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Regional Depositional Systems of the Woodbine, Eagle Ford, and Tuscaloosa of the U.S. Gulf Coast

Richard L. Adams and John P. Carr

Carr Resources, Inc., 305 S. Broadway Ave., Ste. 900, Tyler, Texas 75702

ABSTRACT

The Cretaceous Cenomanian and Turonian sediments of the Gulf Coast, including the Woodbine, Tuscaloosa, Eagle Ford, and Sub-Clarksville, form a clastic third order sequence, with multiple preserved fourth and fifth order cycles. The Woodbine interval (lower Cenomanian) of East Texas, is a regressive system capped by a lowstand unconformity, herein named the Eagle Ford Unconformity. The following upper Cenomanian to early Turonian transgressive system is the Eagle Ford/Sub-Clarksville interval; the Tuscaloosa of Louisiana and Mississippi. A minor unconformity separates the Eagle Ford/Sub-Clarksville interval from the overlying Austin Chalk. On the South Texas and Louisiana shelves, the regressive Woodbine Group equivalent is absent due to non-deposition and erosion.

The Laramide Orogeny in Central Mexico folded the Gulf Coast into a series of uplifts and basins. The East Texas Basin was the deepest basin of these; preserving the greatest volume of Woodbine-aged sediments. Longshore currents redistributed lower Woodbine sediments from the emergent Sabine Uplift, to the south and southwest into a large peninsula that partially closed off the mouth of the East Texas Basin (Harris Delta). Sedimentological evidence proves that the Eagle Ford/Sub-Clarksville sands of Madison and Brazos counties were carried from the northwest by the paleo–Brazos River, and are not local reworking of the Harris Delta sands.

The South Texas "Eagle Ford Shale" is a upper Cenomanian to lower Turonian transgressive shale that accumulated in shallow silled basins. The "Eagle Ford Shale" of Burleson, Grimes, and Brazos counties is actually the regressive lower Cenomanian Maness Shale (Lower Woodbine) preserved in anoxic silled basins behind the Lower Cretaceous shelf margin.

INTRODUCTION

The Woodbine, Eagle Ford/Sub-Clarksville, and Tuscaloosa have been studied for well over 100 years. Hill (1887, 1901) named the Eagle Ford and Woodbine, respectively, from outcrops in and around the Dallas, Texas, area. After oil was discovered in the Woodbine at Mexia in 1920 and at East Texas Oil Field in 1930, the Woodbine Group began to be a topic for research. The mix of outcrop and subsurface studies has led to a great deal of confusion when attempting to understand the regional geological history of this interval. Not only must one determine the geologic history across the Gulf Coast, but one must also decode the various layers of formational, member, and sand names used in the literature to correlate on an age basis.

The late 1960s and 1970s saw development of the "downdip Woodbine" in Polk and Tyler counties of southeast Texas. Mitchell Energy discovered and began developing Hortense, Leggett, and Seven Oaks fields in Polk County between 1962 and 1969, while Cities Service discovered Sugar Creek Field in Tyler County in 1975.

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In the mid-1970s, Chevron made a series of very large natural gas discoveries in the "Deep Tuscaloosa" of South Louisiana. The very high flow rates associated with these deep gas reservoirs spawned a large volume of research on porosity distribution and preservation in the "Deep Tuscaloosa," as well as the depositional and diagenetic properties that led to this unique preservation.

The discovery of gas at Double A Wells Field downdip of the Hortense–Leggett–Seven Oaks area in Polk County began quietly in 1985 with the Blackstone #1 Trostman (API [American Petroleum Institute] 42-373-30603) well. By the mid 1990s, a very large incised valley complex composed of Eagle Ford–aged sediments had been documented there with both well control and seismic data. This complex was originally described as a submarine canyon about 4.5 mi (7.5 km) wide, but has been reinterpreted by these authors as an incised valley complex backfilled by Eagle Ford sands and shales.

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REGIONAL STRATIGRAPHIC RELATIONSHIPS

The Woodbine–Eagle Ford/Sub-Clarksville third-order sequence, found across much of the U.S. Gulf Coast, encompasses the greater part of the Cretaceous Cenomanian and Turonian stages of the lower part of the Upper Cretaceous (Haq et al., 1986). Figure 1 (after Murray et al., 1985) shows the study area, as well as some of the major locations and/or trends referenced in this study. The stratigraphy of the Woodbine–Eagle Ford/Sub-Clarksville–Tuscaloosa interval is intimately tied to the structural history of the Gulf Coast as well as its eustatic sea-level history. The structural history has been influenced by tectonic compression from the southwest, caused by Laramide activity in Mexico and the southwestern United States (Adams, 2006). The orientation, strength, and timing of that compression resulted in localized areas of uplift and downwarping. The resultant unconformities extend over large areas and the proper correlation of the unconformities is critical to unraveling the correct regional geologic history of the Woodbine–Eagle Ford interval. The missing rock units provide the timing of uplifts, and the interval isopachs of the preserved intervals provide the timing of the intervening down-warps. The overprint of the eustatic sealevel curve is both a complication and an aid to understanding the timing of the uplift. The regressive nature of the Woodbine interval and the transgressive nature of the Eagle Ford interval provide a guide for understanding regional correlations. The boundary between the Woodbine and the Eagle Ford (the Eagle Ford Unconformity) is not equivalent to the boundary between the Cenomanian and the Turonian. Figure 2 shows the interpreted stratigraphic relations for several locations across the Texas and Louisiana Gulf Coast as well as the interpreted sequence stratigraphy for the interval. The position and duration of the various unconformities are critical to the understanding of these geologic relationships.

The Woodbine–Eagle Ford–Sub-Clarksville–Tuscaloosa represents a third-order regressive-transgressive sequence (Dawson, 1997; Van Wagoner et al., 1990) on which multiple minor fourth- and fifth-order sequences are locally overprinted. Barrell (1997) described four sequences within the overall "Deep Tuscaloosa" of southern Louisiana, but he included these smaller sequences as part of a larger +/- one million year sequence. This author interprets the third-order sequence of this study to be equivalent to the larger sequence of Barrell (1997) and the internal sequences/cycles (fourth-order sequences) to be equivalent to the shorter internal sequences.

Compression from the southwest caused large asymmetric fold pairs to form from Mexico and southern Texas to northeastern Louisiana. The Chittum Anticline, the San Marcos Arch, the Sabine Uplift, and the Monroe Uplift are separated by the Maverick Basin, the East Texas Basin, and the North Louisiana Salt Dome Basin (see Figures 1 and 3). Woodbine-aged sediments are found only in the deepest synclinal fold (East Texas Basin) and south of the Sligo/Edwards shelf margin. Eagle Ford–aged sediments are found in most areas except on the highest areas of the anticlinal folds (San Marcos Arch and Sabine Uplift). Compressive folding had stopped by the time the Austin Chalk was deposited, and the Austin beds were deposited as flat-lying beds over both the basins and the uplifts, except where the entire Upper Cretaceous and Tertiary section have been removed by later erosion. The angular nature of the unconformity at the Base of the Austin Chalk confirms the timing and extent of uplift and erosion (Granata, 1963; Halbouty and Halbouty, 1982; Jackson and Laubach, 1988, 1991).

Shelf sediments of Woodbine age are only preserved in the East Texas Basin. Adkins (1932) mentioned 625 ft (200 m) of Woodbine in Fannin County, Texas, with the Woodbine interval thinning southward along the outcrop belt to near Waco, Texas, where the Woodbine disappears and the Eagle Ford directly overlies the Buda. In outcrop in Arkansas and Oklahoma, the Eagle Ford interval contains volcanic beds, some of which are apparently water-laid deposits (Ross et al., 1928; Adkins, 1932). Volcanic sediments are rare in the Woodbine in the East Texas Basin, but are commonplace in the Eagle Ford/Sub-Clarksville interval. The transgressive nature of the

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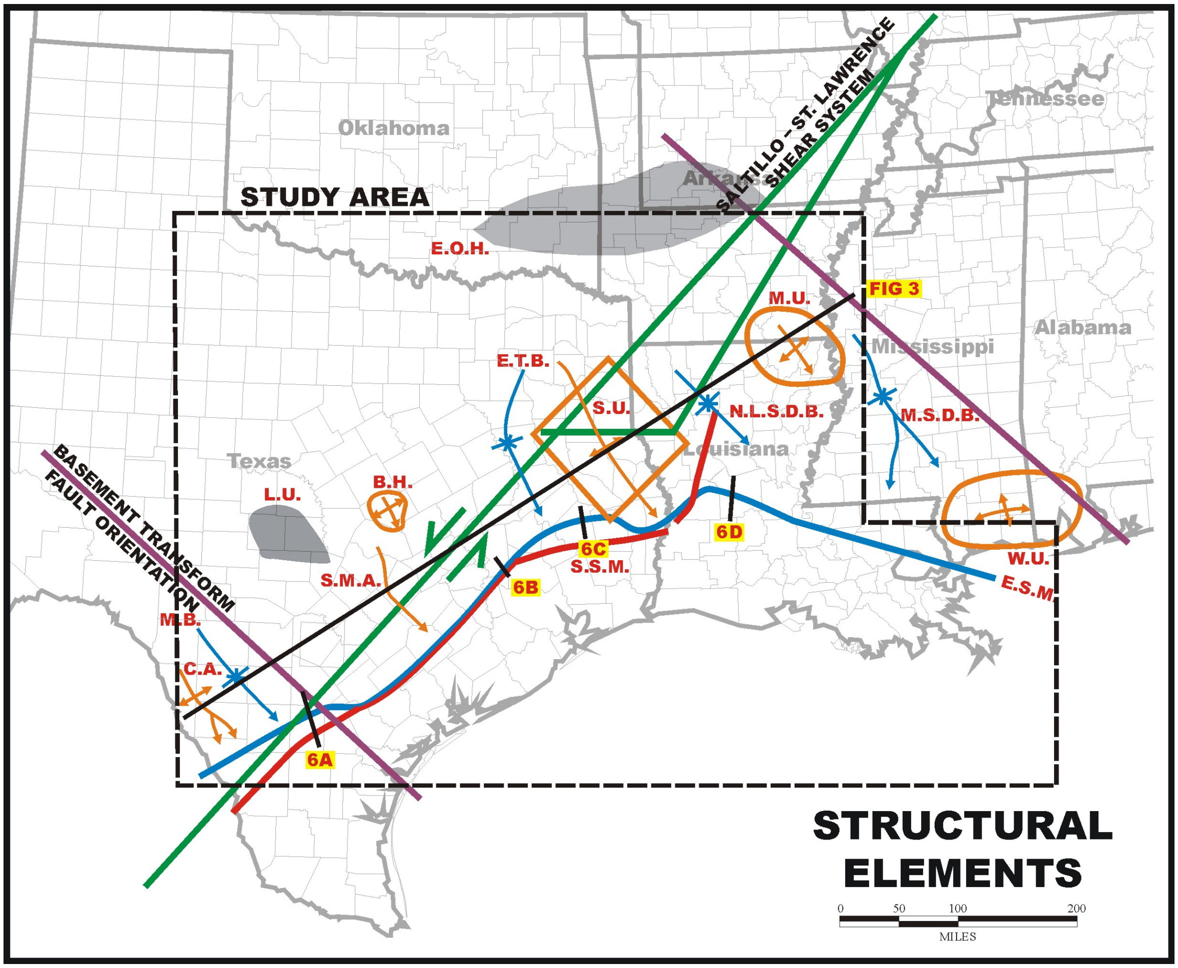

Figure 1. Location map of study area with major structural elements identified. Positive elements: C.A., Chittum Anticline; L.U., Llano Uplift; S.M.A., San Marcos Arch; B.H., Belton High; E.O.H., Exposed Ouachita Highlands; S.U., Sabine Uplift; M.U., Monroe Uplift; and W.U., Wiggins Uplift. Negative elements: M.B., Maverick Basin; E. T. B., East Texas Basin; N.L.S.D.B., North Louisiana Salt Dome Basin; and M.S.D.B., Mississippi Salt Dome Basin. Other elements: E.S.M., Edwards shelf margin; and S. S. M., Sligo shelf margin. Locations of cross-sections 3, 6A, 6B, 6C, and 6D (see Figures 3 and 6A-6D) are highlighted.

Eagle Ford–Tuscaloosa–aged sediments may contribute to the greater probability of preservation of volcanic deposits.

