

DIACHRONOUS DEVELOPMENT OF LATE QUATERNARY SHELF-MARGIN DELTAS IN THE NORTHWESTERN GULF OF MEXICO: IMPLICATIONS FOR SEQUENCE STRATIGRAPHY AND DEEP-WATER RESERVOIR OCCURRENCE

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ABSTRACT: For the most part, delta development across the northern Gulf of Mexico shelf during the last glacioeustatic cycle occurred throughout the falling limb of sea level. The deltas have different morphologies, sediment facies patterns, and stratigraphic architectures. Depending on the sediment supply of their fluvial feeders, these deltas reached the shelf margin at different times. The Rio Grande, Colorado, Trinity, and Sabine rivers remained fixed in their locations on the shelf throughout the late stages of sea-level fall and into the lowstand. Hence, they all formed lowstand deltas and all nourished slope fans. In contrast, the Brazos and western Louisiana rivers abandoned their shelf-margin deltas prior to the lowstand. Hence, neither the Brazos nor the western Louisiana fluvial systems have linked lowstand delta and slope fans. Because growth of the different shelf-margin deltas spans different portions of the sea-level cycle, the location of the sequence boundary and associated correlative conformity relative to the shelf-margin stratigraphic package varies from one deltaic system to the next.

INTRODUCTION

During the last glacioeustatic cycle, no fewer than ten large shelf-margin deltas existed on the northern Gulf of Mexico margin (Anderson and Fillon, 2004). Of these ten deltas, only five have been linked to lowstand fans. This paper addresses the question of why some rivers nourished lowstand delta and fan complexes and others did not. It also addresses a long-standing problem concerning the position of the sequence boundary and associated correlative conformity within the shelf-margin stratigraphic package.

Discussion focuses on the deltas of the northwestern Gulf of Mexico, where long sediment cores provide the opportunity for acquiring chronostratigraphic and lithological information. These deltas include the Rio Grande, Colorado, Brazos, Trinity–Sabine–Brazos, and western Louisiana shelf-margin deltas (Fig. 1). Previous studies of these deltas (Suter and Berryhill, 1985; Morton and Price, 1987; Morton and Suter, 1996; Anderson et al., 1996) provide an important foundation for this work, but they lacked detailed chronostratigraphic information.

Recent studies by Fraticelli and Anderson (2003), Banfield and Anderson (2004), Abdulah et al. (2004), and Wellner et al. (2004) provide the chronostratigraphic framework needed to relate evolution of shelf-margin deltas to a well-established sea-level curve. This includes radiocarbon dates that precisely bracket the timing of delta formation, with the exception of the Rio Grande Delta. The only other area where data of this kind exist is the Lagniappe Delta of offshore Mississippi and Louisiana (Kolla et al., 2000; Roberts et al., 2004; Fillon et al., 2004; Kohl et al., 2004). Discussions of the late Quaternary shelf-margin deltas of the northeastern Gulf of Mexico margin are provided by Roberts et al. (2004) for the Lagniappe Delta, Sager et al. (1999) for the Mobile Delta, Bart and Anderson (2004) for west Florida deltas, and McKeown et al. (2004) for the Apalachicola Delta.

METHODS

The data set used for this study consists of several thousand kilometers of high-resolution seismic data, lithological information from oil-company-platform borings, and paleontological,

sedimentological, and geochronological data from several long (average 100 meters) cores.

The relationship between the oxygen isotope record and global ice volume (Shackleton and Opdyke, 1973) provides a proxy for changes in global sea level (Shackleton, 1987) (Fig. 2). The proxy sea-level curve in Figure 2 is constrained by U-Th dated sea-level stands for the interval between stage 5e and early stage 2. It is more tightly constrained for the time interval between late stage 2 (18,000 cal BP) to present by radiocarbon-dated corals (Bard et al., 1990; Chappell et al., 1996). This is the most precise sea-level record for all of geological time.

Classical seismic stratigraphic methods were used to describe the external forms and internal stratal geometries of depositional units and to characterize the nature of the bounding surfaces and the reflection configurations of the units (e.g., Mitchum et al., 1977; Vail et al., 1977). Deltaic deposits are assigned to systems tracts using their bounding stratigraphic surfaces. It is possible to assign ages to these surfaces using the established oxygen isotope stages shown in Figure 2. The oldest of these surfaces is the Stage 5e maximum flooding surface (Fig. 3A), which formed during a high sea-level stand at approximately 120,000 yr BP (Fig. 2). The highstand systems tract (in the Exxon sense) occurs between this flooding surface and the Stage 2 sequence boundary (Fig. 3). There is another prominent flooding surface (Stage 3 maximum flooding surface) associated with the Stage 3 sea-level rise. The third stratigraphic surface is the Stage 2 sequence boundary. It is a prominent unconformity, marked by deep fluvial valleys and truncation of delta topset beds (Fig. 3). It is the surface of maximum fluvial incision and, as such, is traceable across the shelf (Anderson et al., 2004). The transgressive surface is a diachronous surface formed by wave erosion as the shoreline advanced landward during the Stage 2 to Stage 1 transgression (Fig. 2). It is a planar surface that, on the inner shelf, is amalgamated with the sequence boundary.

The chronostratigraphic framework used in this study was established through integration of biostratigraphy, radiocarbon dating, and oxygen isotope stratigraphy. Chronostratigraphic analysis was conducted on five long cores from across the study area (Anderson et al., 2004) (Fig. 1). Oxygen isotope curves were generated for three outer-shelf cores (B-2, B-92, and B-146) that

