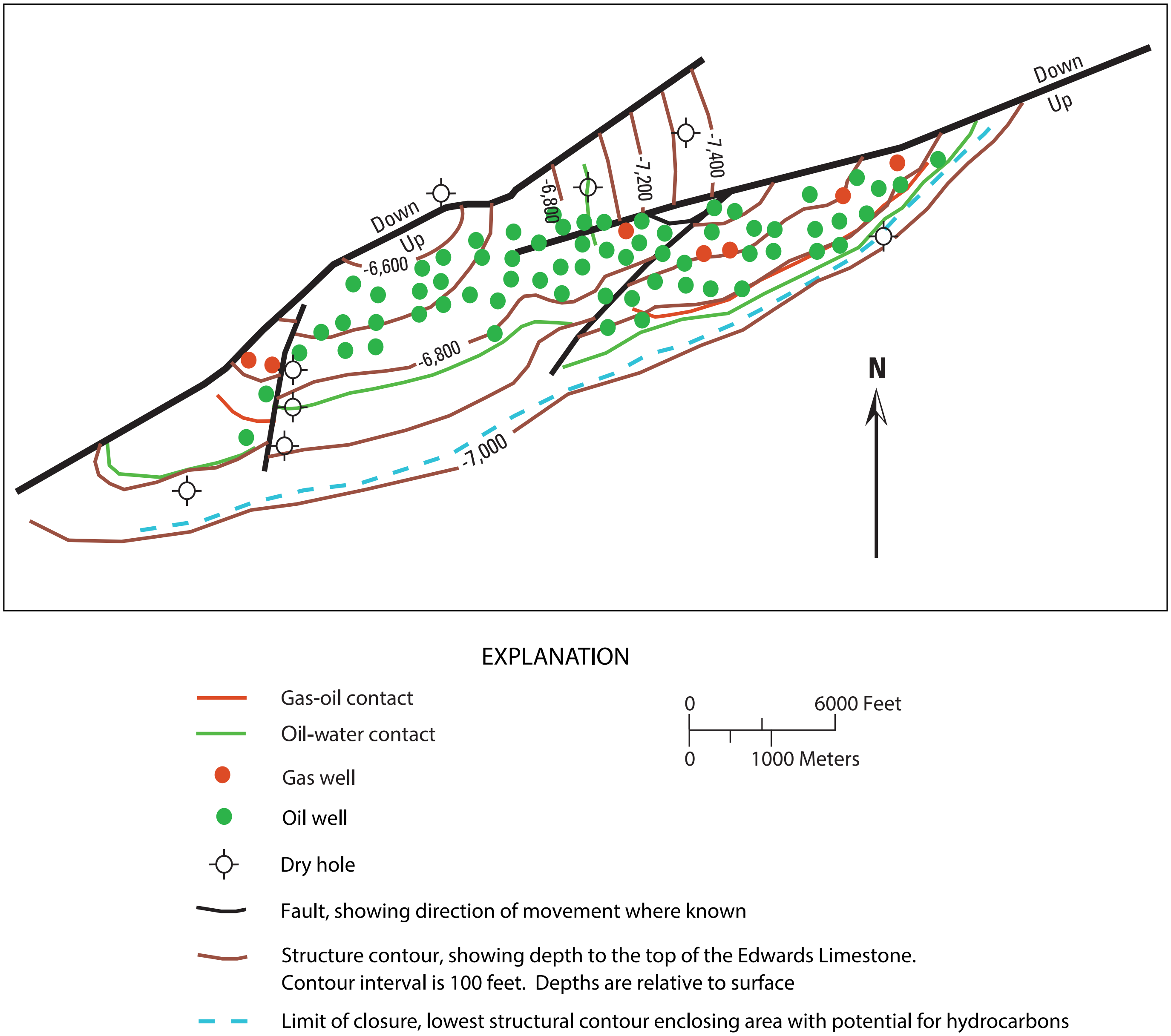


Figure 15. Generalized structure-contour map of the top of the Edwards Limestone in the Jourdanton field, Atascosa County, Texas (fig. 13) (modified from Cook, 1979). The trap is typical of other reservoirs in the Atascosa trough. Wells that were productive in 1978 from the Edwards Limestone are shown.

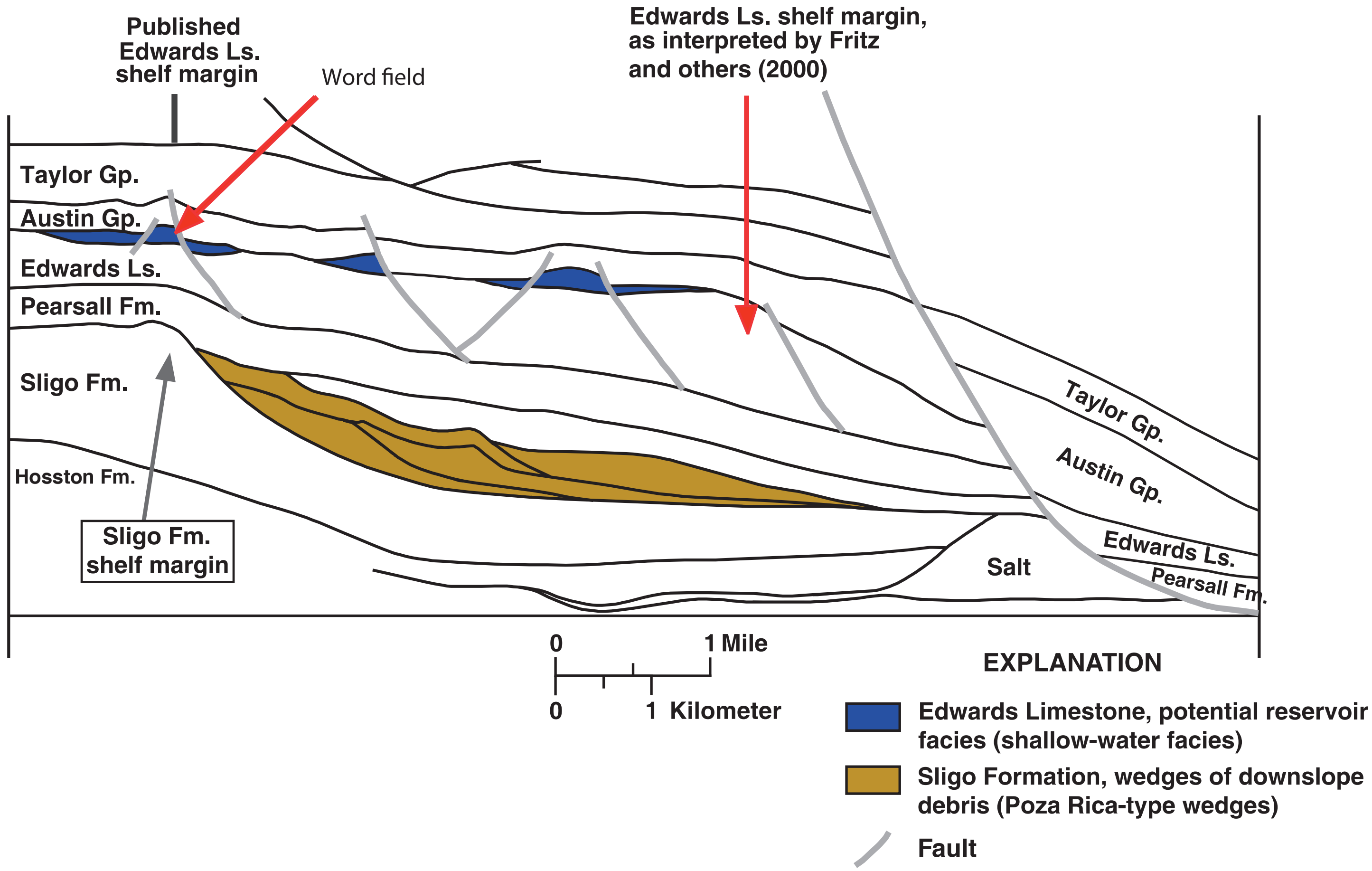


Figure 16. Schematic dip cross section of Cretaceous strata in onshore Texas (modified from Fritz and others, 2000). The Edwards Limestone shelf margin consists of grainstone and reef facies, with both sets of facies repeating themselves several times as the margin prograded from the position of the commonly recognized Edwards margin (published Edwards Ls. shelf margin) to a position about 3 miles seaward (Edwards Ls. shelf margin, as interpreted by Fritz and others (2000)). General location of the Word field is in figure 14. Abbreviations: Fm., Formation; Gp., Group; Ls., Limestone.

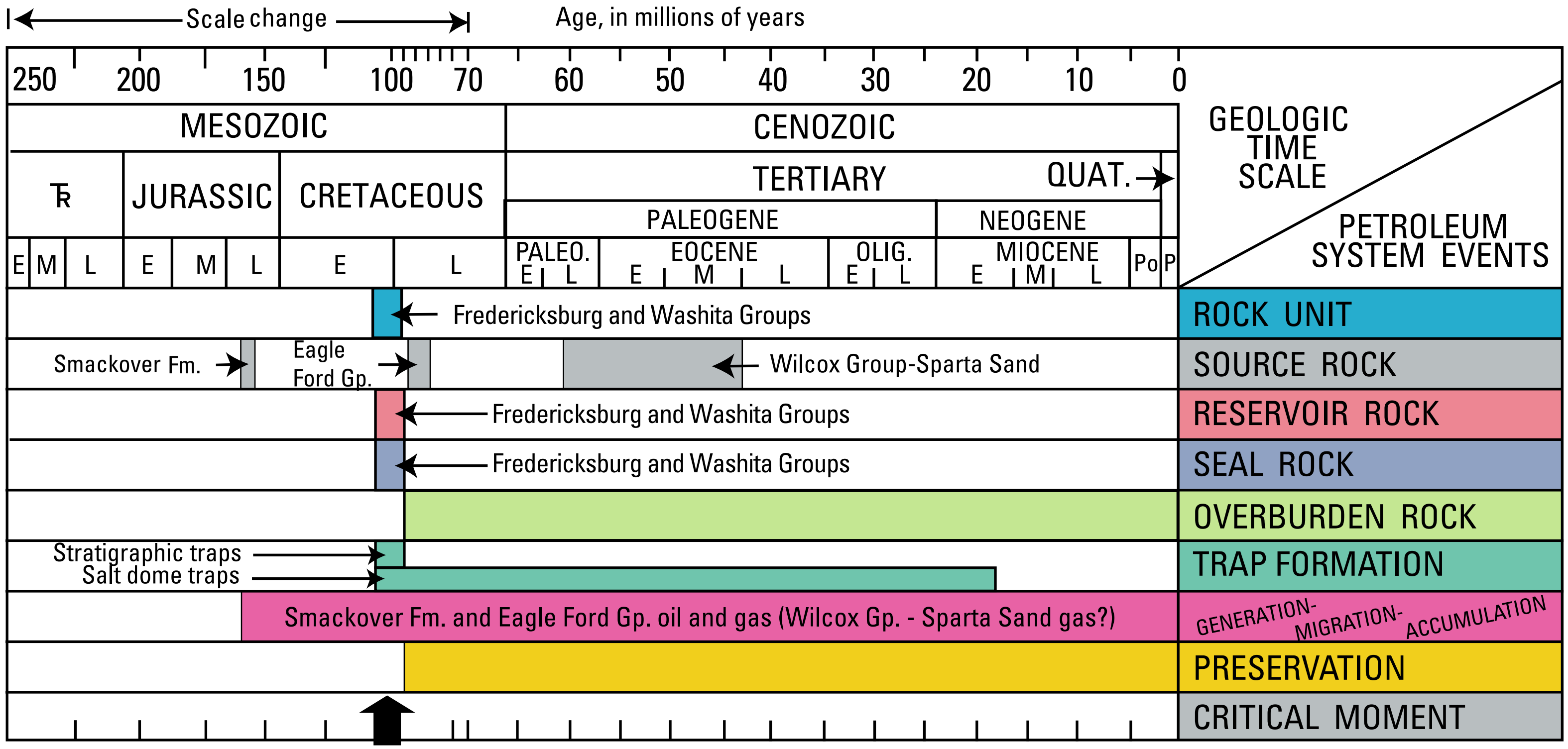


Figure 17. Petroleum system events chart for Fredericksburg and Washita Group hydrocarbon reservoirs in carbonate rocks within the Upper-Jurassic-Cretaceous-Tertiary Composite Total Petroleum System. The "critical moment" (shown by the heavy black arrow) is the point in time that best depicts the generation, migration, and accumulation of most hydrocarbons in a petroleum system (Magoon and Dow, 1994). Abbreviations: E, early or Early; Fm., Formation; Gp., Group; L, late or Late; M, middle or Middle; Ma, mega-annum (millions of years before present); Olig., Oligocene; P, Pleistocene; Paleo., Paleocene; Po, Pliocene; Quat., Quaternary; ꝶ, Triassic, ?, uncertain.