The lowstand at the Woodbine–Eagle Ford boundary is a very widespread event. Regional facies evaluations suggest that the shoreline at the maximum lowstand had regressed to a position near the current Sligo shelf margin. The Monroe Uplift, Louisiana Shelf, Sabine Uplift, San Marcos Arch, Maverick Basin, and Chittum Anticline were exposed and any existing Woodbine sediments were removed. The East Texas Basin was exposed, but not all of the Woodbine were removed prior to the transgression of the Eagle Ford–aged sea. This transgression is probably due to a combination of eustacy and structural relaxation.

The Eagle Ford of East Texas has time-equivalency with the Tuscaloosa of southern Louisiana and Mississippi (Hazzard, 1939; Christopher, 1980), and with the Eagle Ford of South Texas. Figure 4 shows the relationship of the East Texas Basin, the Sabine Uplift, and the Tuscaloosa sediment on the Louisiana Shelf. The Eagle Ford interval is absent over portions of the Sabine Uplift, while the Austin Chalk unconformably overlies beds as

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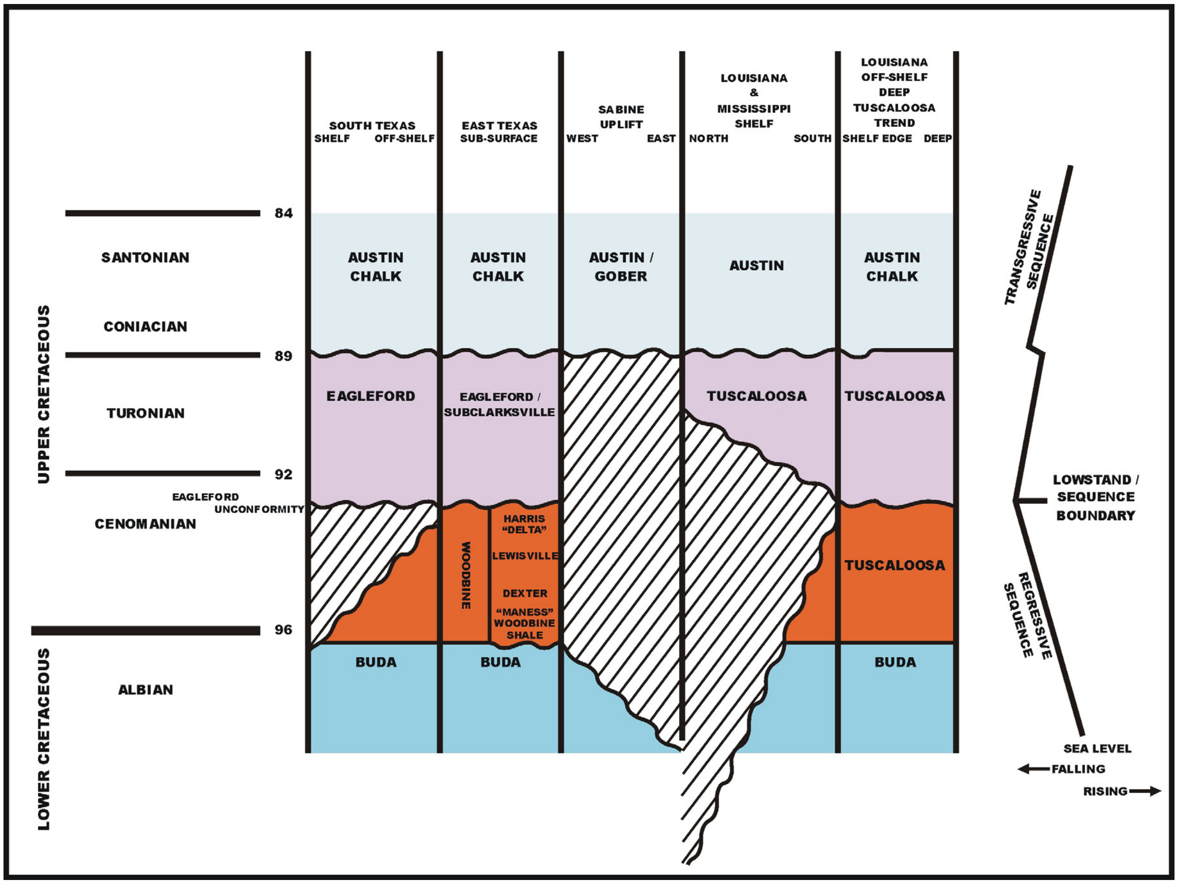

Figure 2. Stratigraphic column of the middle Cretaceous within the study area, including our simplified sequence stratigraphic interpretation.

old as the Glen Rose. Across much of the San Marcos Arch in Central Texas, the entire Upper Cretaceous and Tertiary section is missing due to both nondeposition and erosion. In South Texas, the Eagle Ford has been preserved below the Austin Chalk, similar to the relationship on the southern Louisiana Shelf.

Locally, an unconformity is present between the Eagle Ford and the Austin Chalk. In some areas this has more the appearance of a nonconformity than an unconformity. This contact has been noted to have pyrite, fish bones, phosphate nodules, and other indicators of exposure and/or nondeposition (Brown and Pierce, 1962; Adkins, 1932; McNulty, 1954, 1965, 1966; Stephenson, 1929). W. Ambrose (2009, personal communication) made an excellent point that this better fits the definition of a condensed section. However, the senior author has mapped minor erosion at the Base Austin Chalk horizon at Madisonville Field in Madison County, Texas.

REGIONAL WOODBINE–EAGLE FORD DEPOSITION

Dexter Deposition

Woodbine deposition began in East Texas with sediments being shed southward off of the Ouachita front in southern Oklahoma and Arkansas. Figure 5 was modeled after the excellent work of Oliver (1971), and shows the paleogeography of the East Texas Basin during the Dexter (Lower Woodbine) interval. These sands are

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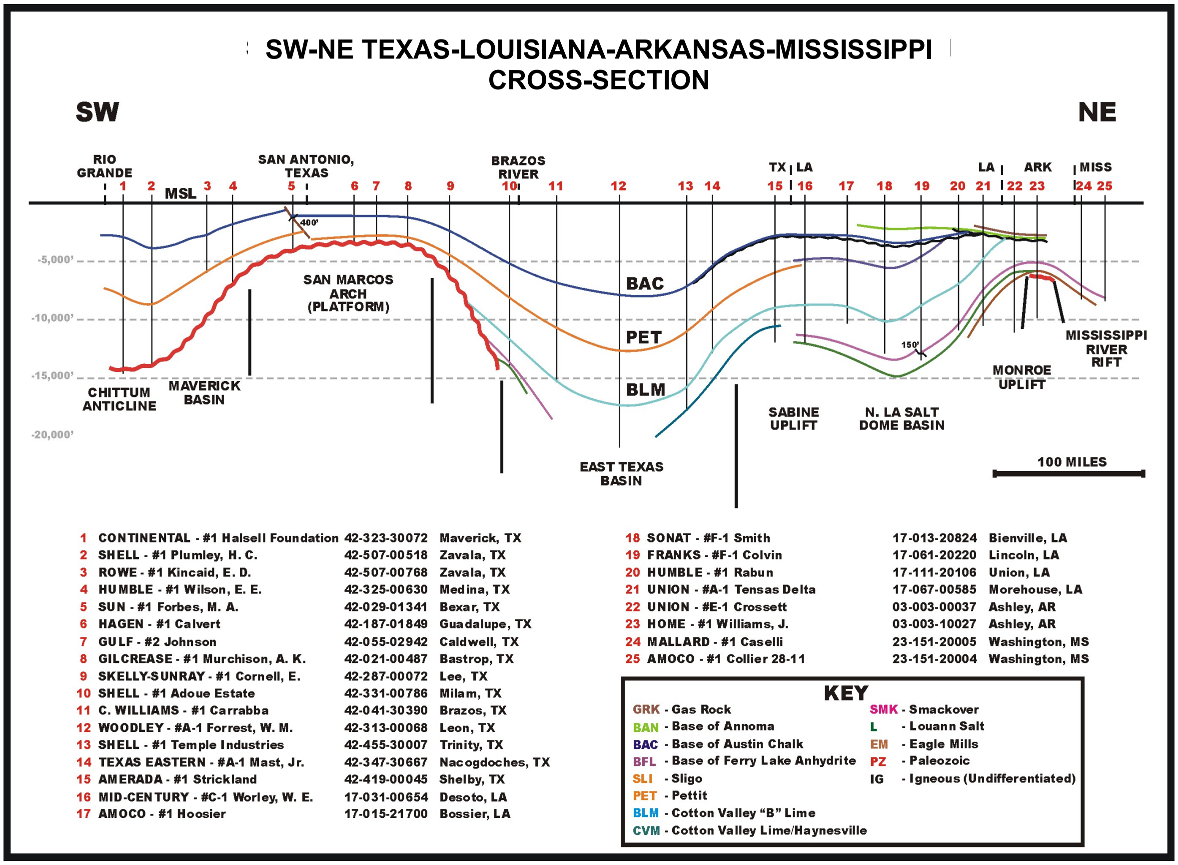

Figure 3. Regional southwest-northeast structural cross-section: Texas, Louisiana, Arkansas, and Mississsippi.

called the Dexter fluvial system across the north end of the East Texas Basin (Oliver, 1971), and extend eastward across south Arkansas, and a portion of north Louisiana. In the northern part of the East Texas Basin, the base of the Woodbine is an unconformable contact with the underlying Buda (Oliver, 1971). A thin transgressive section is present in this area where the unconformable contact is noted at the base of the lowermost Dexter (Oliver, 1971. South of the present-day outcrop, the contact between the Buda and the Woodbine is conformable (Oliver, 1971). In this area the Lower Woodbine is interpreted by the authors to be one large overall regressive sequence. The Lower Woodbine is part of a third-order cycle and therefore contains numerous partial fourth- and fifth-order cycle components. Ambrose et al. (2009) recorded fourteen partially-preserved fourth-order sequences from the East Texas Basin within the Woodbine interval. During Dexter Sand deposition, the Sabine Uplift was not a positive element. The Dexter originally covered the current Sabine Uplift and may have extended over 100 mi (160 km) west of its current outcrop limit across the Llano Uplift and the Bend Arch. Also, well logs from Live Oak County, Texas, south of the Sligo shelf margin, contain about 350 ft (120 m) of low resistivity shale just above the Buda, which look very comparable in log character to the Lower Woodbine shales of Grimes County, Texas, and the Lower Woodbine shales of central Polk County, Texas (see Figure 6A)

Figure 6 is a series of dip cross-sections in LaSalle County of South Texas (Fig. 6A); Grimes County, Texas (Fig. 6B); Polk County, Texas (Fig. 6C); and Rapides Parish, Louisiana (Fig. 6D). All four cross-sections demonstrate a truncated wedge of low resistivity deep-water shale in front of the shelf margin. This wedge is truncated to the north by the Eagle Ford Unconformity with Eagle Ford sands and shales above the Eagle Ford Unconformity. The entire system is capped by the Austin Chalk which changes in character from north to south.