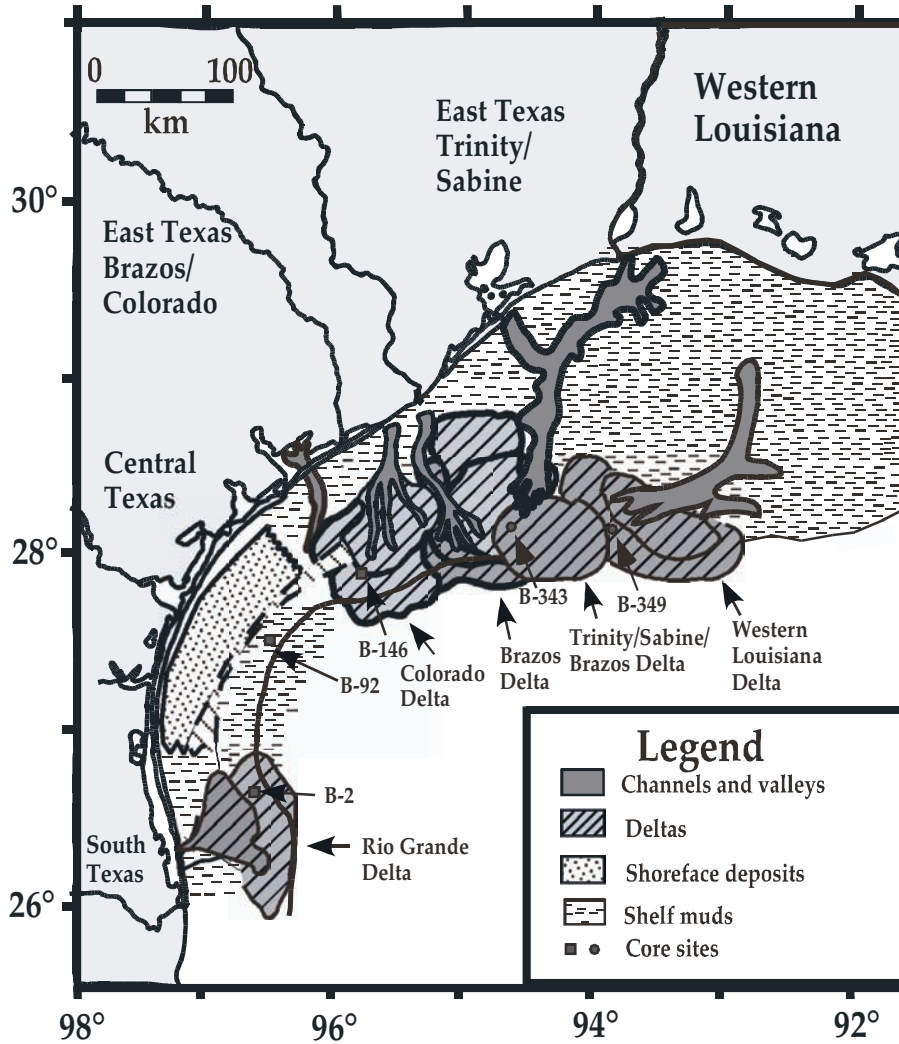


FIG. 1.—Paleogeographic map showing shelf-margin deltas of the northwestern Gulf of Mexico that formed during the last glacioeustatic cycle. Also shown are the locations of sediment cores used for chronostratigraphic analyses.

contained sufficient monospecific foraminifera for analysis. Cores B-343 and B-349 did not contain enough monospecific foraminifera for isotopic analysis, but biostratigraphic analysis and radiocarbon dating was conducted on these cores. Key biostratigraphic markers include the last occurrence of *Globorotalia menardii flexuosa*, which corresponds to approximately 85 ka (Kohl, 1986) and relative concentrations of *Globorotalia menardii* and *Globorotalia inflata*, which define well established Ericson–Wollin zones (Ericson and Wollin, 1968), (Fig. 4A, C). Detailed analysis of benthic foraminifera was performed on cores B-146, B-343, and B-349 and was used to construct paleobathymetry curves (e.g., Fig. 4C).

Conventional and accelerator mass spectrometer (AMS) radiocarbon dates provide the most precise age control for the shelf-margin deltas. Radiocarbon ages younger than 20,000 years are reported in radiocarbon years (ka) and calendar years (cal BP) for direct comparison to the sea-level curve of Bard et al. (1990) (Fig. 2). Ages greater than 40,000 years are considered radiocarbon dead.

Chronostratigraphic results from long sediment cores provide age constraints on key seismic units and stratigraphic sur-

faces (Figs. 3, 4) and a means of correlating these surfaces and depositional events to the eustatic curve shown in Figure 2. More detailed discussion of the chronostratigraphic methods and interpretations are provided by Abdulah et al. (2004), Banfield and Anderson (2004), and Eckles et al. (2004).

The distinction of river-, tide-, and wave-dominated deltas is, to a large degree, based on the shape of a delta (e.g., Coleman and Wright, 1975; Galloway, 1975; Bhattacharya and Walker, 1992). Detailed mapping of deltas was conducted and their shapes established using isopach maps (Banfield and Anderson, 2004; Abdulah et al., 2004; Wellner et al., 2004; and <http://gulf.rice.edu>). Deltas with elongate, shore-parallel orientations are interpreted as wave-dominated deltas whereas those with lobate shapes are interpreted as river-dominated deltas.

The relative fluvial versus wave influence on delta evolution was also determined using clinof orm geometries and height. The modern toe of the shoreface ranges from -8 to -12 meters and corresponds to the depth of shoreface erosion (transgressive ravinement surface) (Rodriguez et al., 2001). Below this depth, shoreface deposits are rarely preserved and marine muds rest directly on Pleistocene deposits. Given the assumption that the