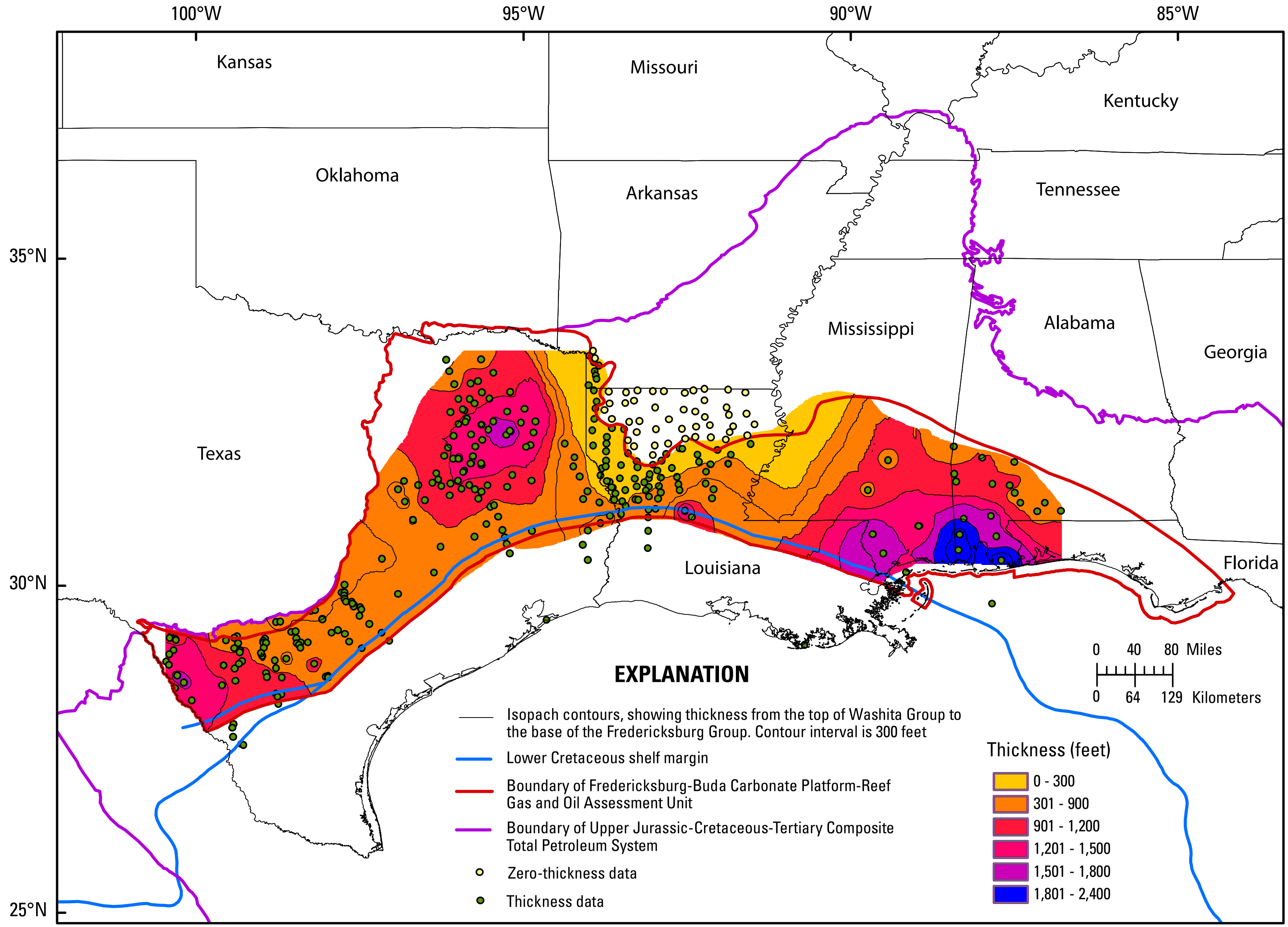


Figure 18. Isopach map showing apparent thicknesses (in feet) of the assessed stratigraphic interval, from the top of the Washita Group to the base of the Fredericksburg Group in the U.S. Gulf Coast region. The updip boundary of the assessment unit in northern Louisiana and western Mississippi represents the eroded boundary of the assessed formations. Estimates were made in areas where data were sparse or lacking. Data for the isopach were derived from Cullom and others (1962); Mosteller (1970); Bebout and Schatzinger (1977); McFarlan (1977); Wood and Guevara (1981); Stoudt, Hutchinson, and Gordon (1990); Stoudt, McCulloh, and Eversull (1990); Badali (2002); Mancini and Goddard (2004); and Mancini and others (2008).

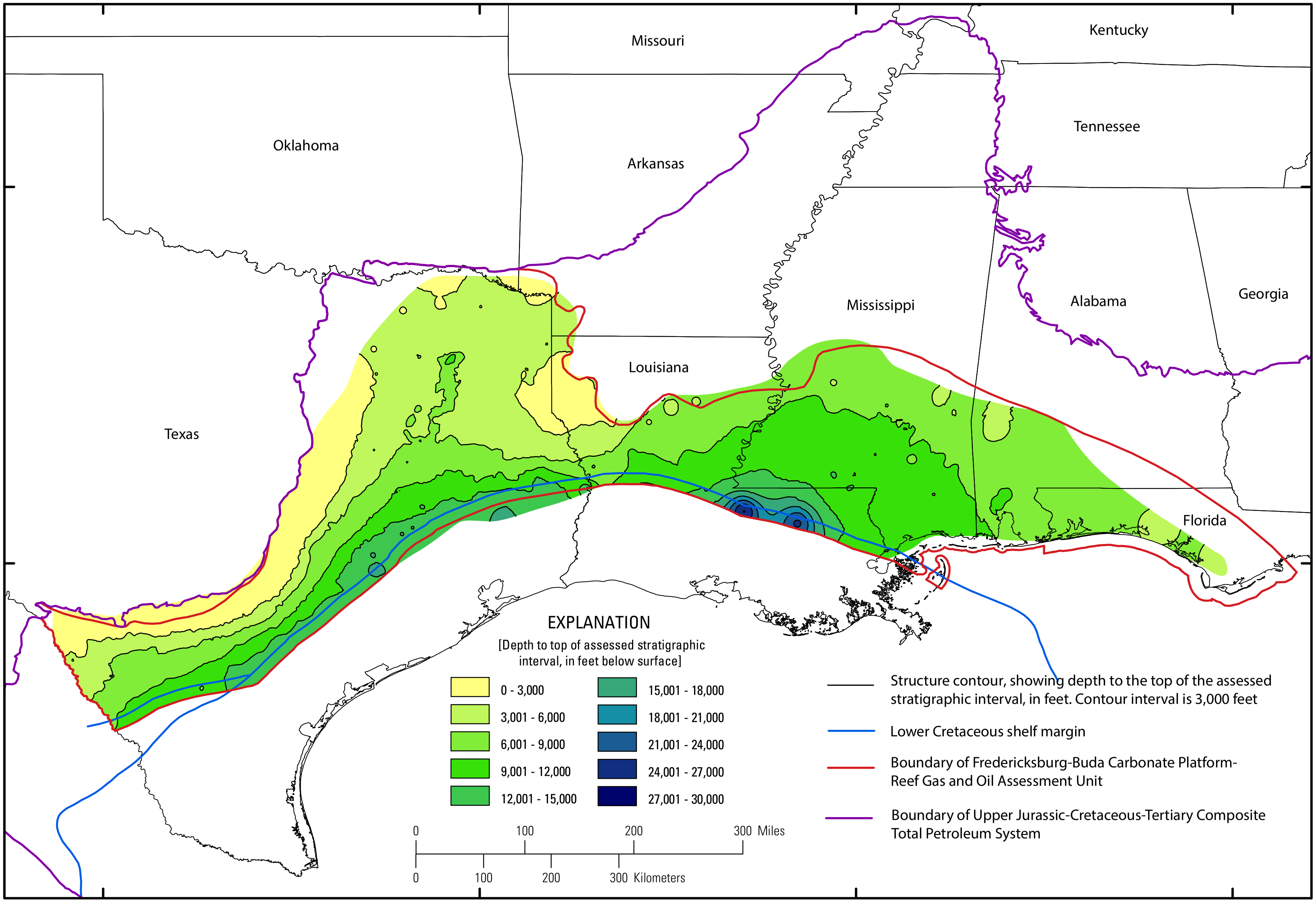


Figure 19. Structure-contour map showing the depth to the top of the assessed stratigraphic interval in the U.S. Gulf Coast region. Contours are based on well data (IHS Energy Group, 2009). Units are in feet below the surface.