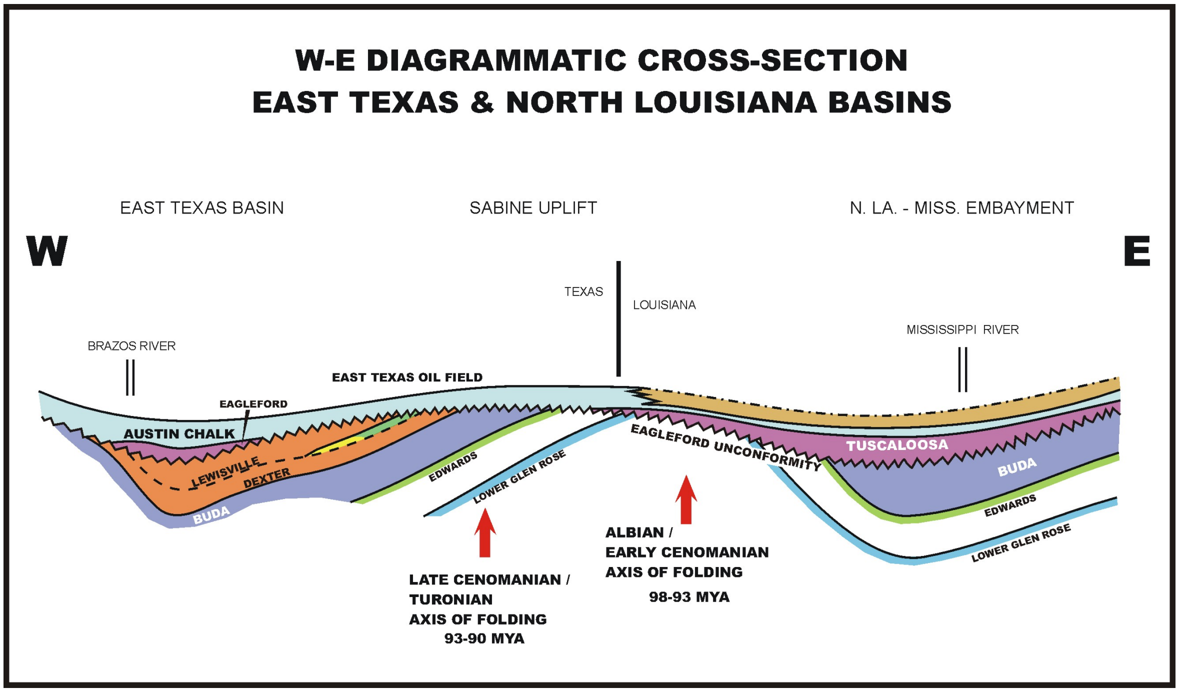

Figure 4. West-east diagrammatic cross-section across the East Texas Basin, Sabine Uplift, and North Louisiana Salt Basin. Note the locations of unconformities (modified after Granata, 1963).

Lower Woodbine Shale

The deeper-water shale equivalent of this Dexter fluvial system is the Maness Shale. This interval in the subsurface may also be equivalent to what is called the Pepper Shale in some outcrop sections. In recent industry terminology, this interval has been commonly referred to as the "Eagle Ford" Shale in Burleson, Brazos, and Grimes counties, Texas, although it is clearly Woodbine (Cenomanian) in age. Several operators, especially Apache, have been very actively developing both oil and gas from this shale interval as Giddings (Eagle Ford) Field. Figure 7 is a log from the Getty #C-1 Giesenschlag well (API 42-051-31485) in Burleson County, Texas. This well was re-entered by Apache in 2008, and flowed oil from the Lower Woodbine (Maness) Shale. Over much of the subsurface portion of the East Texas Basin, this interval is recognized on well logs by the presence of high resistivity on electric logs, a "hot" or high Gamma Ray signature from uranium associated with the high percentage of organic matter, and mud logs shows where the interval had been buried sufficiently to generate hydrocarbons. This shale is 40-150 ft thick, and is interpreted to have formed in low areas on the Cretaceous shelf where organic matter could accumulate and be buried under anoxic conditions. This same mechanism is seen today in intra-shelf basins on the Gulf Coast where closed lows are formed by salt migration (Bouma and Coleman, 1986). Demaison and Moore (1980) reported that the total organic content (TOC) in the Cariaco Basin, a silled basin off the coast of Venezuela averages eight times the organic content of oxic bottom sediments. The high TOC values, low oxygen values, and ultra-stable water column are all necessary elements to the preservation of organic-rich shales.

Lower Lewisville Deposition

Figure 8 is a map of the paleogeography of the Gulf Coast during the lower part of the Lewisville strandplain system (after Oliver, 1971). By Lewisville time, there were at least two main sediment supplies feeding the East

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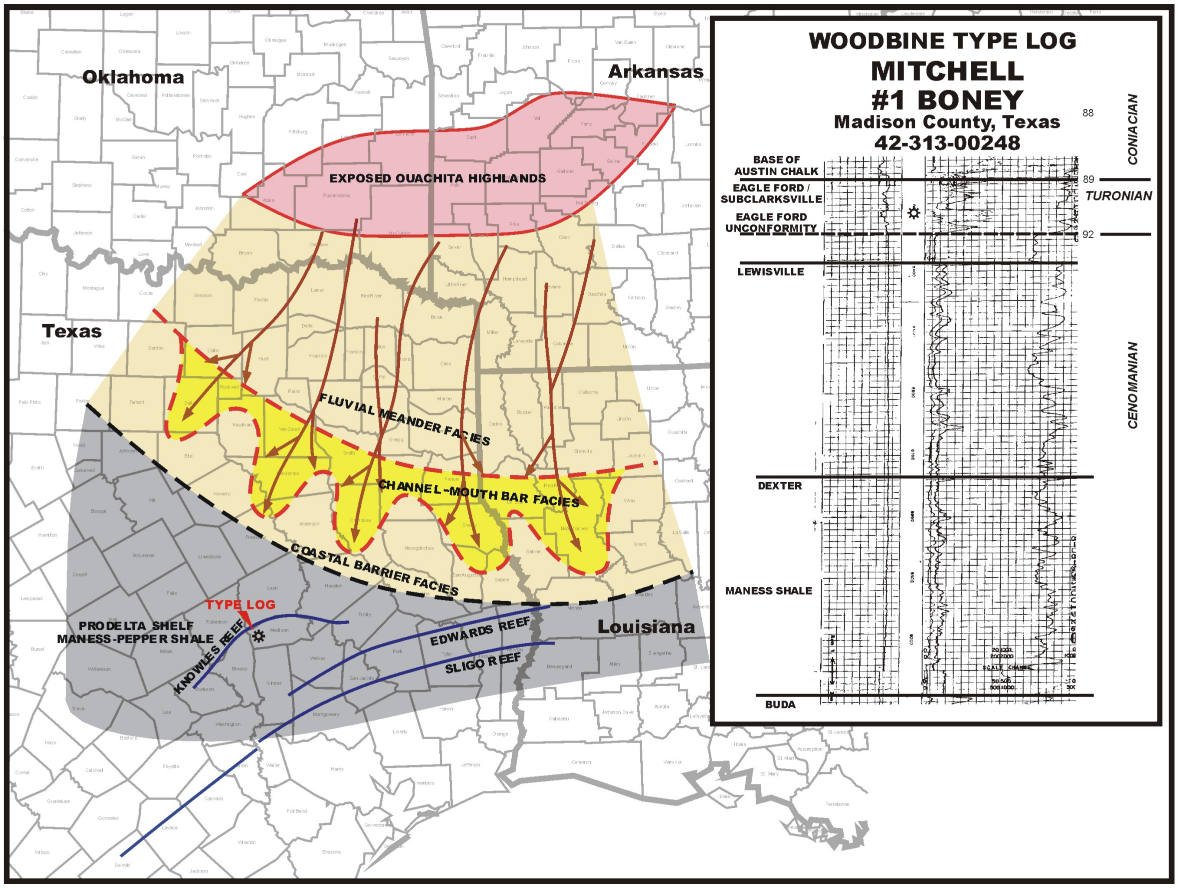

Figure 5. Paleogeographic map of the Lower Woodbine Dexter fluvial system interval (modified after Oliver, 1971).

Texas Basin (Ueckert, 1981). The Lewisville strandplain system of Oliver (1971) and a western sediment supply, possibly from the Arbuckle Mountains in southern Oklahoma, or from an unknown source now totally eroded further west (Ueckert, 1981). This western source may also be from erosion of both previously-deposited Dexter-aged sediments and earlier Paluxy-aged sands (Dodge, 1965; Oliver, 1971). This shift in provenance may be heralding the start of folding and uplift that was to form the Sabine Uplift and raise the San Marcos Arch (Llano Uplift) to its current elevation. Like the Dexter fluvial system, the Lewisville strandplain system also apparently originally extended across the current Sabine Uplift.

Upper Lewisville/Harris Delta

Only by the late Lewisville time did the Sabine Uplift begin to become an emergent feature and shed sands east, west and south into northern Louisiana and into the southern part of the East Texas Basin. This erosional event is herein called the Eagle Ford Unconformity. It reflects folding and the uplift associated with the emergence of the Sabine Uplift and San Marcos Arch.

This local supply of eroded Lewisville sands from the Sabine Uplift began to develop into an elongate lobe that extended southwest through Houston, Walker, and Madison counties as far southwest as Grimes and Brazos counties. As the lobe grew it began to shield the East Texas Basin from the open ocean to the southeast. These sediments are locally referred to as the Harris sands or Harris Delta (Oliver, 1971, Theiss, 1983), although the

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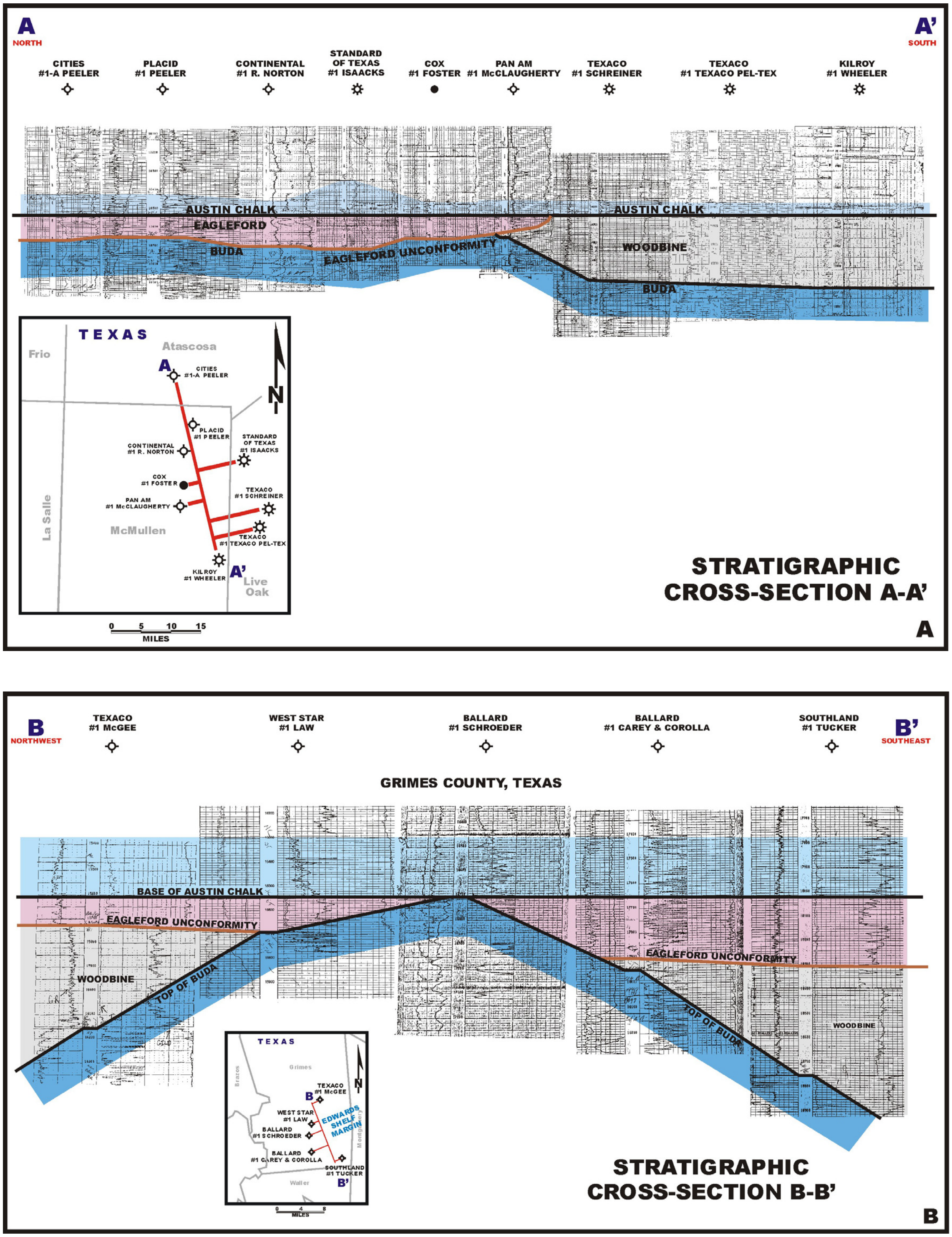

Figure 6. North-south stratigraphic cross-sections across the Edwards shelf margin: (A) McMullen County, South Texas; (B) Grimes County, Central Texas; (C) Polk County, Southeast Texas; and (D) Rapides Parish, Southwest Louisiana.