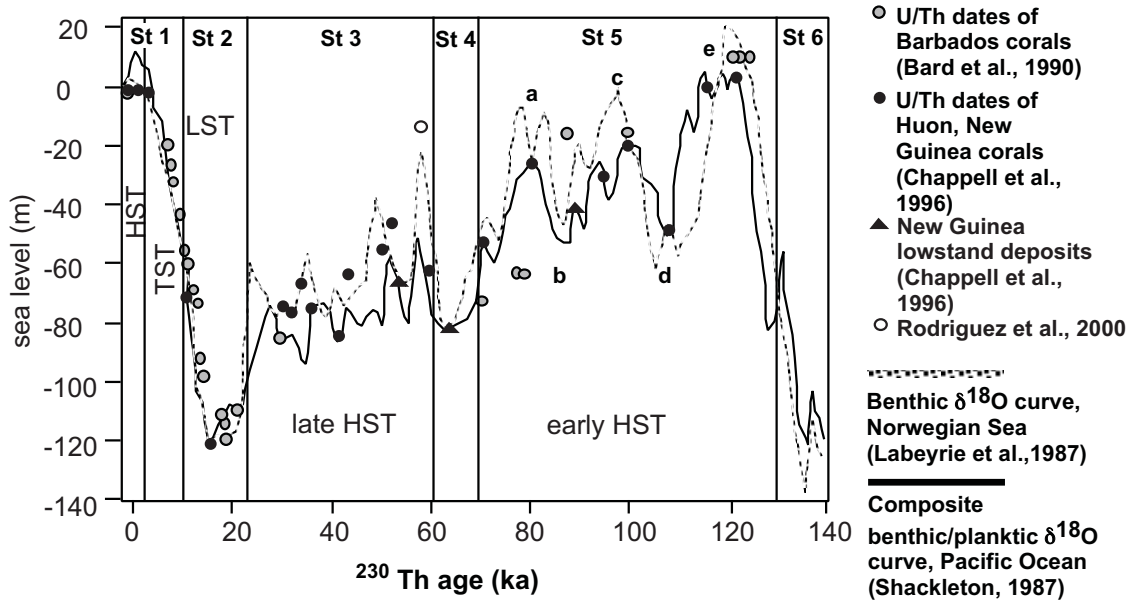


FIG. 2.—The composite oxygen isotope curve used in this study as a proxy sea-level curve. Also shown are actual sea-level datums that help constrain the curve.

depth of wave erosion has not changed significantly during the last glacial-eustatic cycle, clinoforms thicker than 12 meters indicate that deltas prograded seaward of the toe of the shoreface, beyond the limits of wave influence, which indicates strong river influence. Finally, clinoform dips were used to distinguish delta types. Wave-dominated deltas display unidirectional, seaward dips whereas river-dominated deltas display variable dips and thus variable progradation of individual lobes.

RESULTS

The Rio Grande Delta

Banfield and Anderson (2004) studied the evolution of the Rio Grande river-deltaic system during the last glacioeustatic cycle. The chronostratigraphic control for the evolution of the Rio Grande Delta is based on a single core (Core B-2) that was collected to the north of the shelf-margin delta (Figs. 4, 5). While this core provides independent chronostratigraphic constraints on the seismic stratigraphic interpretation, it was not possible to acquire radiocarbon dates within the shelf-margin delta itself.

During the initial fall in sea level, the ancestral Rio Grande formed a wave-dominated delta on the inner shelf (Banfield and Anderson, 2004). As sea level continued to fall, the river shifted its course to the south, abandoning its former highstand delta on the inner shelf to construct a new delta on the outer shelf (Fig. 6A). After the river shifted to the south, the delta prograded more or less continuously across the outer shelf during the Stages 3 through 2 fall. These falling-stage deltas were river-dominated. When the shoreline reached the shelf margin, the Rio Grande formed a large and thick shelf-margin delta linked to a slope fan (Fig. 6B).

Seismic profiles across the delta show complex sigmoid-oblique to oblique tangential reflection configurations (Fig. 7). Clinoform angles are generally less than 3°. Individual clinoform sets indicate variable directions of progradation, and the overall shape of the delta displays a lobate to fan morphology (Fig. 6).

Near the shelf margin, clinoforms are up to 70 meters thick, from offlap break to the toe of the clinoforms. The lower portions of clinoforms are acoustically laminated, which implies that they are muddy. The upper portions of the delta are characterized by a chaotic seismic facies that downcuts into the underlying clinoforms. This upper seismic unit is interpreted as distributary channels, whose grades were lowered as sea level fell, and their associated mouth-bar deposits. This interpretation is supported by the single platform boring (SP-1, Fig. 7B) that penetrated the delta. This boring sampled mud in the lower clinoform unit and sand in the upper chaotic unit. The upper sand unit is just over 30 meters thick.

The data indicate that the Rio Grande shelf-margin delta was a river-dominated delta with a sediment supply that was large enough to enable progradation into water depths up to 70 meters. Banfield and Anderson (2004) calculated values of long-term sediment flux for the Rio Grande using volumes of individual deltas. Their results indicate an increase in sediment supply and an increase in sand content of the delta as it prograded across the shelf. They attributed this to the increase in fluvial gradient and cannibalization of older shelf deltas as sea level fell. The shelf-margin delta itself spans the late fall and lowstand. The delta backstepped onto the shelf at the initial rise in sea level (Banfield and Anderson, 2004). Seismic lines collected near the center of the delta show evidence of failure and downslope transport at the delta front (Fig. 7A). Seismic lines collected near the margins of the delta show little evidence of mass wasting (Fig. 7B).

At the shelf margin, the delta displays low-angle downlap onto the Stage 3 flooding surface (Fig. 7). The top of the delta is truncated by an erosion surface that corresponds to the base of the incised valley. This is the Stage 2 sequence boundary. Near the center of the delta, the Stage 2 sequence boundary and correlative conformity (SB/CC) is difficult to discern but occurs within the clinoform package (Fig. 7A). Along the flanks of the delta the SB/CC is more discernible and is marked by low-angle onlap onto that surface (Figs. 7B, 8A). A strike-oriented seismic profile (Line