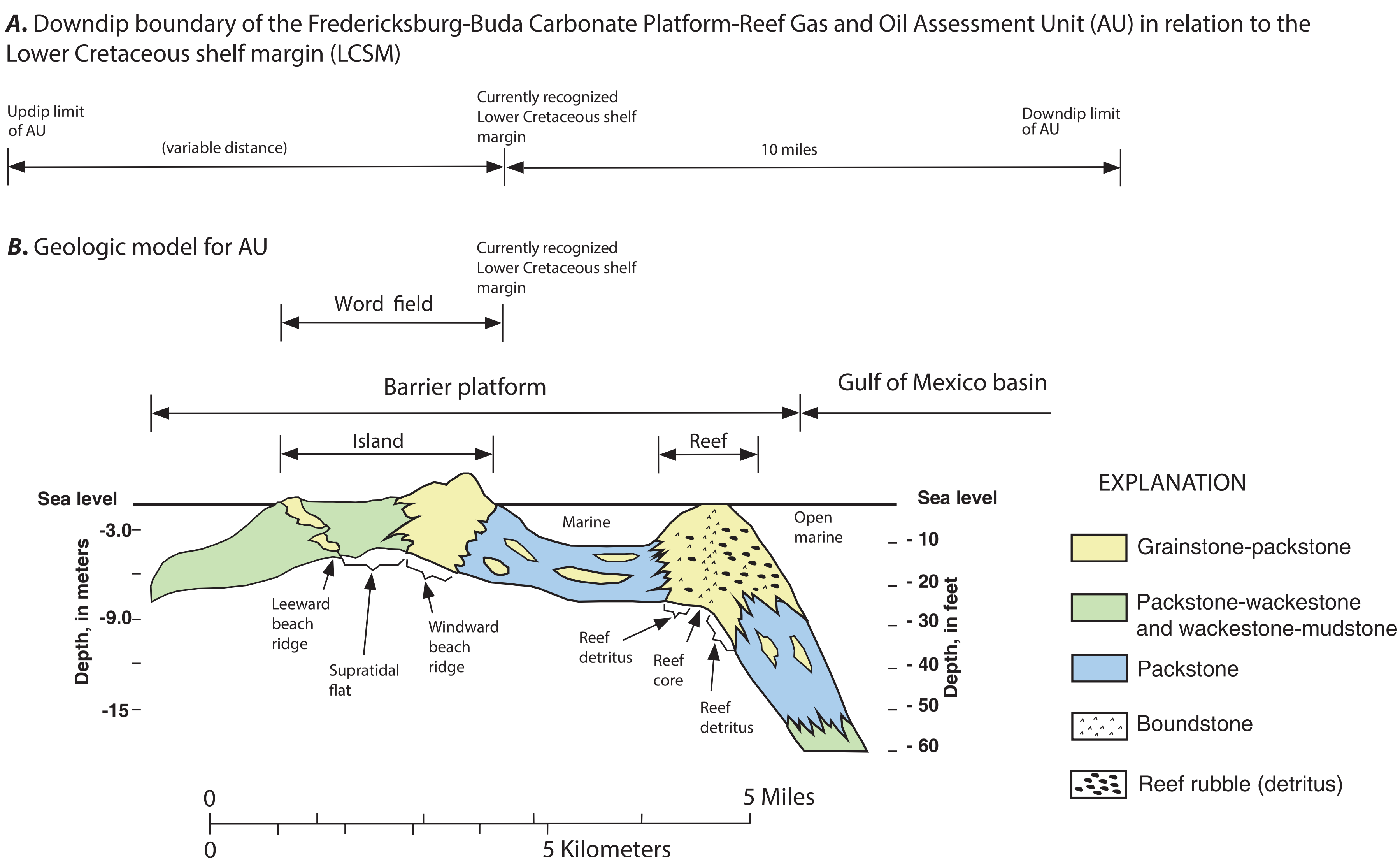


Figure 20. Downdip boundary of the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil Assessment Unit (AU) (shown in *A*) in relation to the geologic model used to define the AU (shown in *B*) (modified from Fritz and others, 2000); note different scales. The model suggests the presence of a shallow-water facies of the Edwards Limestone seaward of the currently recognized shelf margin, using the Word field as an example (Fritz and others, 2000; figs. 14, 16). The boundary of the AU was drawn 10 miles downdip of the currently recognized Lower Cretaceous shelf margin. Two factors were important in determining the downdip limit of the AU: (1) progradation of the shelf margin, and (2) deposition of reef debris. Abbreviation: AU, assessment unit.

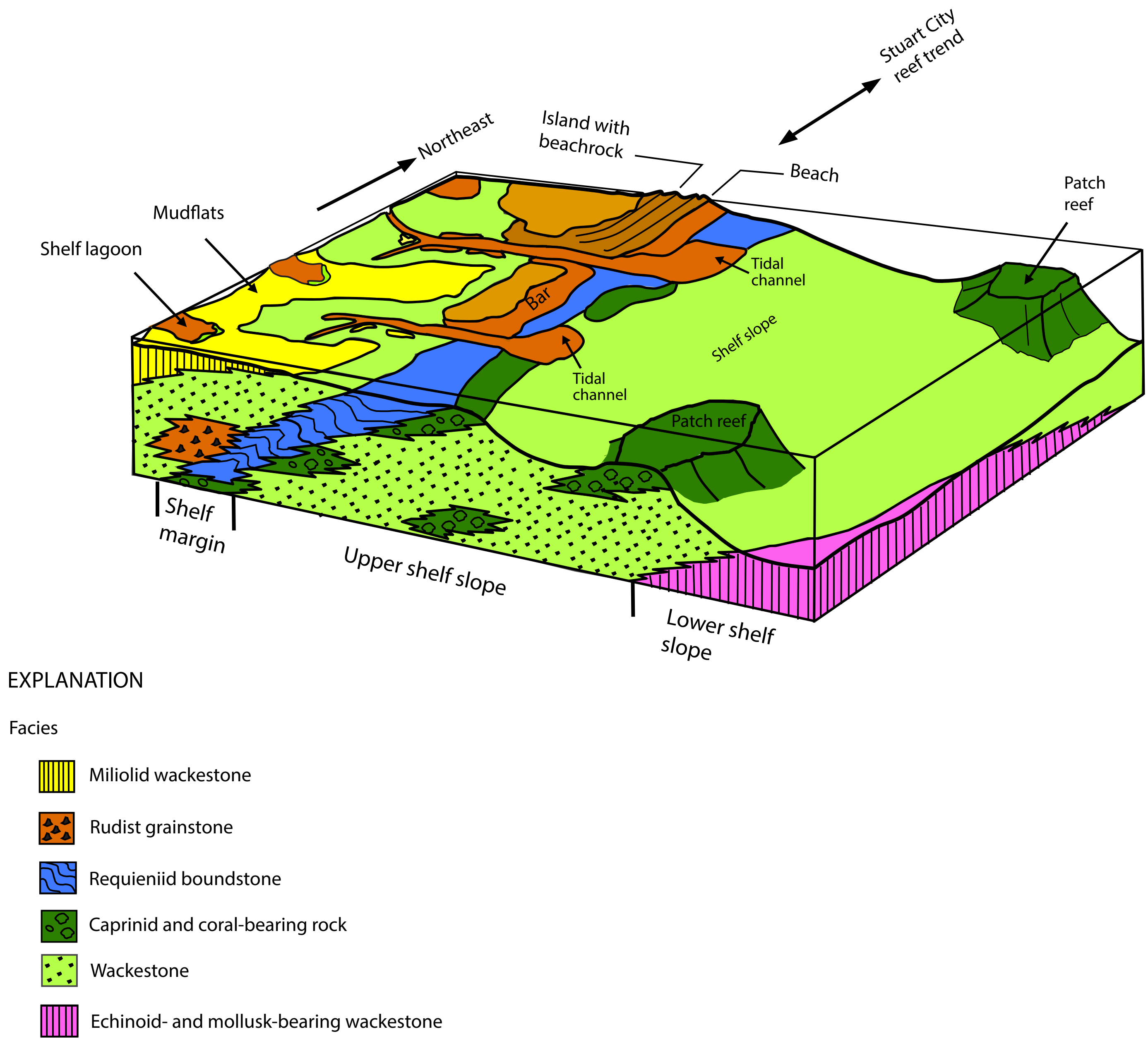


Figure 21. Block diagram illustrating facies and interpreted depositional environments of the Stuart City reef trend in south Texas (modified from Bebout and Loucks, 1983).

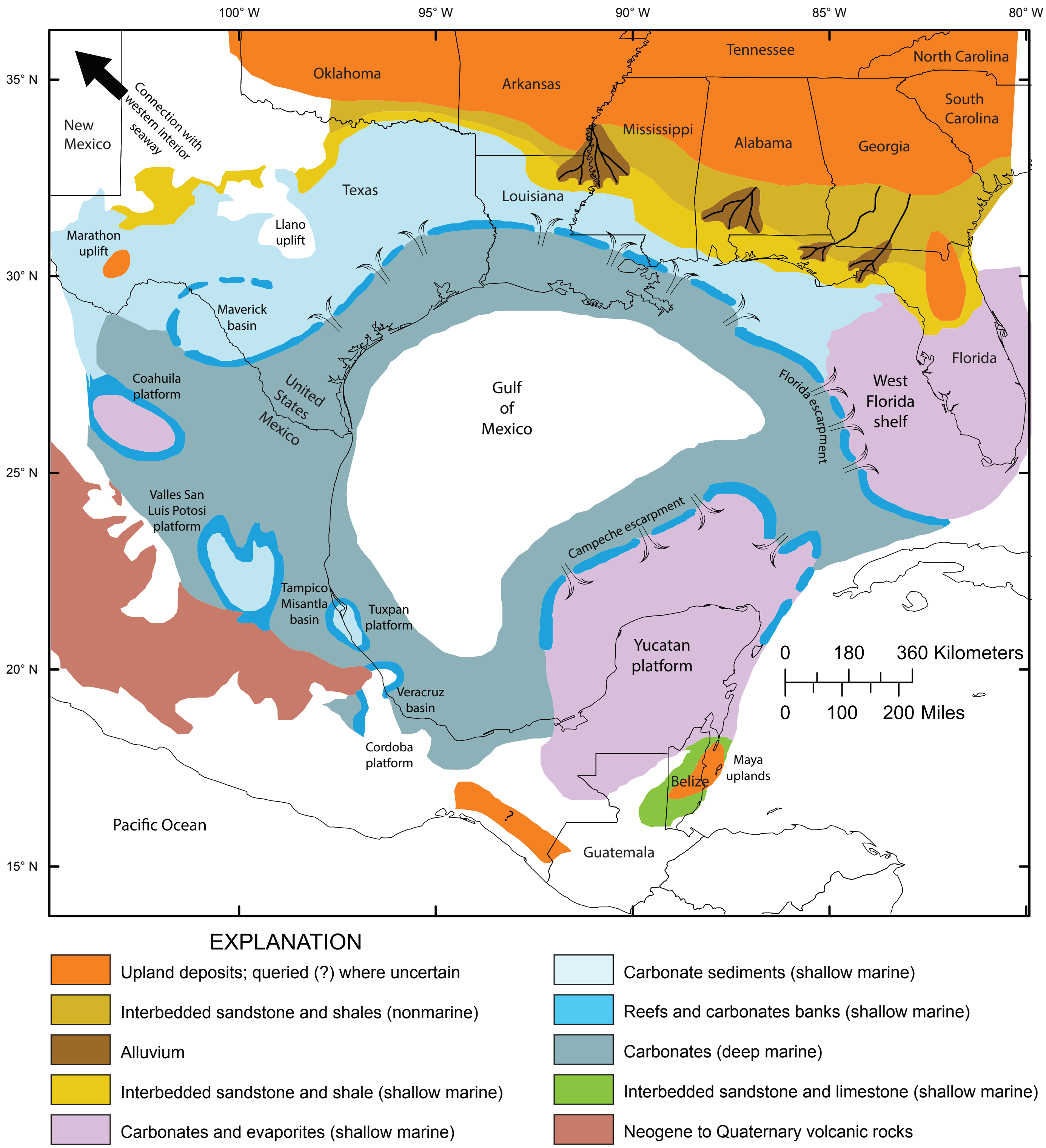


Figure 22. Map of the southeastern United States and Central America showing (1) Albian lithofacies and paleogeography and (2) Neogene and Quaternary volcanic rocks (modified from McFarlan and Menes, 1991). The distribution of siliciclastic deposits in the northeastern Gulf of Mexico basin was a consideration in defining the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil Assessment Unit for carbonate rocks of the Fredericksburg and Washita Groups and equivalents strata.