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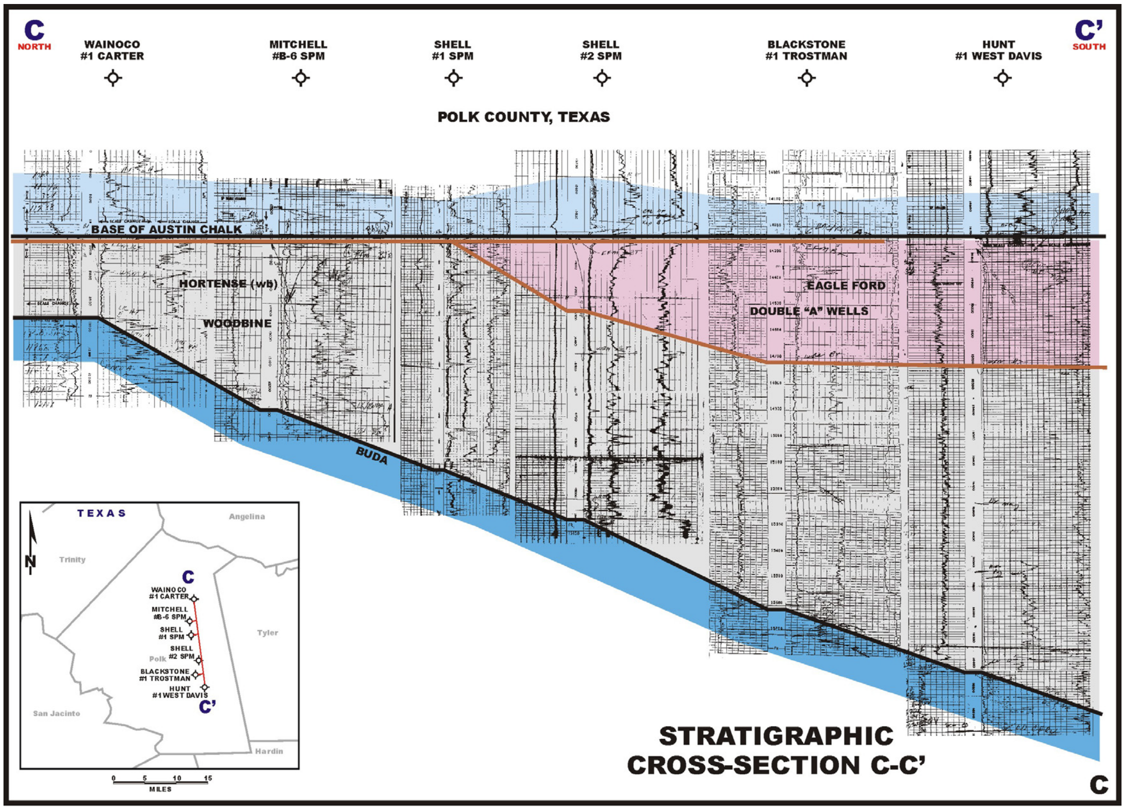

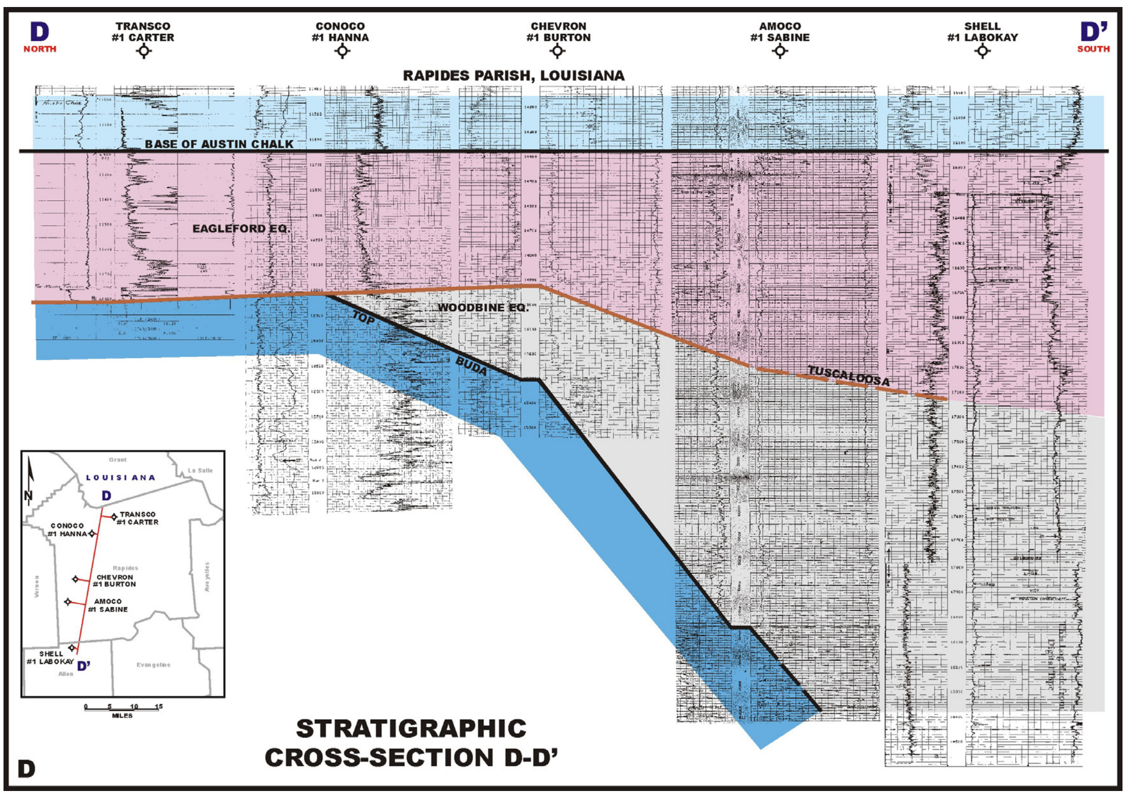

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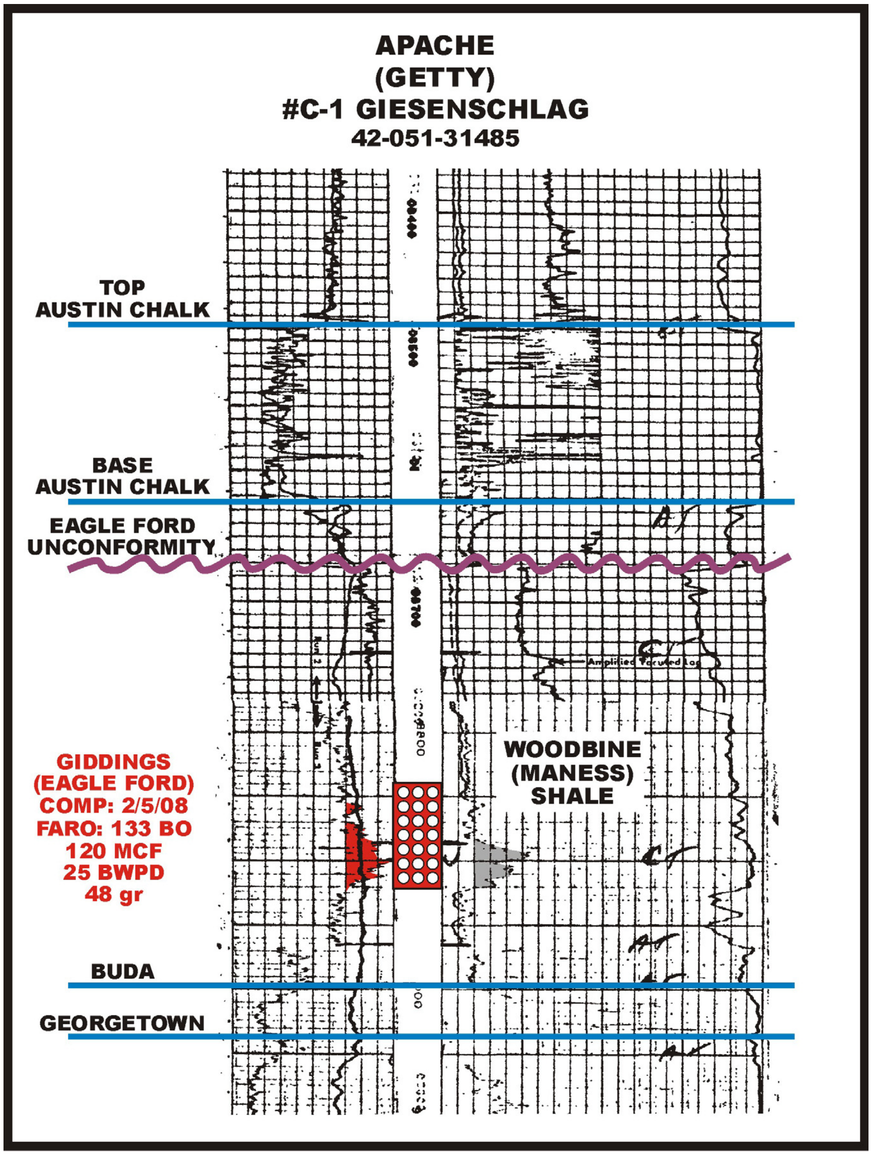

Figure 7. Well log of the Apache (formerly Getty) #C-1 Giesenschlag well (API 42-051-31485), Burleson County, Texas. This well produces oil from the lower Woodbine Maness Shale.

shape and orientation are much more suggestive of a spit or peninsula than a delta lobe. By the start of Harris time, the upwarping of the San Marcos Arch had developed to the point where it was an emergent feature actively shedding sediments to the east, west, and south. This uplift closed off the west side of the East Texas Basin, turning it into a closed embayment. This tilting and erosion of these western Woodbine sediments fed sand into this closed embayment and these sands would eventually become a part of the Sub-Clarksville sands (a local name for Eagle Ford–aged sands) preserved in the basin center and in the southern part of the basin. Figure 9 demonstrates the paleogeography at this time. This embayment was open to the south, with a shelf extending to the Sligo shelf margin. South of the Sligo shelf margin the depositional slope steepened into the ancestral Gulf of Mexico Basin.

As the Harris "Delta" accreted to the southwest as a spit or peninsula, it continued to close off the mouth of the East Texas Embayment, thus restricting tidal flow in and out of the embayment to an ever-narrowing tidal

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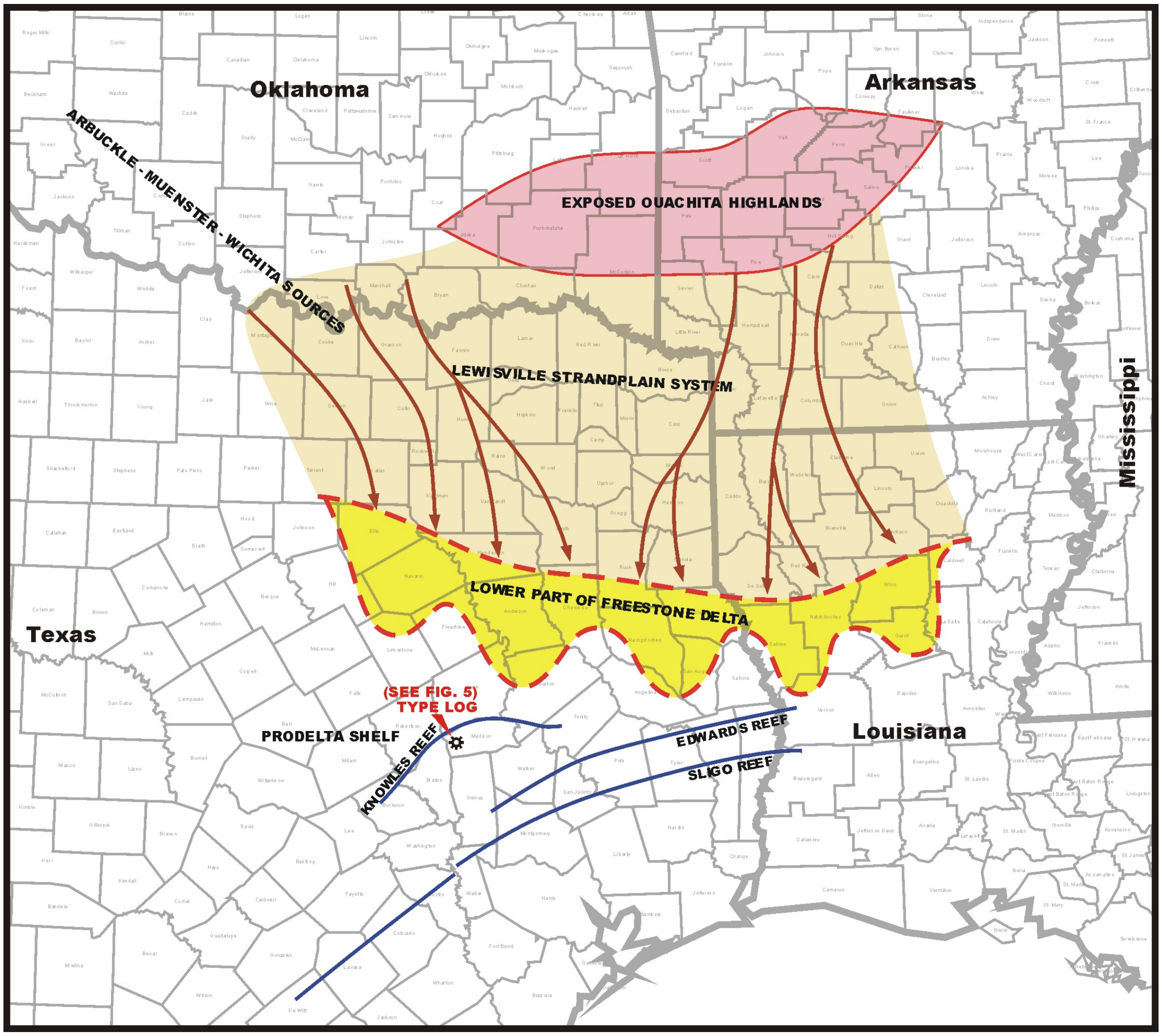