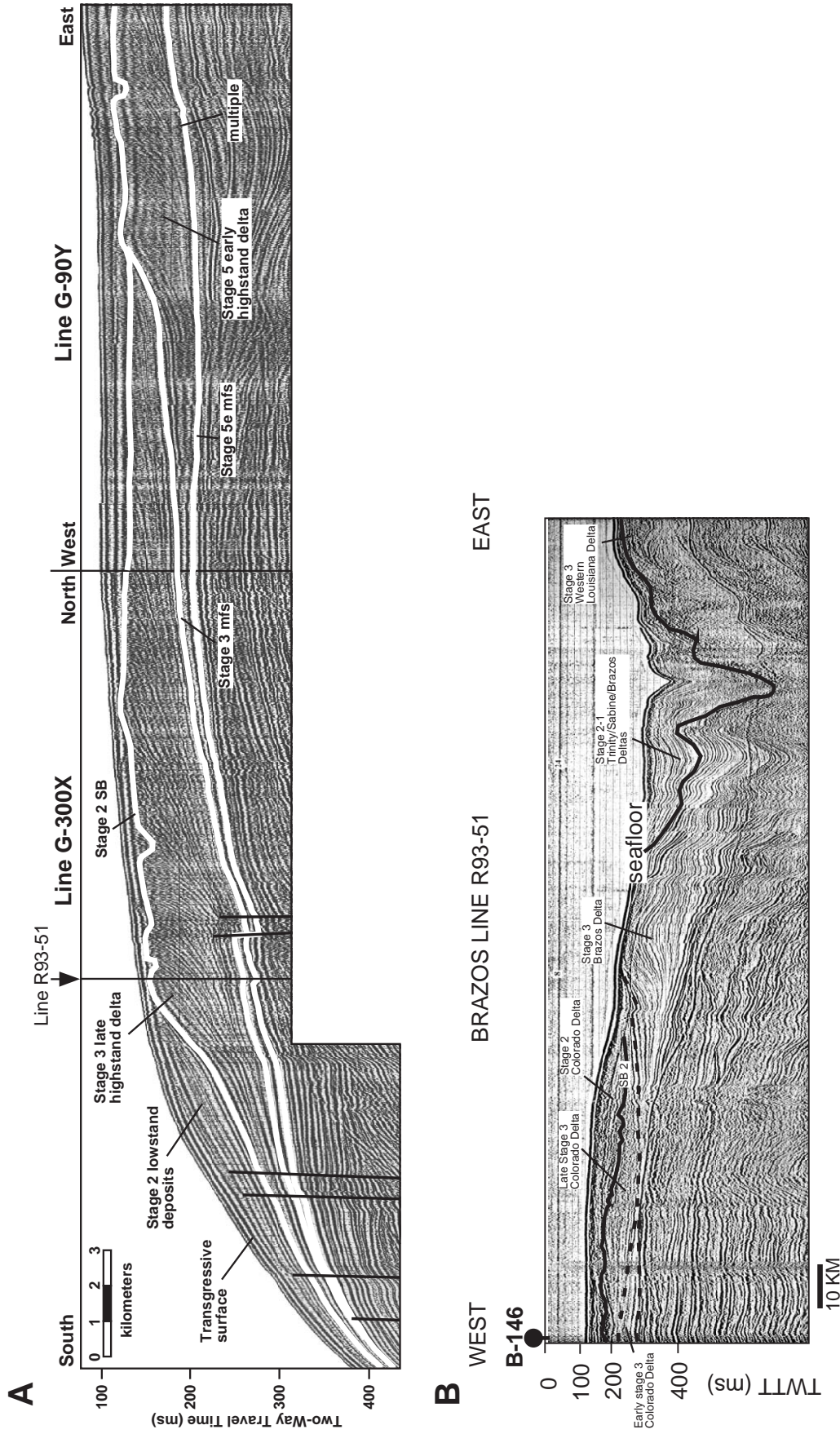


FIG. 3.—Seismic lines G300X, G-90Y, and R 93-51 are used to illustrate key bounding surfaces and systems tracts. Lines G300X and G-90Y were collected along the depositional axis of the Brazos Delta and show two phases of delta progradation that occurred during isotope stages 5 and 3 (Fig. 2). Brazos Line R93-51 is a strike line collected across the outer shelf. This line shows the different stratigraphic levels of the Colorado, Brazos, Trinity-Sabine-Brazos, and western Louisiana shelf-margin deltas and demonstrates the diachronous evolution of these deltas. Note the more chaotic seismic character of the Colorado and western Louisiana deltas relative to the Brazos and Trinity-Sabine-Brazos deltas, which reflects the sandier nature of the former deltas. See Figure 2 for associated sea-level curve. Mfs = maximum flooding surface; SB = sequence boundary.