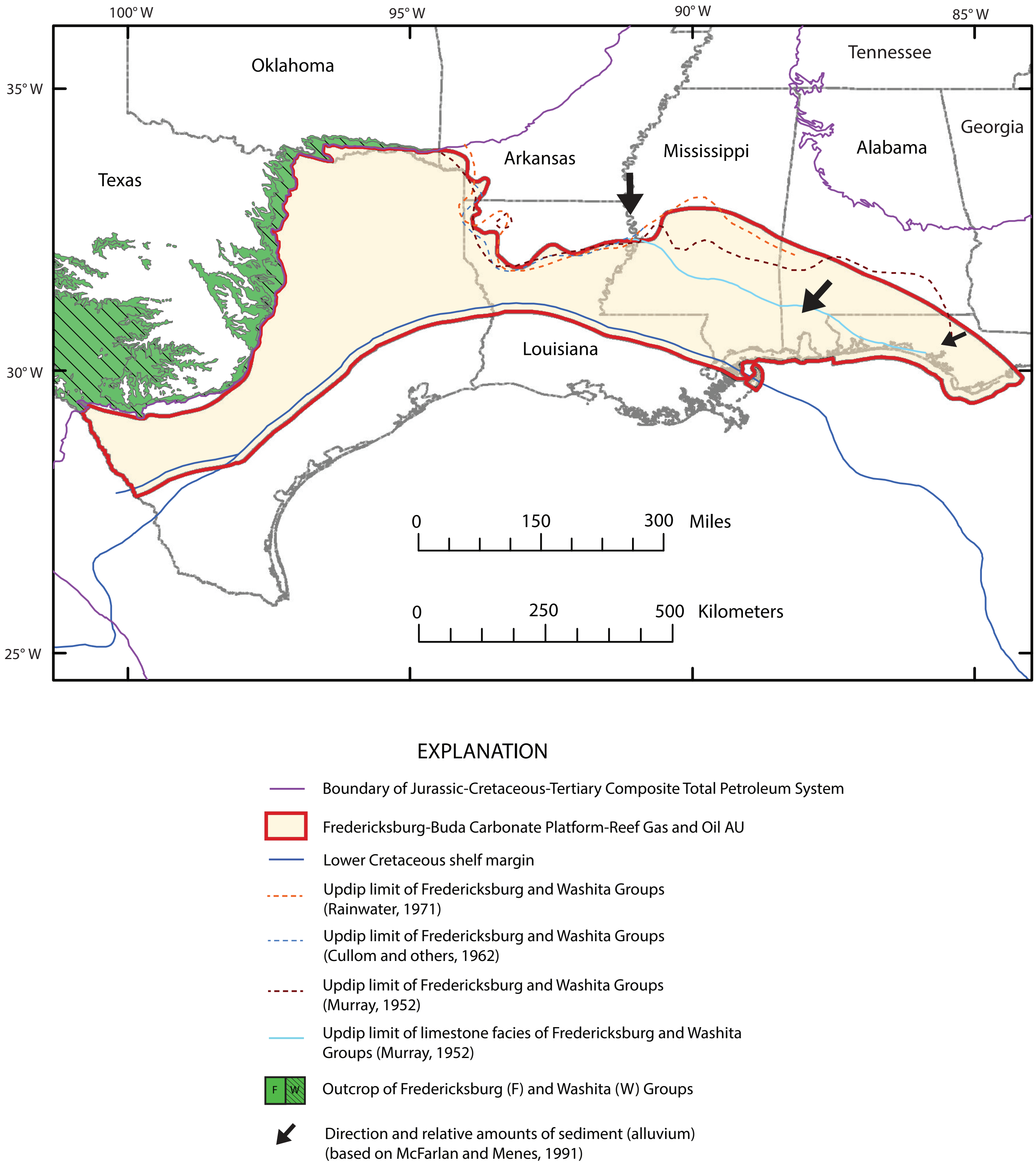


Figure 23. Map of the U.S. Gulf Coast showing the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil Assessment Unit (AU) and the boundaries used to define its limits.

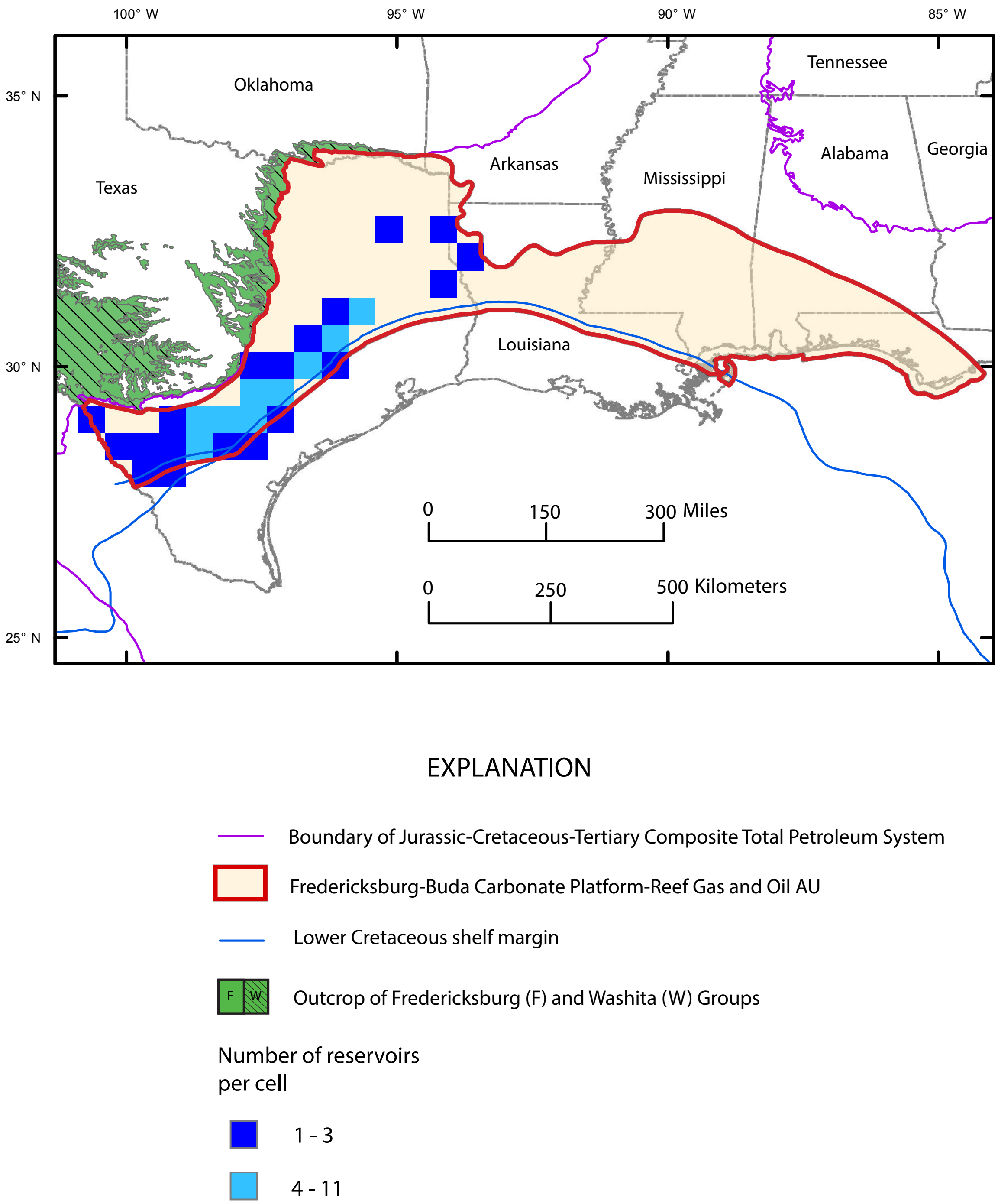


Figure 24. Map of the U.S. Gulf Coast showing the number of reservoirs in fields producing from Fredericksburg and Washita Groups and equivalent strata, based on data from Nehring Associates, Inc. (2009). Cells are about 900 square miles in area. Abbreviation: AU, assessment unit.

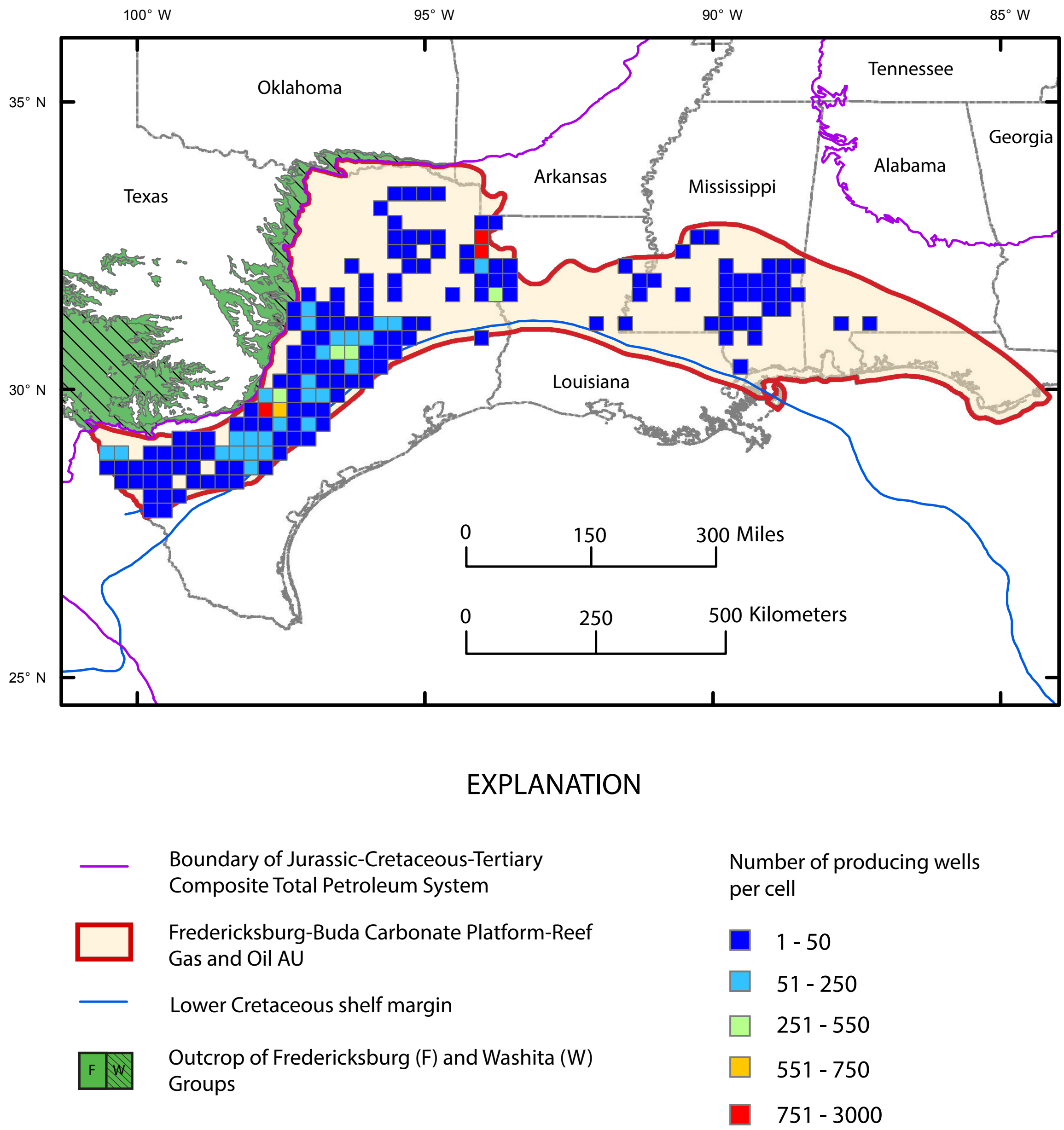


Figure 25. Map of the U.S. Gulf Coast showing the number of producing wells from reservoirs in carbonate rocks of Fredericksburg and Washita Groups and equivalent strata, based on data from IHS Energy Group (2009). Cells are about 251 square miles in area. Although producing wells from carbonate rocks of the assessed interval are shown in Louisiana, Mississippi, and Alabama, production is traditionally assigned to sandstone reservoirs in the Fredericksburg and Washita Groups, undifferentiated (referred to as the Washita-Fredericksburg Groups, undifferentiated, in the literature), or assigned to sandstone reservoirs in the Dantzler Formation in these areas. Abbreviation: AU, assessment unit.