Figure 8. Paleogeographic map of the Woodbine Lower Lewisville strandplain interval (modified after Oliver, 1971).

mouth. Upper Woodbine fields such as Kurten Field in Brazos County and OSR Field in Madison County show strong evidence of tidal influence in their deposition. Longshore current activity greatly favored the sediment transport to the west over the east. The tilting and uplift of the San Marcos Arch and the Sabine Uplift were accompanied by concurrent erosion across the East Texas Basin. This unconformity is generally used as the boundary between the underlying Dexter and Lewisville portions of the Woodbine and the overlying Eagle Ford/Sub-Clarksville/Tuscaloosa interval, and is herein referred to as the Eagle Ford Unconformity. The Eagle Ford Unconformity varies in absolute age and duration based on location in the basin. Over the Sabine Uplift, erosion associated with the Eagle Ford Unconformity has eroded down through the Top of the Lower Cretaceous into the Glen Rose, while in the area south of the Sligo shelf margin the contact is a disconformity. Please see Figure 4 for a diagrammatic view across the Sabine Uplift and Figure 6 for views of the Buda–Woodbine–Eagle Ford/Tuscaloosa and Austin Chalk relationship at the shelf edge. In northeast Louisiana, near the Monroe Uplift, the Tuscaloosa is resting on Jurassic-aged rocks of the Cotton Valley, Haynesville/Buckner, and Smackover (see Figure 3).

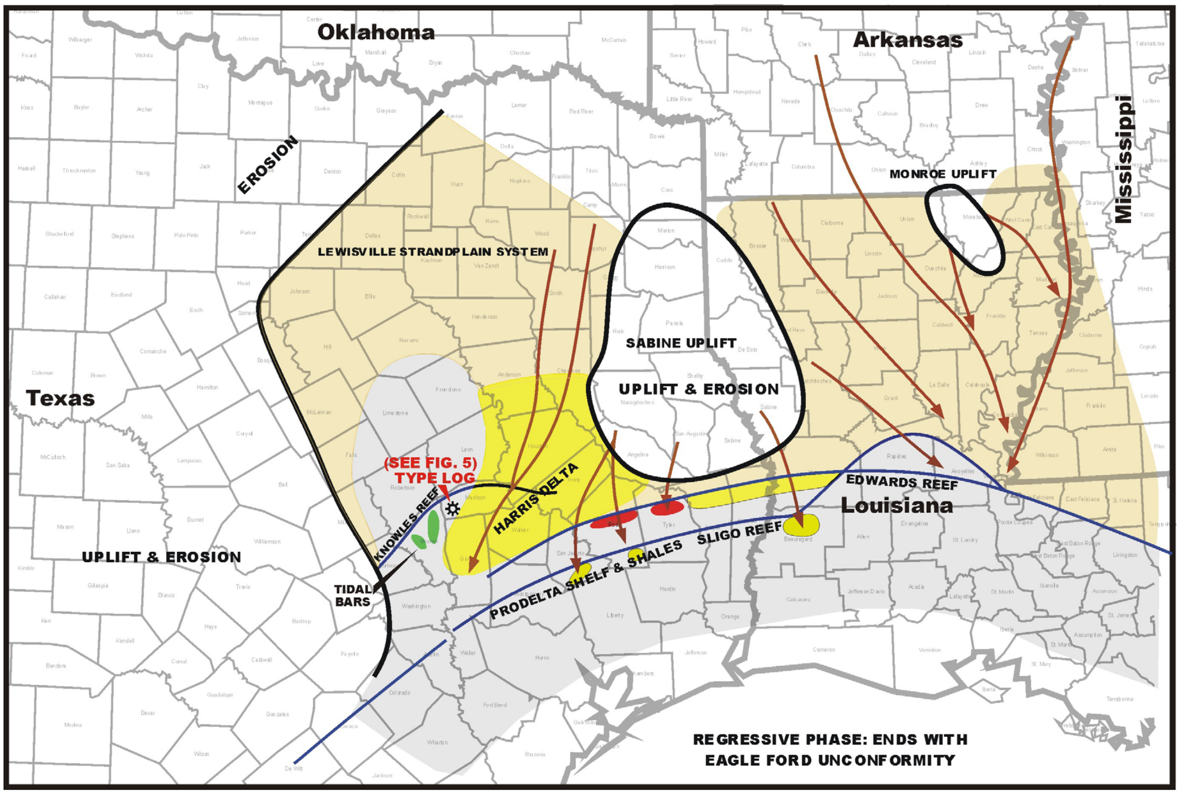

Figure 9. Paleogeographic map of the Woodbine Upper Lewisville Harris Delta interval (modified after Oliver, 1971).

Eagle Ford/Sub-Clarksville Deposition

The Eagle Ford, Sub-Clarksville, and Tuscaloosa are all names applied to rocks of the same age. The name Eagle Ford was applied by Hill (1887) to the argillaceous shales in the Cross Timbers region of northern Texas. As stated earlier, the Eagle Ford interval is transgressive in nature. Thus the base of the Eagle Ford interval is oldest and most widespread near the Sligo shelf margin, and gets progressively younger as you move north. The interval isopach is related more to sediment sources and paleotopography of the Eagle Ford Unconformity surface than to the duration of the time of deposition. The Sub-Clarksville sands of the northern East Texs Basin are mostly non-marine to very shallow marine sediments shed off of the Ouachita highlands like the underlying Woodbine.

Locally the Eagle Ford contains limestone facies that include foraminiferal and pelecypod grainstones and peloidal packstones and grainstones (Dawson, 1997). These are interpreted as bays and lagoons between deltas growing from the north and northwest (Dawson, 1997), or as a foraminiferal biomicrite lagoon that was protected behind a small spit or bay-mouth bar and capped by marsh sediments (Silver, 1963). These limestones are not found in the center of the East Texas Basin. The lagoonal areas seem to be related to quiet clear water along the edges of the San Marcos Arch where only limited clastic influx was possible. The subtle early uplift of the San Marcos Arch may have influenced water circulation to the extent that sediment-laden waters bypassed the near shore western shoreline of the East Texas Basin and deposited sand and shale in the basin center. Multiple thin bentonite layers are preserved in the lagoonal limestones.

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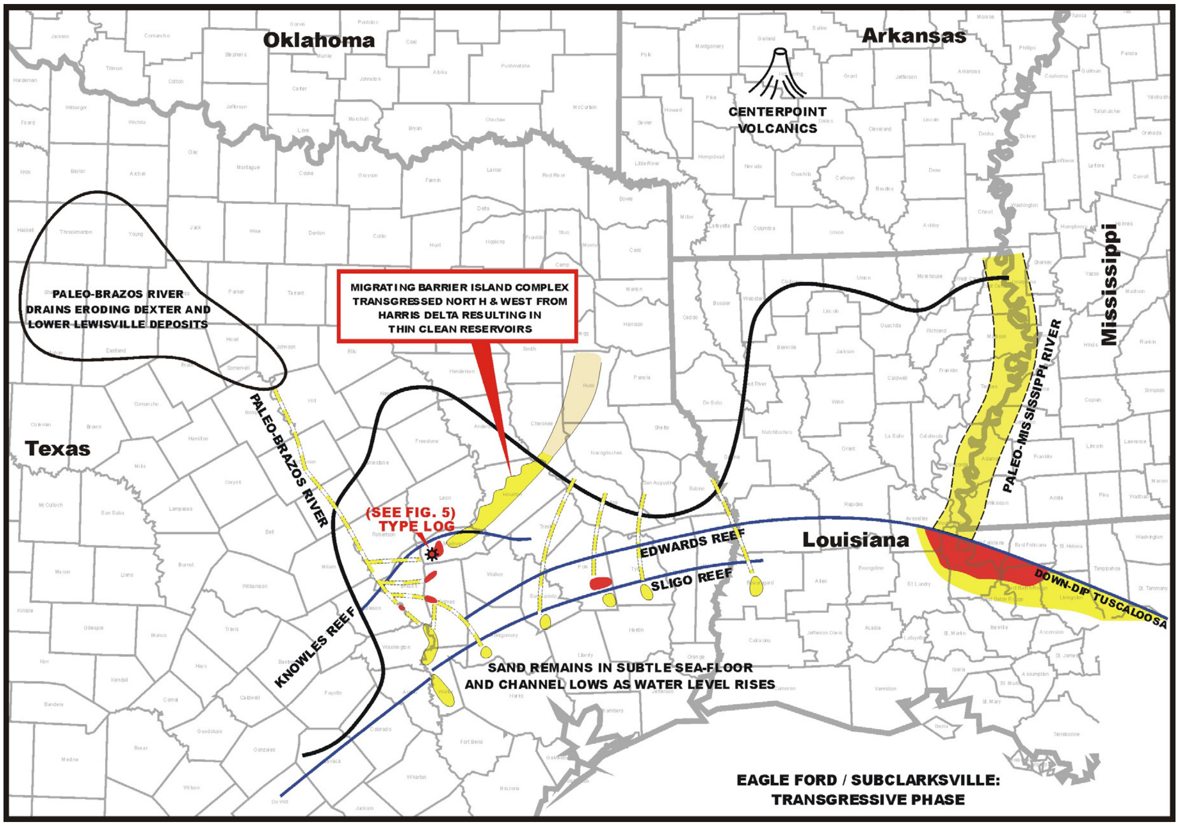

Figure 10. Paleogeographic map of the Eagleford/Sub-Clarksville interval (modified after Oliver, 1971).

EAGLE FORD INCISED VALLEYS

Two main sediment sources are inferred for the sands in the Eagle Ford interval in the southwestern portion of the East Texas Basin (Fig. 10). North and east of a line from Madisonville in Madison County, Texas, to approximately the town of Groesbeck in Limestone County, Texas, the Sub-Clarksville sands are fine-grained shallow marine transgressive sands transported north as barrier island complexes (landward) by reworking from the Harris Delta. As sea level rose, sands eroded from the Harris Delta in Grimes, Walker, and Madison counties, Texas, were carried north and west to be deposited at successively younger shorelines in Leon and northern Madison counties. These transgressive shoreface sands form stratigraphic traps at fields such as BSR Field in Madison County, Texas, where they are described as fine-grained quartzose sands (Henk et al., 2002). Similar sands also produce at Leona and Red Oak fields in Leon County.