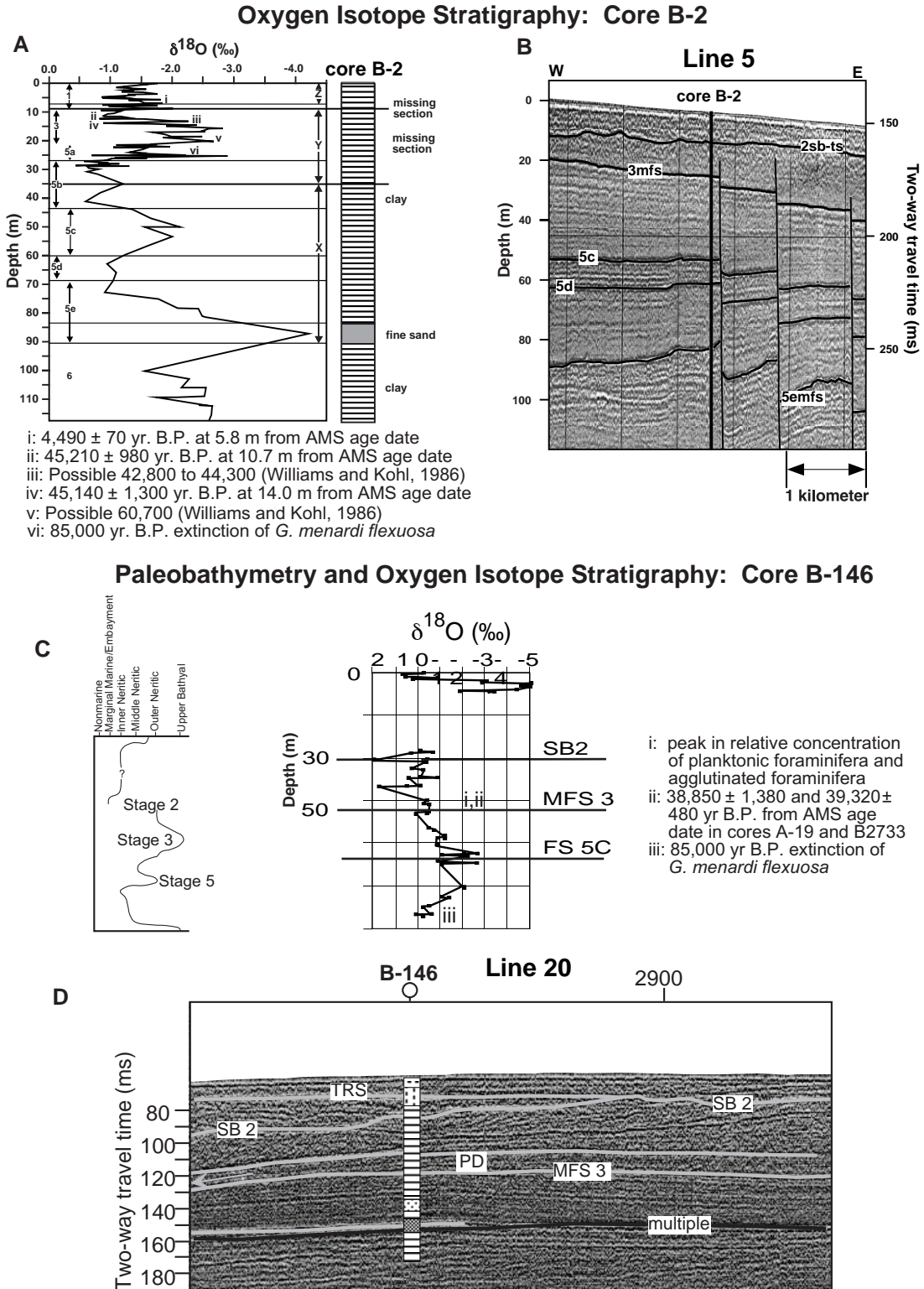


FIG. 4.—**A**) Combined oxygen isotope curve, biostratigraphic markers, and radiocarbon ages for core B-2 and correlation of these chronostratigraphic data to key seismic surfaces illustrated using **B**) a segment of seismic line 5, which crossed the location of B-2 on the south Texas shelf (Fig. 2). **C**) Core B-146 was used to generate an oxygen isotope stratigraphy and for biostratigraphic analysis for the east Texas shelf (Fig. 2). Two radiocarbon dates were derived from nearby cores A-19 and B 2733 and correlated to Core B-146 using prominent seismic reflectors. This chronostratigraphic benchmark was used to constrain the ages of seismic units and bounding surfaces, as illustrated using **D**) a segment of seismic line 20. Modified from Banfield and Anderson (2004) and Eckles et al. (2004).

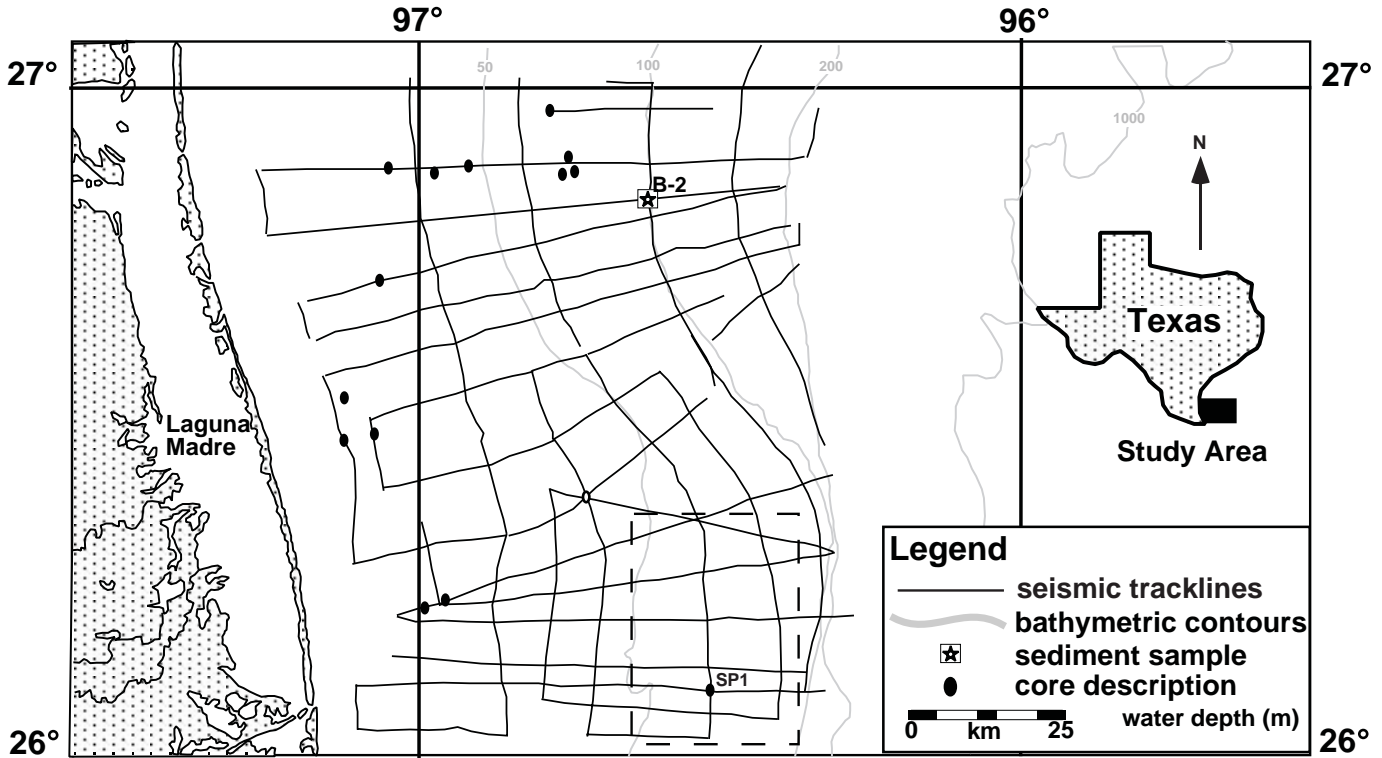


FIG. 5.—The data used to study the Rio Grande delta.

24, Fig. 8B) collected along the upper slope (Fig. 6) shows expansion of the lowstand systems tract toward the south or center of the delta. Significantly, the mounded onlapping fill, the presence of a filled submarine canyon, and the chaotic seismic facies are consistent with a fan origin (Fig. 8B). Sidner et al. (1978) and Rothwell et al. (1991) have previously described the Rio Grande Fan. The transgressive surface is situated at or near the seafloor near the center of the delta, while at the delta flanks it occurs at a deeper stratigraphic level and the overlying transgressive systems tract is thicker (Fig. 8A).