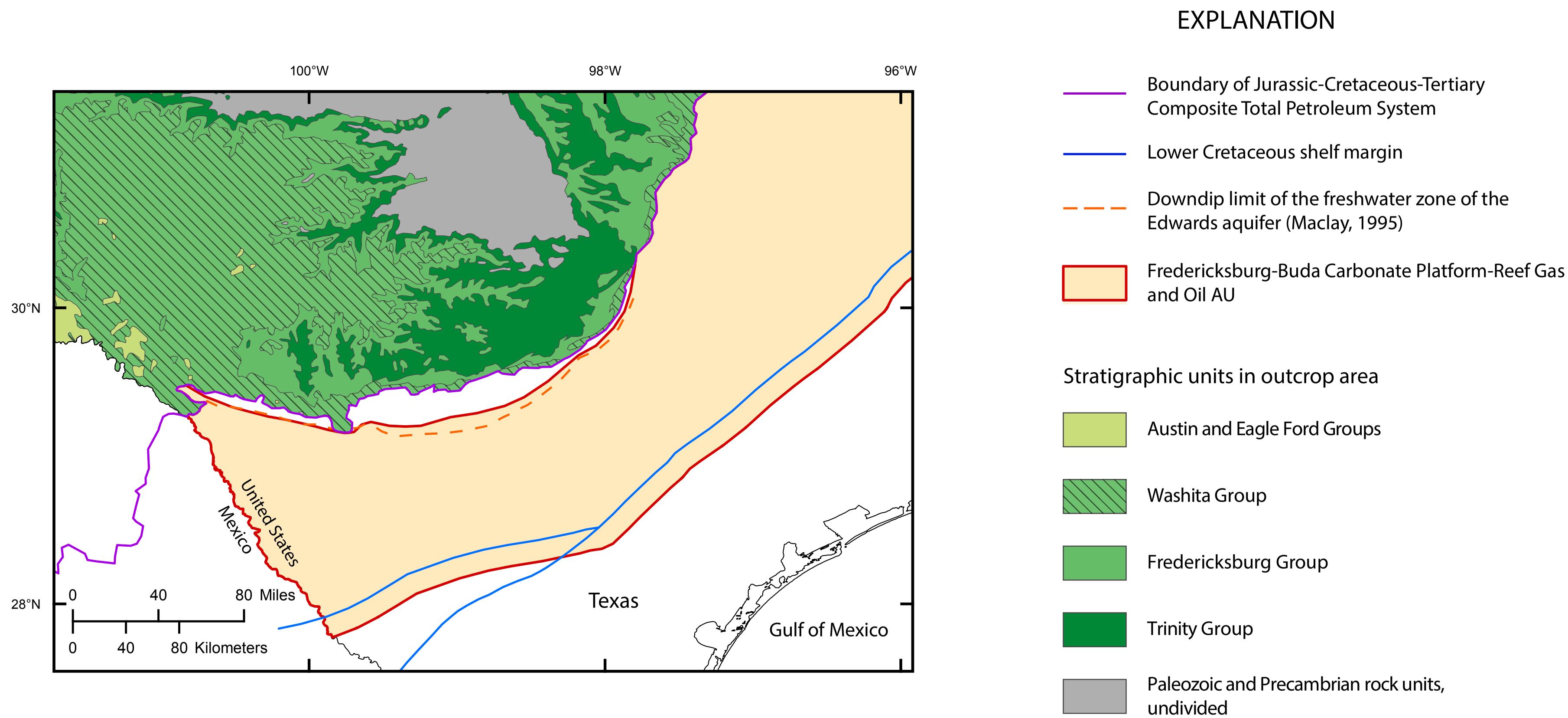


Figure 26. Map showing the approximate downdip limit of the freshwater zone of the Edwards aquifer in southwest Texas; map was constructed on the basis of data given in Maclay (1995). The boundary of the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil Assessment Unit (AU) was constructed to be downdip of the Upper Jurassic-Cretaceous-Tertiary Composite Total Petroleum System (TPS) boundary due to the potential for water washing of hydrocarbons. The geologic map is from Schruben and others (1998); based on King and Beikman (1974).

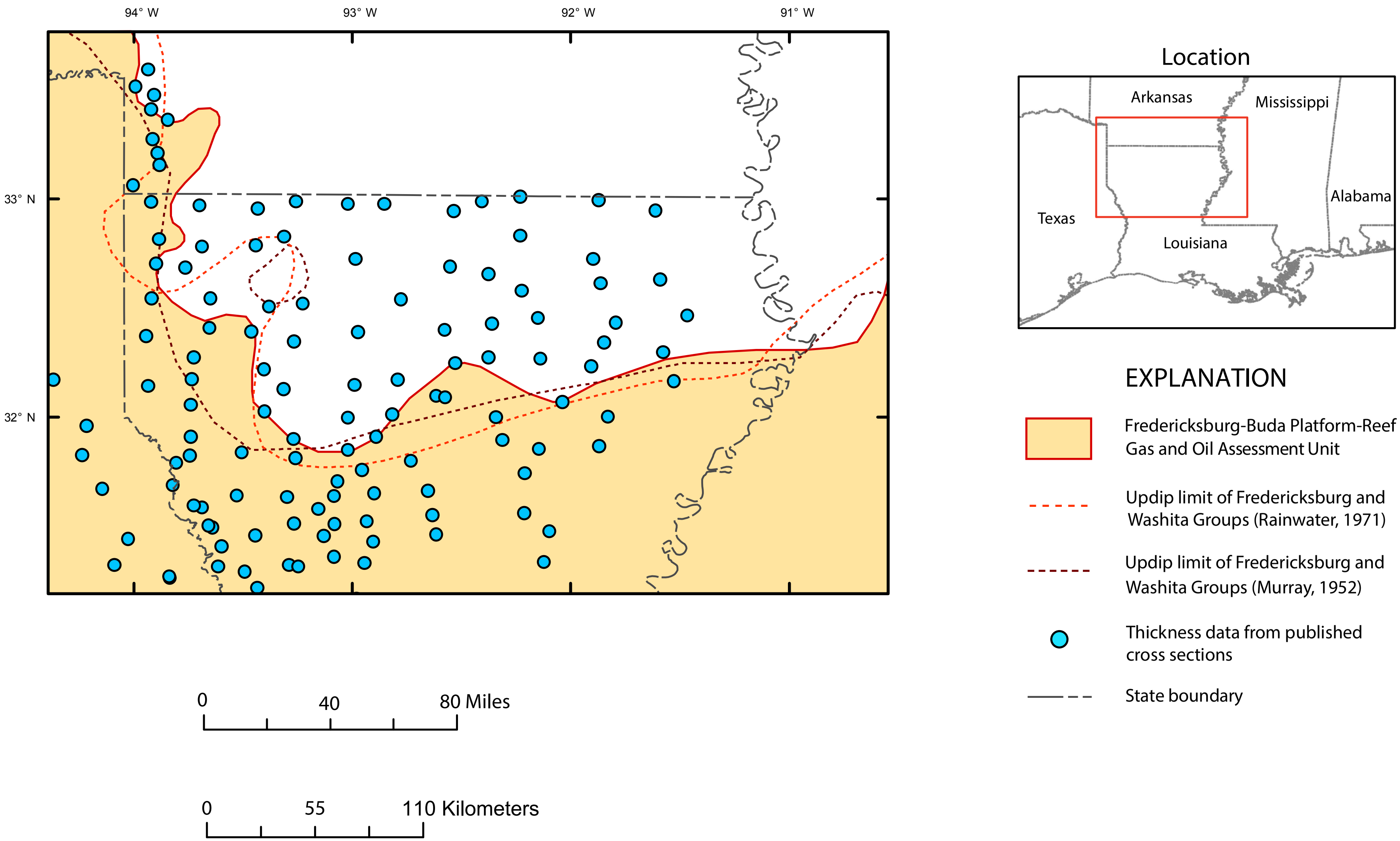


Figure 27. Map of southernmost Arkansas and north-central Louisiana showing thickness data points that were used to determine the eroded areas in the Fredericksburg and Washita Groups and equivalent stratigraphic units and define the updip boundary of the AU in these areas. Data was compiled from published cross sections (Mancini and Goddard, 2004; Stoudt, Hutchinson, and Gordon, 1990; Stoudt, McCulloh, and Eversull, 1990; McFarlan, 1977).