Paleo–Brazos River Incised Valley

South and west of this line from Madisonville to Groesbeck a different sand facies appears. Within and adjacent to the paleo–Brazos River valley extending from Milam County downstream to near Navasota in Grimes County, Texas, an incised valley estuary was formed (Fig. 11). Incised valleys (Blum, 1993; Bowen et al., 1993)

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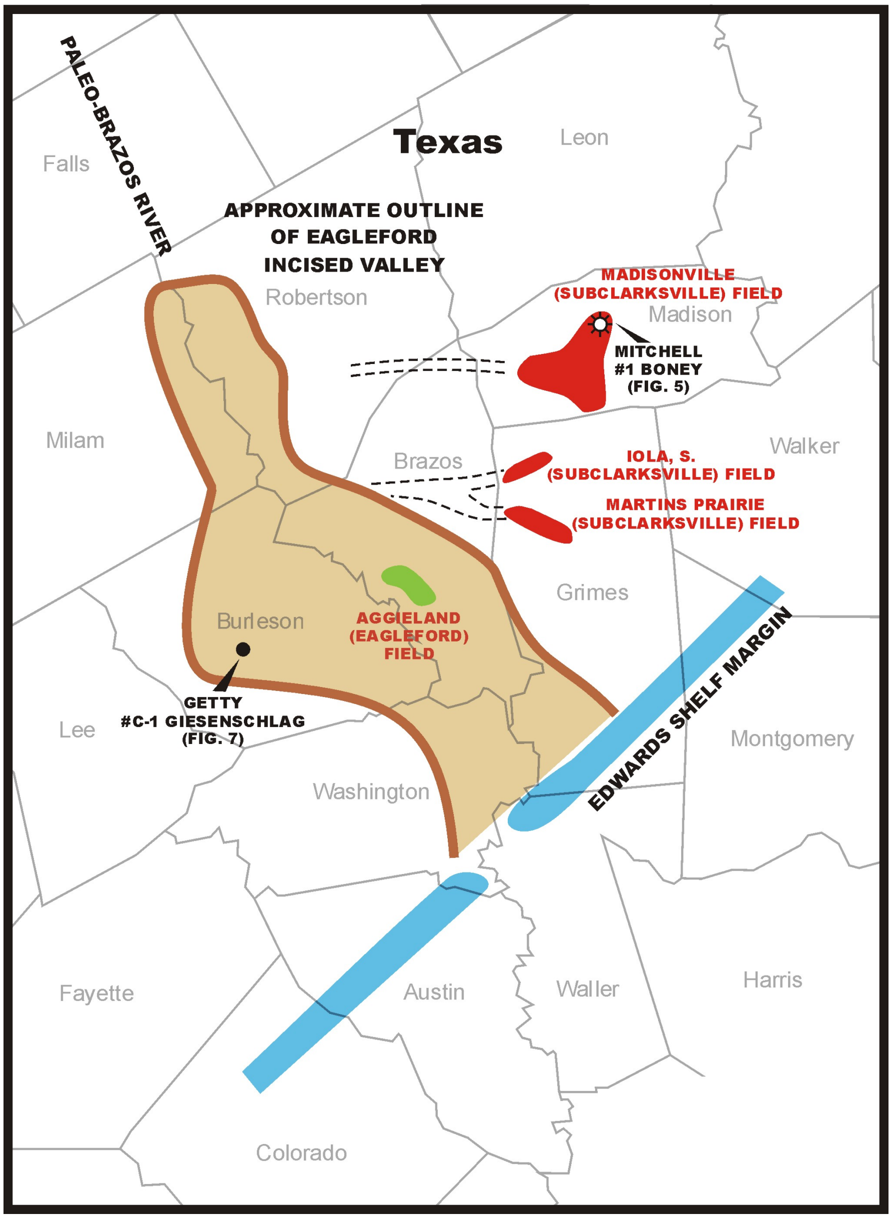

Figure 11. Map of approximate outline of Eagle Ford–aged incised valley formed by the Paleo–Brazos River, and some of the related Sub-Clarksville fields: Brazos, Grimes, Madison, Burleson, Robertson, Milam, and Washington counties, Texas.

are an under-recognized reservoir objective in the Woodbine and Eagle Ford, where most models have been based on shelf sands, deltas and turbidites (Berg, 1982; Phillips and Swift; 1985; Siemers and Hudson 1981, 1985; Walker and Bergman, 1993).

The sands within this incised valley are much different than the sands at BSR, Leona, and Red Oak fields. They are coarser grained and texturally more immature. These incised valley sands and related facies produce oil and gas at Aggieland (Eagle Ford) Field in Brazos County, Texas, near Bryan; at Iola South (Sub-Clarksville) Field in Grimes County, Texas; and at Martins Prairie (Sub-Clarksville) Field in Grimes County, Texas (see

Figure 11). Also, at Madisonville Field, these sands produce gas from Sub-Clarksville sands which appear to be possible crevasse splay or flood overbank sands. Sand isolith mapping shows that the coarsest, thickest, and cleanest sands are on the west end, and the sands get thinner and finer grained to the east and to the northeast away from the incised valley. These sands are in sharp contrast to the transgressive shoreface sands outside the incised valley described above.

Textural Comparison of Woodbine and Eagle Ford

Clear differences exist between the sand character of the Woodbine and the Eagle Ford/Sub-Clarksville sands in the incised valley of the Paleo–Brazos River. Table 1 labeled "Textural Comparison of the Woodbine and Eagle Ford" demonstrates the important differences between the Woodbine and Eagle Ford/Sub-Clarksville sands as described from cores. The data summarizes the results from a total of 345 samples point-counted and measured by graduate students and reported in unpublished M.S. theses (Barton, 1982a, 1982b; Frossard, 1982; DeDominic, 1988a, 1988b; Guerra, 1986; Leethem, 1984). These authors only refer to the Eagle Ford/Sub-Clarksville as Sub-Clarksville, so that nomenclature is followed for this discussion.

- The Sub-Clarksville sands (quartz grains only) are coarser than the underlying Woodbine sands of the Harris Delta.
- The percentage of quarts grains in the sands is less for the Sub-Clarksville (62%) than for the Woodbine (79%).
- The percentage of matrix plus rock fragments is greater for the Sub-Clarksville (30.7%) than for the Woodbine (14.3%).
- The Woodbine is predominantly cemented by silica and the Sub-Clarksville is predominantly cemented by carbonate.

None of these data are consistent with the Sub-Clarksville being second-generation sands with their provenance in the underlying Woodbine. Instead, it argues that a second (less texturally mature) source exists for the Sub-Clarksville sands within the incised valley. The intervening lowstand and unconformity provide a mechanism for sand influx from a more distant immature source. Dodge (1965) and Oliver (1971) both attributed potassium feldspars in the Lewisville to granites and low-rank metamorphic of the Arbuckle Mountain area in southwestern Oklahoma being transported southeastward into the East Texas Basin.

There are marked log differences between the Woodbine and the overlying Eagle Ford within the Paleo-Brazos incised valley. Figure 7 is the log from the Getty #1 Giesenschlag (API 42-051-31485) well located west of College Station in Burleson County, Texas. The Upper Woodbine shale has a very low resistivity (1.5 ohm-m) with an average gamma ray reading of 100 API (American Petroleum Institute) units, while the Eagle Ford Shale has a higher resistivity of 3-6 ohm-m and an average gamma ray reading of 60-75 API units. This log character is widespread across several counties and provides a unique way to map the outline of the incised valley.

Double A Wells Incised Valley

Paleontological and palynologic data infer that the downdip sands in Sugar Creek and the Hortense–Leggett–Seven Oaks complex are Late Woodbine (Late Cenomanian) in age (Foss, 1979a, 1979b, 1980). The sands are described as submarine fan deposits by Siemers (1978). The planktonic foraminifera *Rotalia greenhornensis* was

Table 1. Comparison of Woodbine versus Eagle Ford textural elements in Madison, Brazos, and Grimes counties, Texas, within the Paleo-Brazos incised valley.

	Qtz mean size	Qtz %	Rx %	MATRIX %	Si cmt %	CO_3 cmt %
SUB-CLARKSVILLE	0.32	62	6.7	24	1	14
WOODBINE	0.22	79	3	11.3	13	4.2

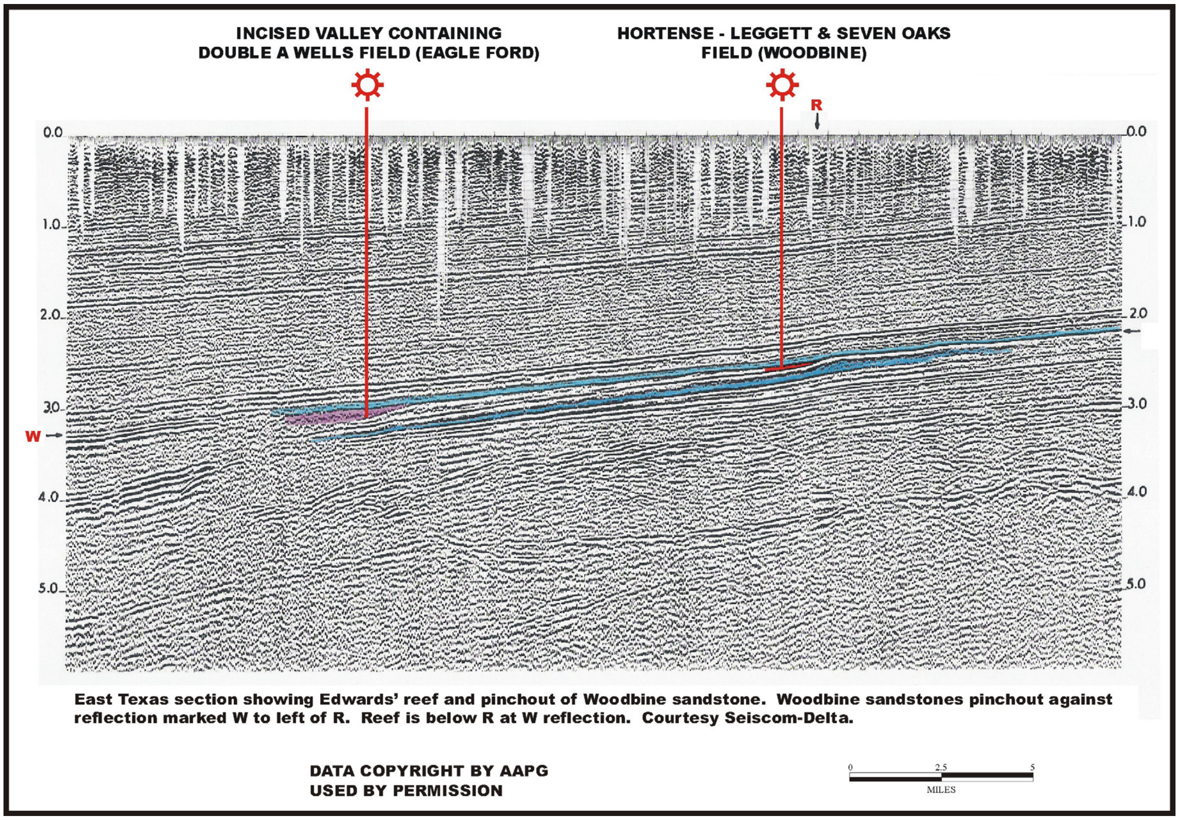

Figure 12. Published north-south seismic line showing the Edwards reef trend and the pinchout of the Woodbine, Polk County, Texas (modified after Sheriff, 1976). Purple wedge shows location of Eagle Ford incised valley at Double A Wells Field. This seismic line is parallel to log cross-section in Figure 6C.

found in the Shell #1 Alexander well at depths of 12,645 ft and 12,715 ft and is diagnostic of the upper Cenomanian for the Upper Woodbine (Foss, 1979a). These sands were carried into deeper water near the end of or possibly right after the Harris Delta deposition. The sands were dropped at locations where slight differences in water depth or downdip constriction of the flow system caused the carrying capacity of the density currents to diminish. The indicated water depths for the Woodbine suggest that Woodbine interval is a regressive shelf sequence in Polk County, Texas (Foss, 1979a). A regional unconformity truncates these Woodbine sands at the Edwards shelf margin and formed an incised valley in the area. Figure 12 (seismic line from Sheriff, 1976) demonstrates both the regional Woodbine truncation and the Eagle Ford–aged incised valley at Double A Wells Field, as does the log cross-section of Figure 6C.