The Colorado Delta

The evolution of the Colorado delta throughout the last glacioeustatic cycle has been described by Morton and Suter (1996), Anderson et al. (1996), Snow (1998), and Abdulah et al. (2004). Abdulah et al. (2004) examined an extensive data set (Fig. 9) and demonstrated that progradation of the delta across the shelf took place in a stepwise fashion as sea level fell intermittently (Figs. 1, 2). By Stage 3 time, the delta was located on the outer shelf, as indicated by two radiocarbon dates of 38.850 ± 1.380 ka and $39.320 \pm .480$ ka near the base of the delta package.

The seismic character indicates that the delta is composed of lobate mounds and lenses that are hundreds of square kilometers in area with prograding clinoforms that display both sigmoidal and oblique tangential geometries (Fig. 10). Clinoform angles increase to a maximum angle of 2.5° in an offshore direction. On the shelf, clinoforms gently downlap and become tangential with underlying parallel, nearly horizontal reflectors, characterized by sheet to sheet-drape geometries. The upper boundary of the delta is characterized by clinoforms whose topset portions have

been deeply eroded (Fig. 10). This erosion surface is the Stage 2 sequence boundary.

Detailed analysis of the highstand Colorado delta by Snow (1998) showed discrete lobes with variable directions of progradation (Fig. 11). This led to the interpretation that the delta was river-dominated. The individual lobes have thick (up to 15 meters) and widespread mouth-bar deposits, characterized by crosscutting erosion surfaces formed by downcutting distributary channels. Their chaotic seismic character indicates that the mouth bars are dominantly sand. This is supported by several platform borings.

An isopach map of the Colorado shelf-margin delta shows a strike-oriented isopach thick (Fig. 11). Clinoforms are up to 50 meters thick, indicating that the delta prograded into water depths this deep (Fig. 10). Near the shelf margin, the seismic character is more chaotic and is disrupted by growth faults. On the slope there is abundant evidence that growth faults contributed to downslope failure at the delta front (Fig. 10).

Chronostratigraphic interpretations for the Colorado Delta were derived from the Brazos 146 core (Figs. 4, 9). This includes oxygen isotopes, biostratigraphic zonation, and radiocarbon ages (Fig. 4C) (Abdulah et al., 2004). In addition, detailed analysis of benthic foraminifera were used to estimate the paleobathymetry for individual units (Abdulah et al., 2004). The delta downlaps the Stage 3 flooding surfaces and is bounded above by the Stage 2 sequence boundary (Figs. 4D, 10). The sequence boundary extends to the shelf break, where it was correlated with submarine canyons updip of the East Breaks Slide (Anderson et al., 1996). Lehner (1969), Tatum (1977), Woodbury et al. (1978), Rothwell et al. (1991), and Anderson et al. (1996) provide descriptions of the East Breaks Slides slope fan complex.

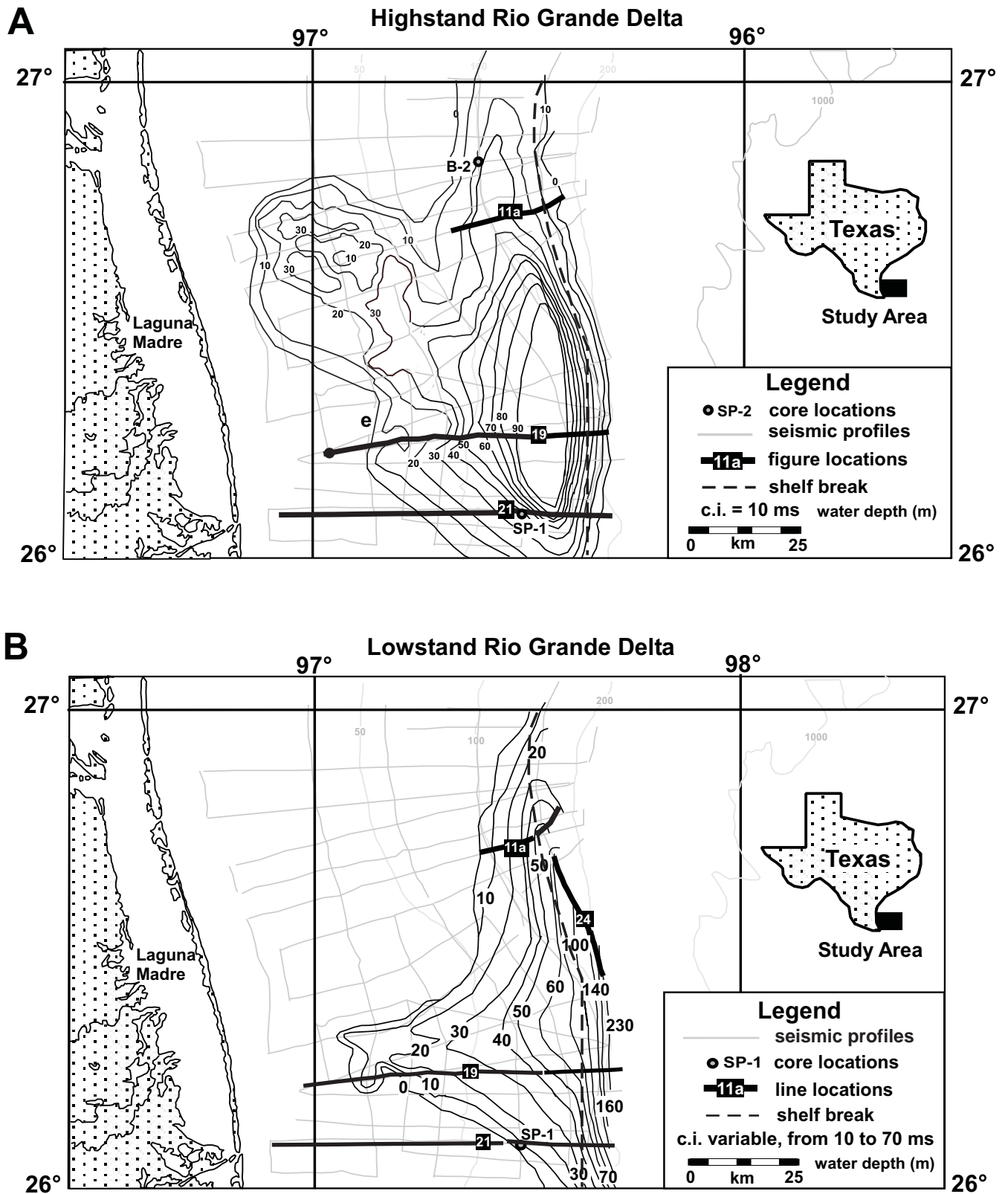


FIG. 6.—Isopach maps showing evolution of the Rio Grande delta. A) The highstand Rio Grande delta was located on the inner shelf, centered around 97° 00' W and 26° 40' S. As sea level fell, the river shifted its course to the south and nourished a shelf-margin delta. B) The lowstand Rio Grande Delta (modified from Banfiel and Anderson, 2004). Also shown are the locations of Core B2 and platform boring SP 1 and seismic lines used to illustrate seismic facies and stratal geometries.