A

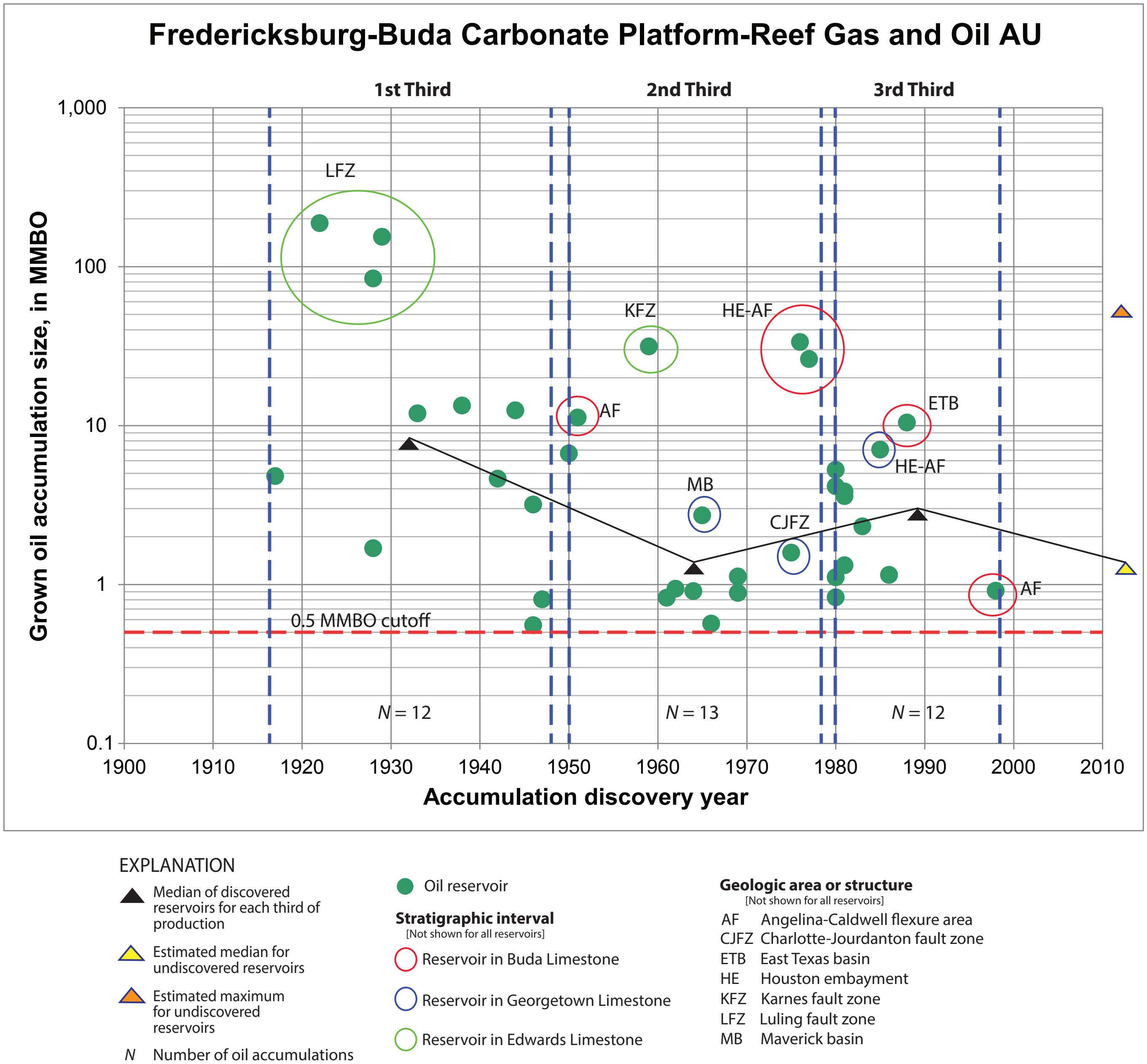
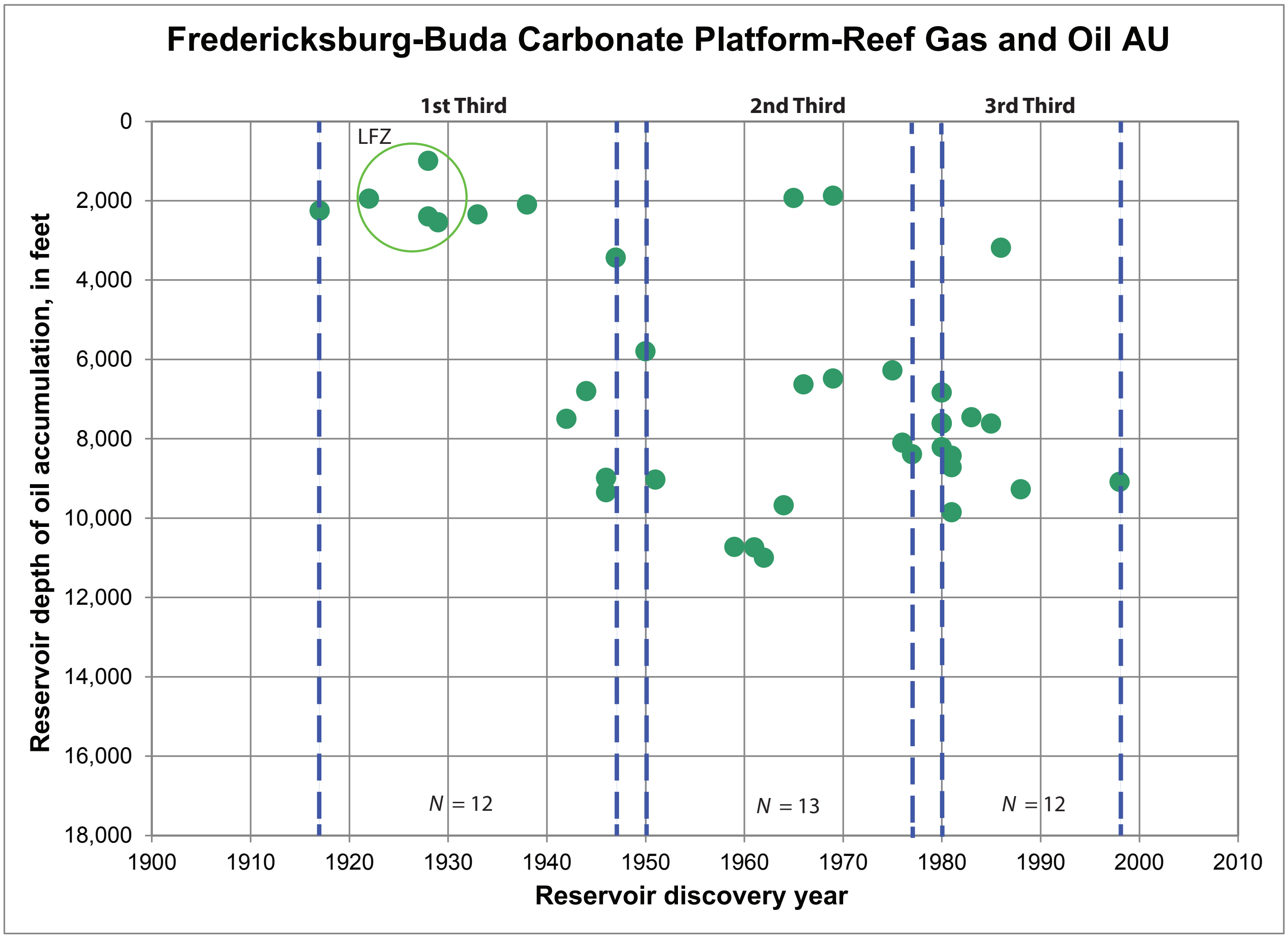


Figure 28 (this page and next 2 pages). Plots showing relations between reservoir discovery year, grown oil accumulation size, reservoir depth, and cumulative grown oil volume for oil accumulations in the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil Assessment Unit (AU). *A*, Accumulation discovery year versus grown oil accumulation size. *B*, Reservoir discovery year versus reservoir depth. *C*, Accumulation discovery year versus cumulative grown oil volume (T. Klett, U.S. Geological Survey, written commun., 2009; plots were generated with data from Nehring Associates, Inc., 2009). The plots have been annotated to indicate the stratigraphic interval and general location of some of the reservoirs (not all reservoirs are labeled). Abbreviation: MMBO, million barrels of oil.

B



EXPLANATION

Oil reservoir

N Number of oil accumulations

Stratigraphic interval
[Not shown for all reservoirs]

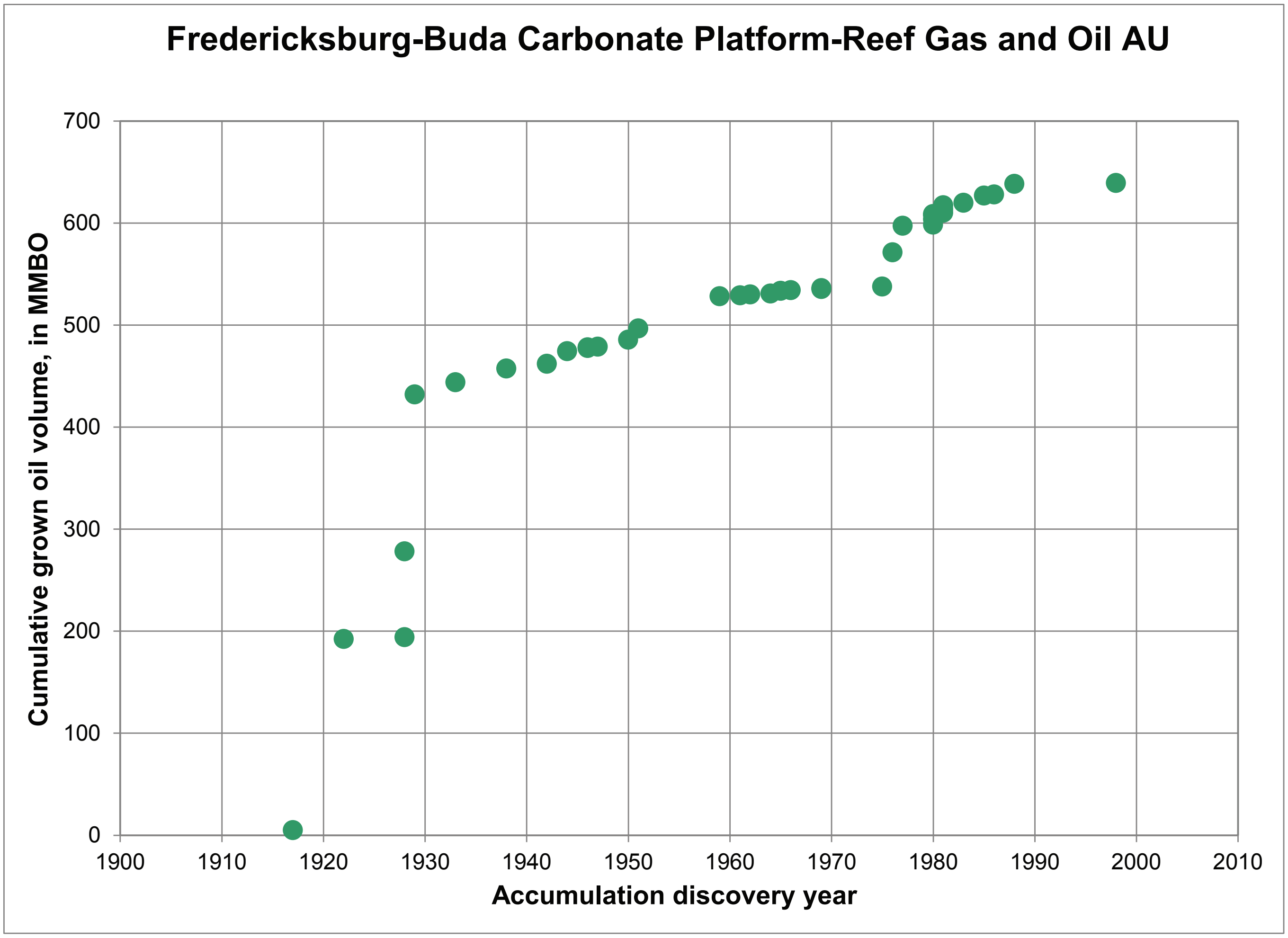
Reservoir in Edwards Limestone

Geologic area or structure
[Not shown for all reservoirs]

LFZ Luling fault zone

Figure 28. Continued.

C



EXPLANATION

Oil reservoir

Figure 28. Continued.