Double A Wells Field is located immediately behind and above the Sligo shelf margin. Published articles by Stricklin (2002a, 2002b) described the sands in this area as submarine fan deposits, but later personal communications from him indicated that he recognized that an alternate and possibly better interpretation was that of an incised valley with an Eagle Ford age. This interpretation would be consistent with the Eagle Ford–aged sands of Aggieland Field in Brazos County, Texas. It is significant that the log characteristics that make it possible to distinguish the Eagle Ford from the Woodbine at Aggieland Field in Brazos County, Texas, can be seen at the base of the incised valley sequence at Double A Wells Field in Polk County, Texas. The Eagle Ford within the incised valley at Double A Wells Field has a higher resistivity and a cleaner Gamma Ray than the underlying incised shelf shale beds. Figure 13 shows a log from Double A Wells with the Eagle Ford Unconformity highlighted—compare this to the log from Burleson County in Figure 7. Barrett and Goodson (2006) confirmed the

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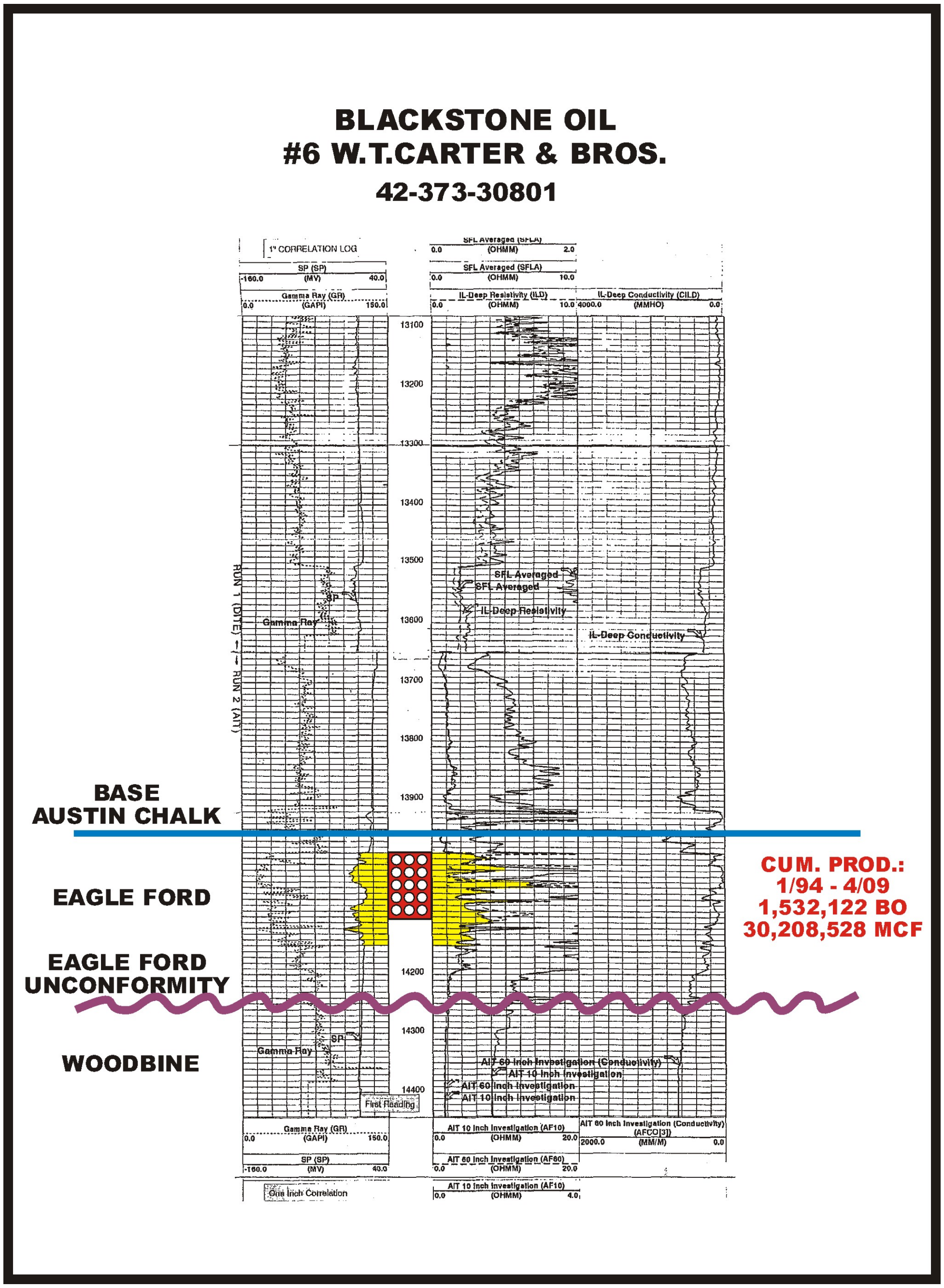

Figure 13. Log of the Blackstone #6 Carter well (API 42-373-30801), Double A Wells Field, Polk County, Texas. This well produces gas from Eagleford-aged sands within the Double A Wells incised valley.

presence of Eagle Ford–aged sands on strike with Double A Wells Field in Tyler County, Texas. They used high resolution foraminiferal biostratigraphy to confirm the Eagle Ford age. Palynologic data provided by Christopher (1980) for the Tuscaloosa in outcrop in Alabama and Georgia supports an Eagle Ford age for the Tuscaloosa.

EAGLE FORD SHALES

The organic rich shales of the Eagle Ford interval were formed by the same processes as the Lower Woodbine "Maness" shale. Charvat and Grayson (1981) confirmed anoxic conditions for the Eagle Ford of Central Texas based on environmental indicators in outcrops of the Eagle Ford near the Balcones Fault System. They attributed the anoxic conditions to water depth, upwelling, and possibly a silled basin due to movement on the San Marcos Arch. Dawson (2000) concluded that the organic-rich shales of the Eagle Ford were deposited in a shallow marine environment and that the deposition coincided with a prolonged episode of lowered oxygen content. Weissert (1981) shed some light on the origin of this type of black shale. He suggested that multiple origins may exist for stratified water masses, including continental climate, floating masses of fresh water, and freshwater turbidity flows rich in terrestrial organic matter. A "hot-house" environment with equable climate and sluggish oceanic currents will contribute to such anoxic conditions. He favored a global rather than local control on the formation of anoxic basins.

The organic-rich shales of the Lower Woodbine/Maness interval are restricted to the mouth of the East Texas Basin, immediately behind the Sligo-Edwards shelf margin. These shales are not tied to a worldwide "oceanic anoxic event" (Arthur and Schlanger, 1979). The Eagle Ford shales of South Texas do correlate with the major oceanic anoxic event of Arthur and Schlanger (1979) and may be related to the stratified water columns associated with such events. The rapid sealevel rise after the Eagle Ford Unconformity (providing greater preservation potential), the partial restriction of the Gulf of Mexico at the time (the Panama Barrier as quoted in Weissert, 1981), and the post-unconformity irregular topography all provided enhanced opportunity for local stratified basins to form along the U.S. Gulf Coast at the same time that a worldwide anoxic event was occurring in the world's deep ocean basins.

Thus, the Lower Woodbine organic-rich shales are probably mostly a local event, while the Eagle Ford organic-rich shales are probably a combination of both local and global circumstances.

UNCONFORMITIES

Forgotson (1958), published one of the first detailed east-west cross-sections from Anderson County, Texas, to Adams County, Mississippi. He put unconformities above the Woodbine in Texas, and above and below the Tuscaloosa in Louisiana and Mississippi. He correlated the unconformity above the Woodbine in Texas to be equivalent to the unconformity above the Tuscaloosa in Louisiana.

The next systematic study of the relationship of the Tuscaloosa to the Woodbine–Eagle Ford was by Granata (1963). Figure 4 is based on his interpretation that the unconformity above the Woodbine and below the overlying Austin Chalk in East Texas is below the Eagle Ford and Tuscaloosa in North Louisiana. This unconformity is called the "Eagle Ford Unconformity" in this paper and is the critical lowstand event between the regressive Woodbine and the transgressive Eagle Ford/Sub-Clarksville of East Texas. Please compare Figure 4 to Figure 14, which is a north-south cross-section through the East Texas Basin.

Unconformities are recognized from the outcrop belt in central and northeast Texas. Hill (1901) recognized that not only did the Eagle Ford thin southward from near Dallas to Austin, but that it did so by the loss of the lower beds. This suggests that perhaps a portion of the San Marcos Arch was emergent throughout a portion of the Eagle Ford similar to the Sabine Uplift where the same loss of Eagle Ford is noted (Granata, 1963).

Badachhape (1988) provided a subcrop map of the Base of the Austin Chalk over the Texas portion of the Sabine Uplift, as well as a discussion of three unconformities in the interval of interest: a pre-Woodbine unconformity, a pre–Eagle Ford unconformity and a pre–Austin Chalk unconformity. He considered the three unconformities of East Texas to be related to the middle Cretaceous lowstand of Vail et al. (1977) and the Mid-Cretaceous Unconformity (MCU).

Figure 15 is a generalized map of the present-day distribution of Woodbine-aged sediments, based on these data and assumptions. The East Texas Basin and the off-shelf thickening south of the Edwards shelf margin account for nearly all of the Woodbine-aged sediments on this map. The widespread nature of the Eagle Ford Unconformity at the end of the Woodbine deposition greatly reduced the preservation of this interval. Lock et al. (2007) described microkarst on the top of the Buda where the Boquillas (Eagle Ford equivalent) fills the microkarst solution pockets. This argues for subaerial exposure at this location during the Eagle Ford unconformity.

Figure 16 is a generalized map of the Eagle Ford–aged sediments across the Gulf Coast. The transgressive nature of this interval greatly increased its preservation relative to the regressive Woodbine interval. These sediments are much more widespread, and reflect the preservation of sediments with widely different provenances. The local depocenters of very rich organic shales are due to local areas of quiet anoxic bottom waters that trapped organic matter, and rising water levels that enhance preservation. The maps in Figures 15 and 16 do not represent original depositional boundaries but preservational boundaries after structural movement and erosion.

IGNEOUS ACTIVITY

Belk et al. (1986) described the Woodbine volcanic sediments in Sevier, Pike, and Howard counties of southwest Arkansas (Figs. 1 and 10) and determined that the most probable provenance for the cobbles of volcanic material in the Woodbine gravels was the igneous province of the Hot Springs–Little Rock area, Arkansas. Hazzard (1939) made a very convincing argument for an Eagle Ford age for those volcanic rocks based on ammonite identifications. Hazzard (1939) described three volcanic beds of tuffaceous sands in Arkansas, the lowest of which he correlated with tuffaceous sands in Grayson County, Texas. Based on plant fossils found in the intervening shales, Hazzard (1939) considered his newly named "Centerpoint Volcanics" of southwestern Arkansas to be age equivalent with the Tuscaloosa in northwest Louisiana and with the Eagle Ford of northeast Texas. Hazzard (1939) provided correlation evidence based on plant species, ammonite identification, and multiple detailed measured sections from southwestern Arkansas to Grayson County, Texas, and detailed core samples, well cuttings, and log sections across northern Louisiana to support his case. Hazzard (1939) also recognized the transgressive nature of the Eagle Ford and his Centerpoint Volcanics. We consider the transgressive nature of the Centerpoint to support an Eagle Ford age for the Centerpoint Volcanics.