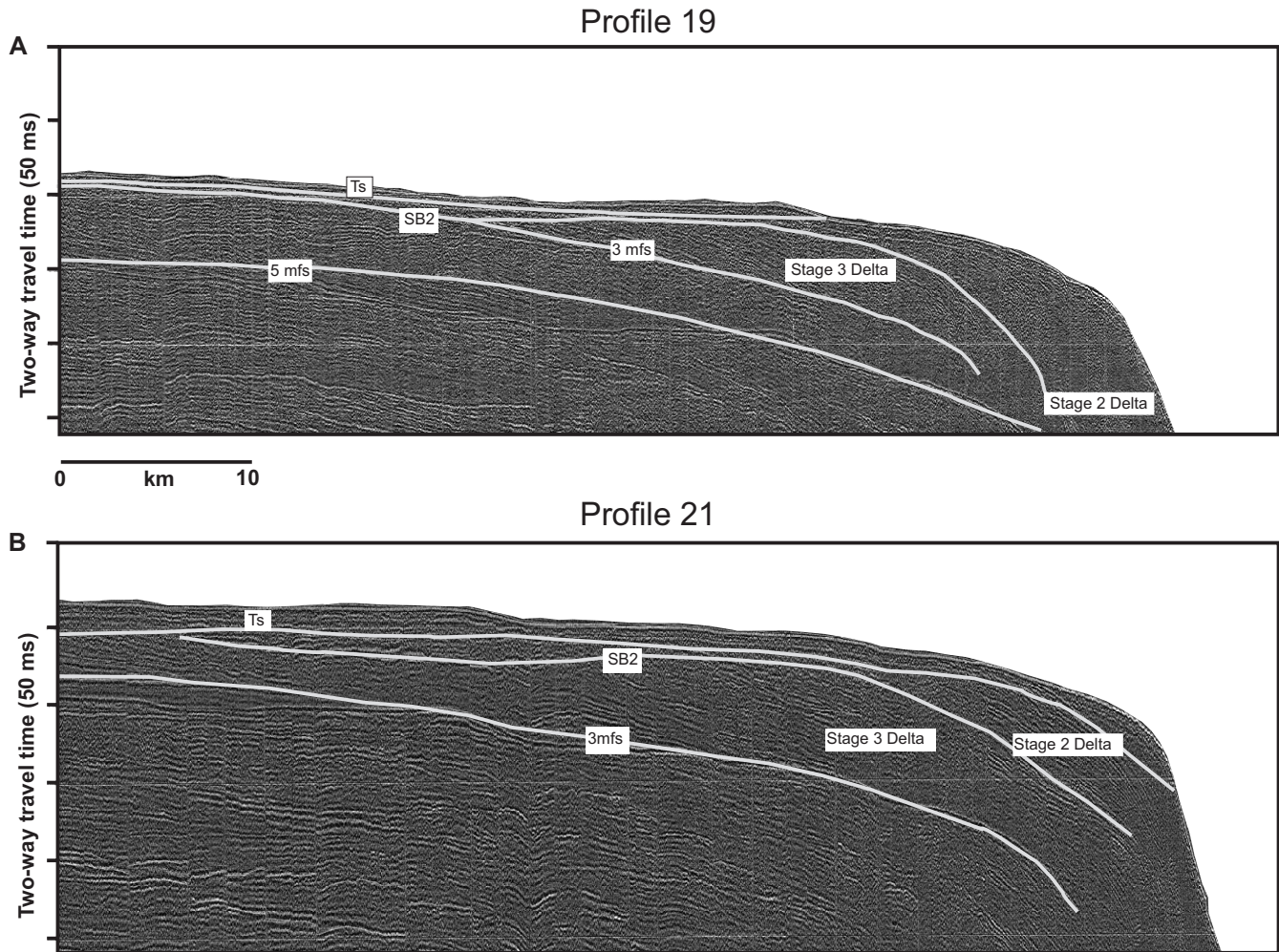


FIG. 7.—Seismic profiles **A**) 19 and **B**) 21 show offlapping clinoform packages that characterize the Rio Grande shelf-margin delta. See Figures 5 and 6 for profile locations. Ts = transgressive surface, 3 mfs = Stage 3 flooding surface, and SB2 = Stage 2 sequence boundary and associated correlative conformity.

As the Colorado delta shifted into an outer-shelf location, sediment supply increased (Abdulah et al., 2004). Laboratory flume experiments designed to mimic the evolution of the delta resulted in a significant increase in the supply of sediment during the late stages of sea-level fall that were caused by headward erosion of rivers and streams and cannibalization of the inner shelf strata (van Heijst et al., 2001).

The Brazos Delta

Anderson et al. (1996) demonstrated that progradation of the Brazos delta during the overall fall in sea level was episodic in nature, with pulses of progradation triggered by interstadial episodes of more rapid fall. Lobate mounds that display discrete directions of progradation mark each phase of delta growth. Clinoforms transition downward into horizontal, parallel reflections that are more or less conformable with the Stage 5e and Stage 3 flooding surfaces on which the whole system rests (Figs. 3, 12). The clinoforms reach a maximum thickness of 80 meters on the outer shelf. There is no evidence of downslope failure, even where the delta reached its most seaward extent (Figs. 3A, 12).

Fraticeilli (2003) conducted a detailed study that focused on the outer shelf and upper slope using a dense high-resolution seismic data grid, several dozen descriptions of platform borings, and several long sediment cores from the upper slope (Fig. 9). Using these data, coupled with a strong chronostratigraphic framework, she was able to map individual delta lobes of the shelf-margin delta (Fig. 13). Her analysis also included sedimentological and paleontological data from several long sediment cores on the upper slope (Eureka cores, Fig. 9).