A

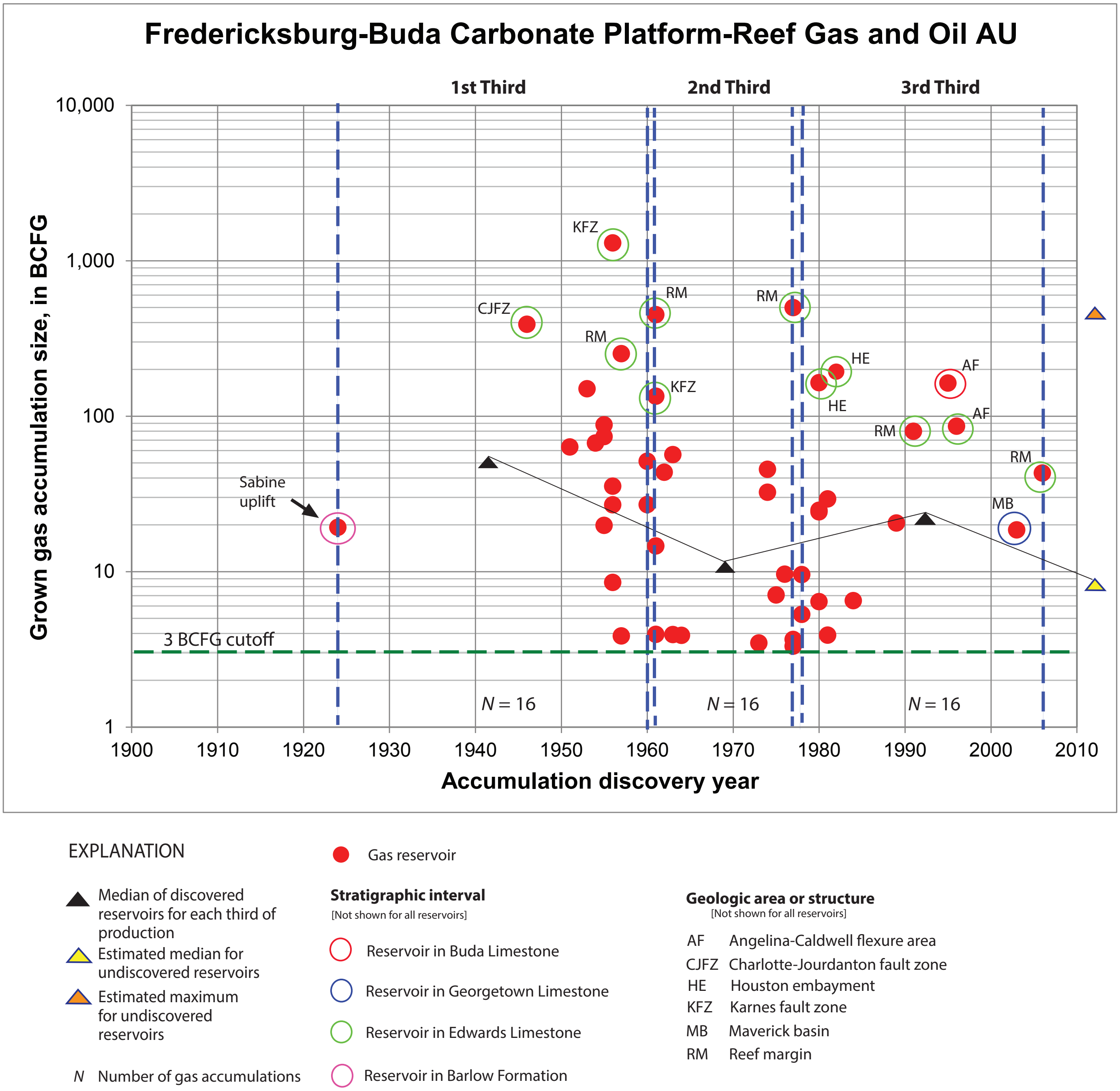
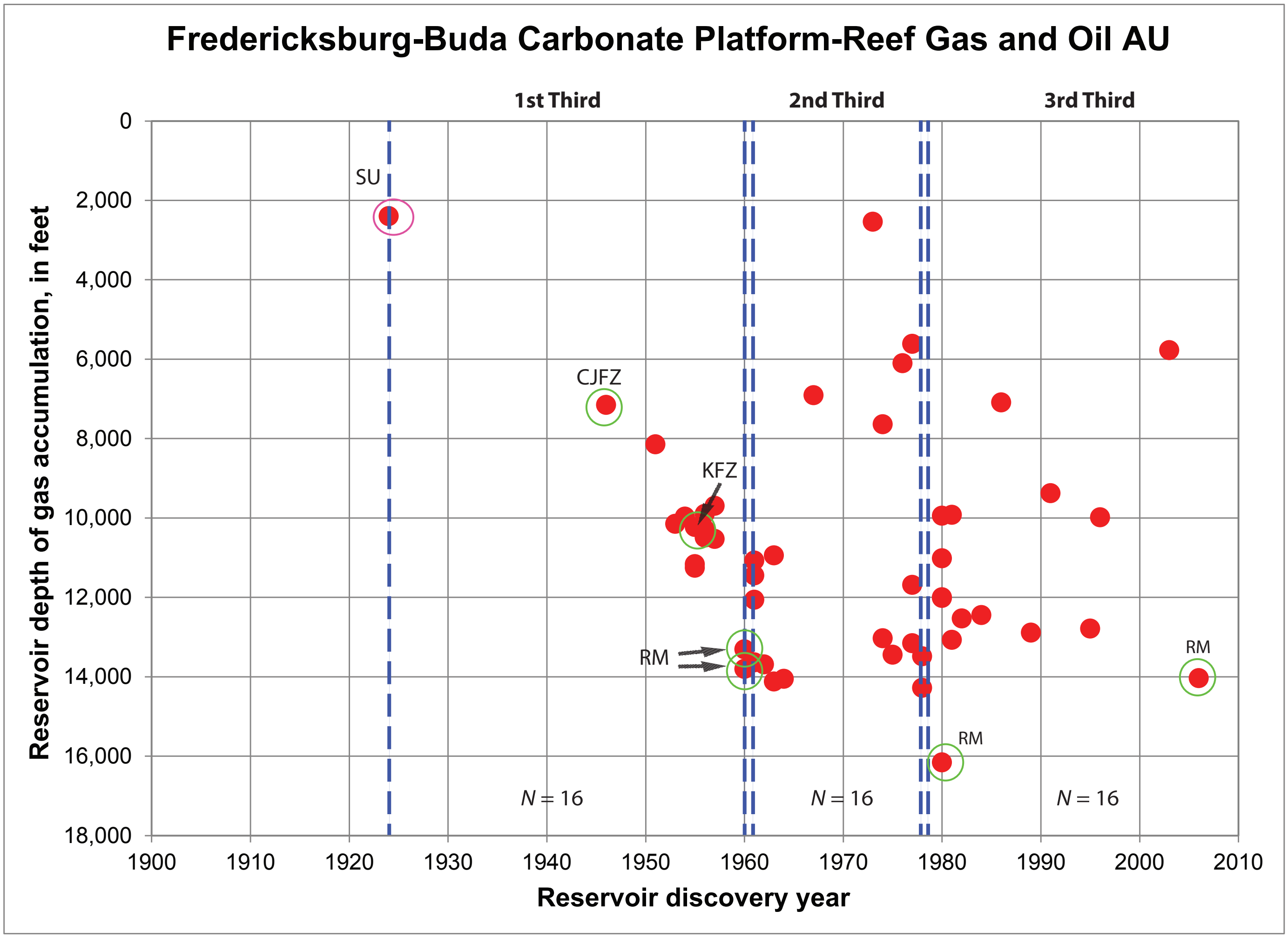


Figure 29 (this page and next 2 pages). Plots showing relations between reservoir discovery year, grown gas accumulation size, reservoir depth, and cumulative grown gas volume for gas accumulations in the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil Assessment Unit (AU). *A*, Accumulation discovery year versus grown gas accumulation size. *B*, Reservoir discovery year versus reservoir depth. *C*, Accumulation discovery year versus cumulative grown gas volume (T. Klett, U.S. Geological Survey, written commun., 2009; plots were generated with data from Nehring Associates, Inc., 2009). The plots have been annotated to indicate the stratigraphic interval and general location of some of the reservoirs (not all reservoirs are labeled). Abbreviation: BCFG, billion cubic feet of gas.

B



EXPLANATION

Gas reservoir

N Number of gas accumulations

Stratigraphic interval
[Not shown for all reservoirs]

Reservoir in Edwards Limestone

Reservoir in Barlow Formation

Geologic area or structure
[Not shown for all reservoirs]

CJFZ Charlotte-Jourdanton fault zone

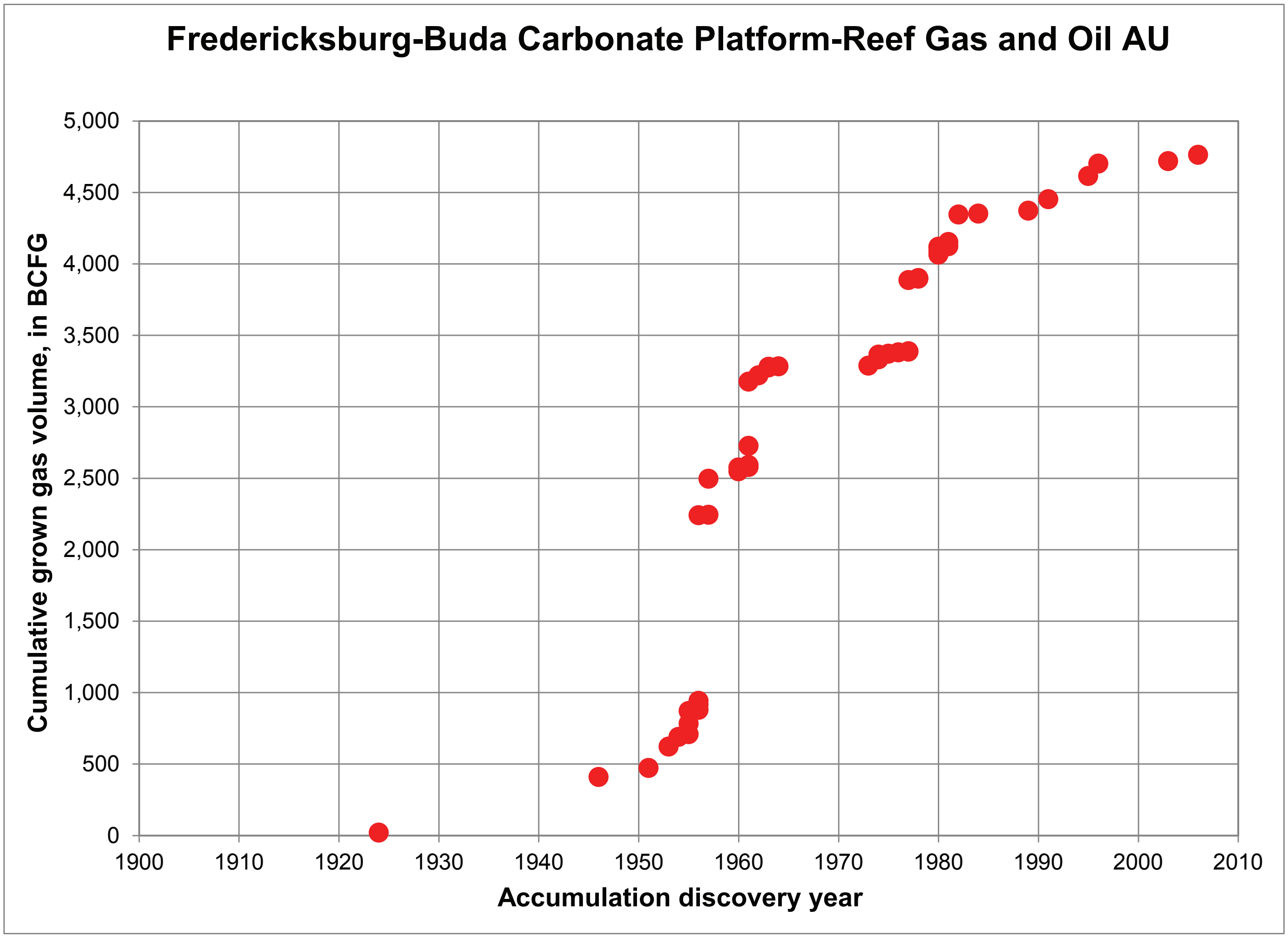
KFZ Karnes fault zone

RM Reef margin

SU Sabine uplift

Figure 29. Continued.