SUMMARY

The Woodbine–Eagle Ford (Cenomanian-Turonian) records a very detailed account of the interplay between a passive margin third-order regressive-transgressive sequence, eustacy, and compressive structuring from a far-

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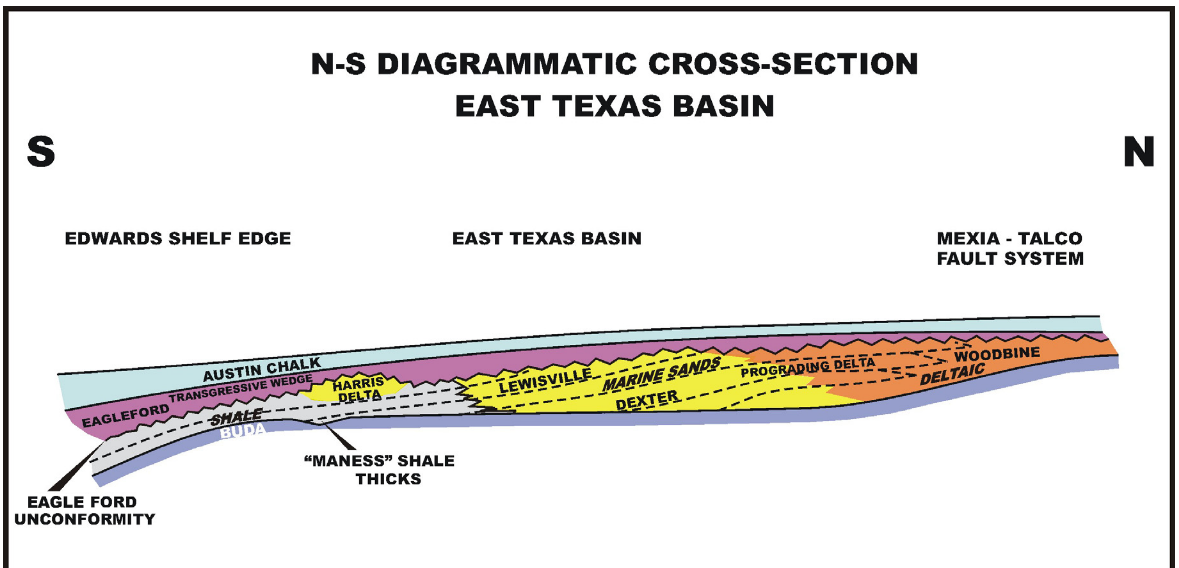

Figure 14. A north-south diagrammatic cross-section across the East Texas Basin which demonstrates the regional stratigraphy within the basin. Compare this to Figure 4 stratigraphy.

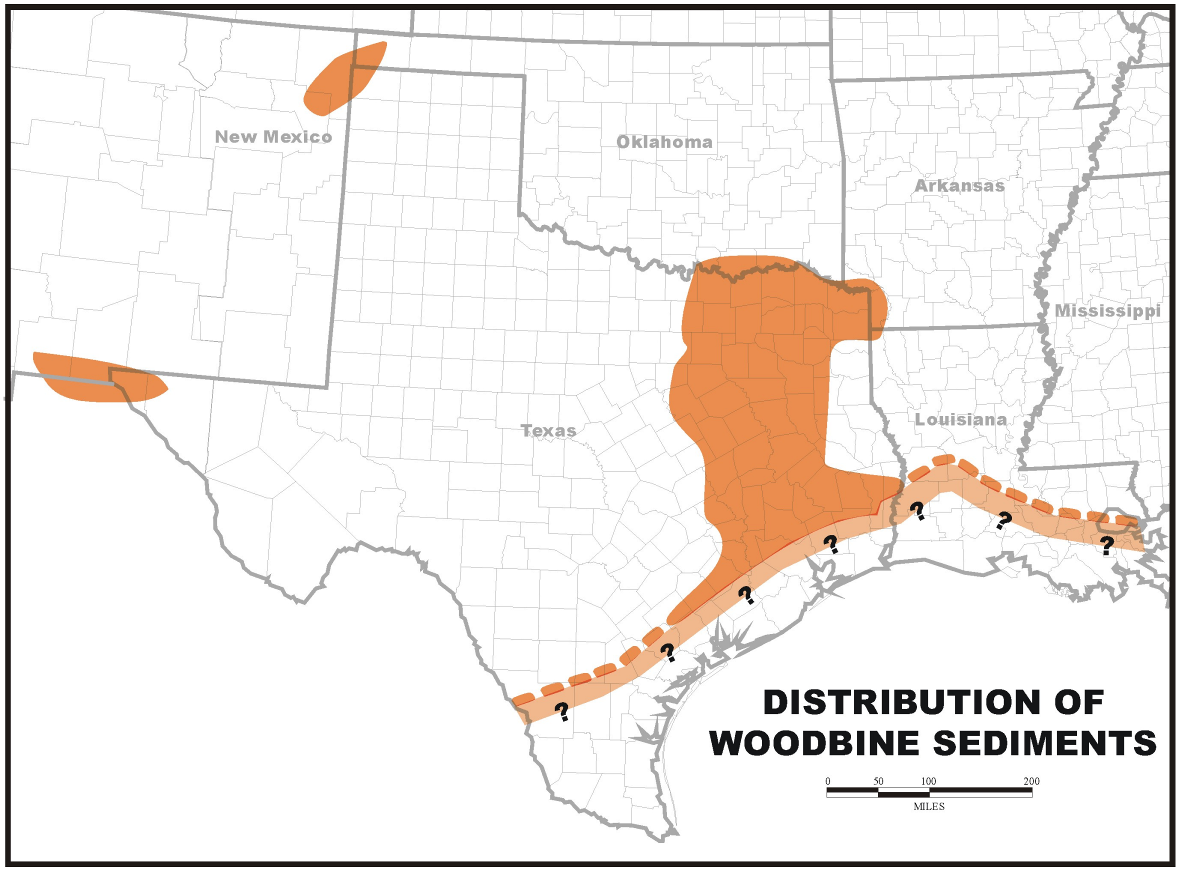

Figure 15. Map of approximate distribution of Woodbine-aged sediments on the U.S. Gulf Coast (modified after Adkins, 1932).

field source. Fortunately, this interval contains some of the earliest and largest oil and gas fields along the Gulf Coast; thus, it has been studied in great detail. The conclusions herein would not have been possible otherwise.

Erosion of the Ouachita Highlands of Oklahoma and Arkansas distributed coarse clastic sediments south into Texas and Louisiana during the Cenomanian and Turonian of the Late Cretaceous. A large delta began to prograde south across the shallow shelf. The shelf edge was coeval with the previous Sligo and/or Edwards reef systems. Due to the reef growth in both of those systems, the reefs acted as sills to the shallow shelf. Large anoxic basins formed in silled depressions on the shelf north of the shelf edge. Today those shales are the Maness facies of the Woodbine Shale and are both a known hydrocarbon source and producing horizon.

During Upper Woodbine Lewisville deposition, sealevel rise continued, but, the East Texas Basin was predominantly an interdeltaic strandplain (Oliver, 1971). A highly-destructive (wave-dominated) deltaic system was deposited south of the Lewisville strandplain system (Ambrose et al., 2009) and extended further south. The continued structural folding and salt mobility aided in generating accommodation space. As expected, this allowed multiple opportunities for both autocyclic and allocyclic channel migration and the facies associated with both local and widespread fourth and fifth order sequences to be preserved. The shallow water shelf was now open to marine circulation, thus the Lewisville shales are not overly organic.

Near the end of Woodbine Lewisville deposition a southwest-northeast–trending wrench fault developed, accompanied by SW to NE compression. Large asymmetric folds developed into alternating uplifts and basins from South Texas to Mississippi. A thick sequence of Woodbine sediments is preserved within the East Texas Basin, but in many other places it is completely missing. Only the suggestion of very low resistivity shales south

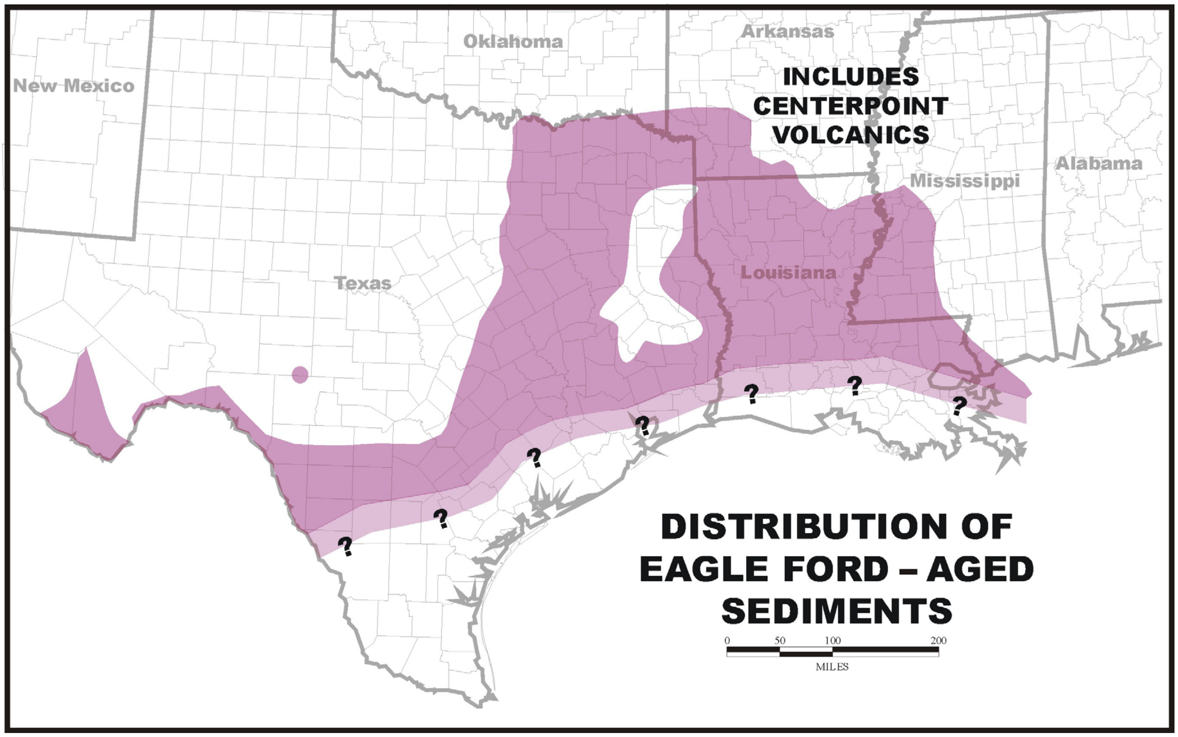

Figure 16. Map of approximate distribution of Eagle Ford–aged sediments on the U.S. Gulf Coast (modified after Adkins, 1932).

of the Sligo/Edwards shelf margin in South Texas (LaSalle County), the Upper Texas Gulf Coast (Grimes and Polk counties) and southern Louisiana (Rapides Parish) support the probability that the Woodbine was originally much more extensive than is now preserved.

A large regional lowstand unconformity is associated with this compression (the Eagle Ford Unconformity) and removed much of the preceding Woodbine, as well as carbonates of the Lower Cretaceous, especially across the upwarping areas. Multiple incised valleys accompanied this lowstand. This lowstand erosion is linked in time to the Middle Cretaceous Unconformity of the Gulf Coast offshore.

Transgression began to cover the shelf from south to north as the southwest-northeast compression was temporarily halted. Eagle Ford–aged sediments covered most of the eroded shelf. The Tuscaloosa of Alabama and Mississippi, as well as the Tuscaloosa of the southern Louisiana Shelf, along with the Eagle Ford/Sub-Clarksville of East Texas, the Eagle Ford of South Texas, and the Centerpoint Volcanics of southwestern Arkansas are all part of this large transgressive sequence. Tuffaceous and ashy sands are common throughout this transgressive sequence. In South Texas, the Eagle Ford is a very organic rich shale similar in some respects to the Maness organic-rich shales. These shales formed in anoxic basins during the Eagle Ford transgression. The transgressive nature of this interval is an important element in making regional correlations of the Tuscaloosa to the Woodbine –Eagle Ford interval of East Texas.

The top of the Eagle Ford is another unconformity that preceded the Austin Chalk. In some places this unconformity had active erosion, while in other locales it was more a surface of nondeposition and hard-ground development. Much of the preceding literature had assumed that this unconformity above the Eagle Ford is the major Middle Cretaceous Unconformity. Our research strongly suggests that the Eagle Ford Unconformity is the major period of nondeposition and erosion, while the unconformity at the end of the Eagle Ford is a much more minor hiatus. The Austin Chalk was deposited in deeper quiet water on a clear water shelf.

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This study was initiated by the senior author as part of a deliberate search for regional stratigraphic traps in the Woodbine–Eagle Ford interval of East Texas for Carr Resources, Inc. Carr Resources, Inc. has provided the opportunity to continue this study outside the East Texas Basin, even though those areas were not part of the original study boundaries. Dr. Bill Ambrose of the Texas Bureau of Economic Geology reviewed the manuscript and greatly helped make the manuscript more readable, as well as providing ideas and insights from his personal experience. Figure 12 is modified from a seismic line published by Sheriff (1976) in the *American Association of Petroleum Geologists Bulletin* (v. 60)—the line is copyrighted by the American Association of Petroleum Geologists and is reprinted here under their fair use terms.

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