C



EXPLANATION

● Gas reservoir

Figure 29. Continued.

Table 1. Hydrocarbon assessment results for Jurassic and Cretaceous strata in the onshore and State Waters of the U.S. Gulf Coast (from Dubiel and others, 2011).

[Results shown are fully risked estimates. For gas accumulations, all liquids are included as NGL (natural gas liquids). F95 represents a 95 percent chance of at least the amount tabulated; other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Abbreviations: AU, assessment unit; MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids; TPS, total petroleum system; —, indicates not applicable]

	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 (50490100)													
Conventional Oil and Gas Resources	Norphlet Salt Basins and Updip AU (50490102)	Oil	13	48	106	53	8	31	73	34	1	2	6	3
		Gas	—	—	—	—	371	1,579	3,709	1,758	12	53	135	61
	Norphlet Mobile Bay Deep Gas AU (50490103)	Oil	0	0	0	0	0	0	0	0	0	0	0	0
		Gas	—	—	—	—	208	1,175	4,029	1,514	0	2	7	3
	Norphlet South Texas Gas AU (50490104)	Oil	0	0	0	0	0	0	0	0	0	0	0	0
		Gas	—	—	—	—	0	153	748	233	0	5	27	8
	Smackover Updip and Peripheral Fault Zone AU (50490105)	Oil	27	76	136	78	29	85	169	90	2	7	15	7
		Gas	—	—	—	—	46	151	304	160	4	15	32	16
	Smackover Salt Basin AU (50490106)	Oil	21	75	149	79	25	90	199	98	2	7	17	8
		Gas	—	—	—	—	265	889	1,693	926	32	112	235	120
	Smackover South Texas AU (50490107)	Oil	6	22	51	25	7	25	62	28	1	2	5	2
		Gas	—	—	—	—	203	699	1,419	744	19	68	151	74
	Haynesville Western Shelf-Sabine Platform Carbonate Gas AU (50490116)	Oil	0	0	0	0	0	0	0	0	0	0	0	0
		Gas	—	—	—	—	143	541	1,180	587	2	8	19	9
	Haynesville Shelf Carbonate and Sandstone Oil and Gas AU (50490117)	Oil	7	27	64	30	9	37	95	43	1	3	9	4
		Gas	—	—	—	—	9	27	75	32	0	1	3	1
	Bossier East Texas Basin Sandstone Gas AU (50490118)	Oil	0	0	0	0	0	0	0	0	0	0	0	0
		Gas	—	—	—	—	590	2,512	5,806	2,765	8	34	86	39
	Bossier Louisiana-Mississippi Shelf Edge Sandstone Gas AU (50490119)	Oil	0	0	0	0	0	0	0	0	0	0	0	0
		Gas	—	—	—	—	211	945	2,368	1,072	3	13	35	15
	Knowles-Calvin Gas AU (50490120)	Oil	0	0	0	0	0	0	0	0	0	0	0	0
		Gas	—	—	—	—	621	3,069	7,382	3,423	6	30	78	34
	Sligo-James Carbonate Platform Gas and Oil AU (50490121)	Oil	11	45	106	50	31	132	336	151	1	6	16	7
		Gas	—	—	—	—	167	587	1,279	640	5	17	41	19
	Lower Cretaceous Basinal Gas AU (50490122)	Oil	Not quantitatively assessed				—	—	—	—	—	—	—	—
		Gas					—	—	—	—	—	—	—	—
	Sligo Sandstone Gas and Oil AU (50490123)	Oil	3	9	19	10	1	4	9	4	0	0	0	0
		Gas	—	—	—	—	140	440	803	453	1	4	9	5
	Greater Glen Rose Carbonate Shelf and Reef Gas and Oil AU (50490124)	Oil	23	71	153	78	78	260	602	290	4	13	32	15
		Gas	—	—	—	—	252	720	1,480	778	7	22	50	25
	Albian Clastic AU (50490125)	Oil	11	35	69	37	9	31	67	33	0	1	3	1
		Gas	—	—	—	—	39	116	207	119	1	3	6	3
	Updip Albian Clastic AU (50490126)	Oil	0	1	3	1	0	0	3	1	0	0	0	0
		Gas	—	—	—	—	0	3	15	4	0	0	0	0
	Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU (50490127)	Oil	10	37	83	40	26	100	246	113	1	5	12	5
		Gas	—	—	—	—	120	466	1,041	509	2	8	20	9
	Eagle Ford Updip Sandstone Oil and Gas AU (50490128)	Oil	41	136	253	141	53	184	381	197	1	4	8	4
		Gas	—	—	—	—	86	289	571	305	3	11	24	12

Table 1. Hydrocarbon assessment results for Jurassic and Cretaceous strata in the onshore and State Waters of the U.S. Gulf Coast (from Dubiel and others, 2011).—Continued

[Results shown are fully risked estimates. For gas accumulations, all liquids are included as NGL (natural gas liquids). F95 represents a 95 percent chance of at least the amount tabulated; other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Abbreviations: AU, assessment unit; MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids; TPS, total petroleum system; —, indicates not applicable]

	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 (50490100)—Continued													
Conventional Oil and Gas Resources	Austin-Tokio-Eutaw Updip Oil and Gas AU (50490130)	Oil	6	19	34	20	1	3	6	3	0	0	0	0
		Gas	—	—	—	—	17	47	92	50	0	1	2	1
	Austin-Eutaw Middip Oil and Gas AU (50490131)	Oil	10	41	95	45	28	118	300	135	2	10	27	12
		Gas	—	—	—	—	109	477	1,192	542	10	46	124	54
	Austin Downdip Gas AU (50490132)	Oil	3	11	32	13	10	43	130	53	1	4	14	5
		Gas	—	—	—	—	406	1,429	3,013	1,542	46	167	385	185
	Post-Ouachita Successor Basin AU (50490201)	Gas	Not quantitatively assessed				—	—	—	—	—	—	—	—
	Triassic Basins AU (50490202)	Gas	Not quantitatively assessed				—	—	—	—	—	—	—	—
	Total Conventional Resources		**192**	**653**	**1,353**	**700**	**4,318**	**17,457**	**41,084**	**19,429**	**178**	**684**	**1,633**	**766**
Continuous Oil and Gas Resources	Haynesville Sabine Platform Shale Gas AU (50490161)	Gas	—	—	—	—	44,268	59,735	80,604	60,734	22	35	55	36
	Haynesville Greater Gulf Basin Shale Gas AU (50490162)	Gas	Not quantitatively assessed				—	—	—	—	—	—	—	—
	Mid-Bossier Sabine Platform Shale Gas AU (50490163)	Gas	—	—	—	—	2,879	4,870	8,240	5,126	5	10	18	10
	Bossier Greater Gulf Basin Shale Gas AU (50490164)	Gas	Not quantitatively assessed				—	—	—	—	—	—	—	—
	Maverick Basin Pearsall Shale Gas AU (50490165)	Gas	—	—	—	—	3,386	7,764	17,801	8,817	0	0	0	0
	Greater Gulf Basin Lower Cretaceous Shale Gas AU (50490166)	Gas	Not quantitatively assessed				—	—	—	—	—	—	—	—
	Eagle Ford Shale Oil AU (50490170)	Oil	341	758	1,687	853	625	1,486	3,533	1,707	12	29	74	34
	Eagle Ford Shale Gas AU (50490167)	Gas	—	—	—	—	23,470	46,150	90,747	50,219	851	1,809	3,842	2,009
	Austin Pearsall-Giddings Area Oil AU (50490168)	Oil	507	839	1,389	879	674	1,233	2,255	1,319	49	97	193	106
	Smackover Downdip Continuous Gas AU (50490169)	Gas	Not quantitatively assessed				—	—	—	—	—	—	—	—
	Total Continuous Resources		**848**	**1,597**	**3,076**	**1,732**	**75,302**	**121,238**	**203,180**	**127,922**	**939**	**1,980**	**4,182**	**2,195**
	Total Undiscovered Oil and Gas Resources		**1,040**	**2,250**	**4,429**	**2,432**	**79,620**	**138,695**	**244,264**	**147,351**	**1,117**	**2,664**	**5,815**	**2,961**

Table 2. Average values of reservoir characteristics in the Edwards, Georgetown, and Buda Limestones (based on data from Nehring Associates, Inc., 2009).

[Abbreviations: API, American Petroleum Institute; H_2S, Hydrogen sulfide; n.d., no data; N, number of reservoirs used in averages]

Stratigraphic interval	Depth to top (feet)	Thickness (feet)	Porosity (percent)	Permeability (millidarcys)	API gravity (degrees)	Sulfur in oil (percent)	H_2S in gas (percent)
Buda Limestone	7,259	63	8	136	33	0.8	0
N	20	20	10	7	19	1	2
Georgetown Limestone	7,518	61	7	0.2	46	n.d.	0
N	16	16	4	1	14	0	1
Edwards Limestone	9,904	82	14	41	45	0.6	0.3
N	57	57	26	21	43	5	16

Table 3. List of primary and secondary traps for reservoirs in the Edwards, Georgetown, and Buda Limestones (based on data from Nehring Associates, Inc., 2009).

Formation	Examples of traps
Buda Limestone	Combination—Growth fault, facies changes
	Structural—Growth fault, fracturing
	Combination—Fracturing, facies changes
	Anticlinal nose—Faulted
Georgetown Limestone	Combination—Growth fault, facies changes (carbonate)
	Stratigraphic—Facies changes (carbonate)
	Structural—Fault, fracturing
	Structural—Anticlinal nose (faulted)
Edwards Limestone	Structural—Growth fault
	Structural—Growth fault, fracturing
	Stratigraphic—Facies changes (carbonate)
	Combination—Facies change (carbonate), fracturing
	Combination—Anticline (tensional), faulted
	Combination—Shelf margin reef, growth fault
	Stratigraphic—Shelf margin reef, dissolution

Table 4. Assessment results for the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil Assessment Unit (modified from Dubiel and others, 2011).

[Results shown are fully risked estimates. For gas accumulations, all liquids are included as NGL (natural gas liquids). F95 represents a 95 percent chance of at least the amount tabulated; other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Abbreviations: AU, assessment unit; MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids; TPS, total petroleum system; —, indicates not applicable]

Total Petroleum System Assessment Unit (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 (50490100)													
Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil AU (50490127)	Oil	10	37	83	40	26	100	246	113	1	5	12	5
	Gas	—	—	—	—	120	466	1,041	509	2	8	20	9
Total Undiscovered Oil and Gas Resources		**10**	**37**	**83**	**40**	**146**	**566**	**1,287**	**622**	**3**	**13**	**32**	**14**

Appendix 1. Input data form for the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil Assessment Unit (50490127)

Basic input data form in appendix 1 for the Fredericksburg-Buda Carbonate Platform-Reef Gas and Oil Assessment Unit (50490127). [Abbreviations: accums., accumulations; bcfg, billion cubic feet of gas; bliq/mmcfg, barrels of liquid per million cubic feet of gas; bngl/mmcfg, barrels of natural gas liquids per million cubic feet of gas; bo/mmcfg, barrels of oil per million cubic feet of gas; cfg/bo, cubic feet of gas per barrel of oil; F, fractile (in percent); m, meters; min., minimum; mmboe, million barrels of oil equivalent; mmbo, million barrels of oil; NGL, natural gas liquids, no., number; NRG, Nehring Associates, Inc.]

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