The paleogeographic maps constructed by Fraticelli (2003) show that the delta prograded seaward and toward the west as sea level fell (Fig. 13). Each of the lobes shown in Figure 13 is separated by minor flooding surfaces that represent autocyclic shifts in the delta that occurred as accommodation was filled (Fig. 12). In general, however, delta growth was fairly continuous during the Stage 3 to 2 fall in sea level. The oldest lobe (lobe 5) prograded across the shelf break.

The Stage 2 sequence boundary cuts into the Stage 3 deltas on the shelf (Figs. 3, 12). At the shelf break, the youngest deltaic deposits are onlapped by transgressive deposits (unit 2). Fraticelli and Anderson (2003) noted that, even though the Brazos Delta

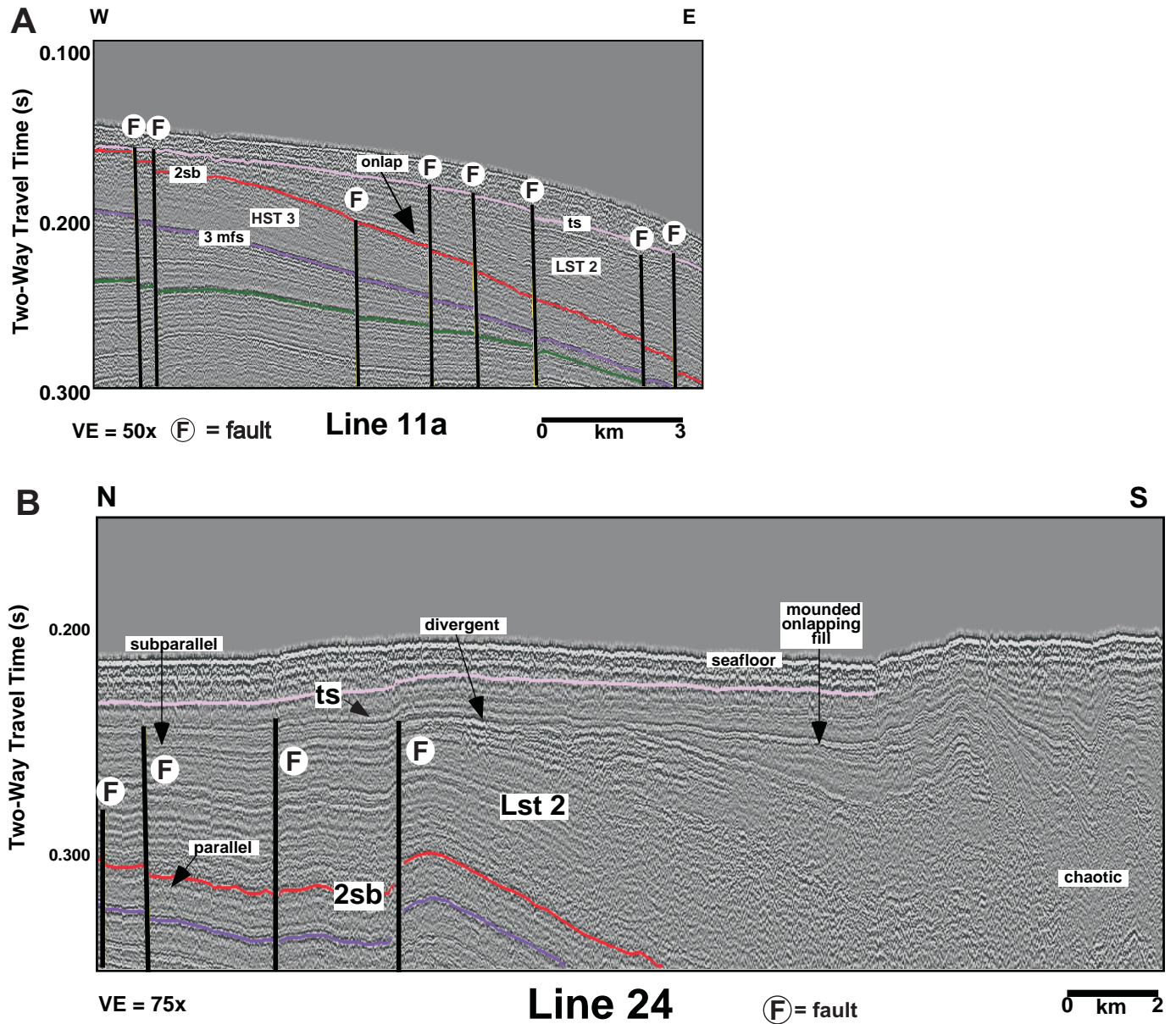


FIG. 8.—A) Seismic line 11a shows the stratigraphic architecture of the Rio Grande shelf-margin delta. At this location near the northern edge of the delta, the Stage 2 sequence boundary (2sb) and the associated correlative conformity are imaged and the correlative conformity is clearly situated within the shelf-margin delta. B) Seismic Line 24 is a strike-oriented profile collected across the upper slope and crosses from the northern flank to the center of the Rio Grande shelf-margin delta and fan complex (Fig. 6). Note the sediment-filled canyon near the southern part of the line, which has a chaotic fill. Ts = transgressive surface; 2sb = Stage 2 sequence boundary, which extends seaward into the correlative conformity; Lst 2 = Stage 2 lowstand systems tract.

reached the shelf margin, it did not significantly affect sedimentation on the upper slope, where this interval of time is represented in the Eureka cores by a relatively thin, brownish-red clay and silt unit 3 to 8 meters thick.

An AMS radiocarbon date of $44.400 \pm .720$ ka (radiocarbon dead) was obtained from the top of the deltaic package. Radiocarbon dates from near the base and the top of the transgressive unit (unit 2) indicates that deposition of this unit began after 33,720 ka and ended around 16,970 ka (20,000 to 19,200 cal BP). These data indicate that the Brazos shelf-margin delta formed during the late

fall in sea level and stopped development around 33,000 years ago, prior to the maximum lowstand at approximately 18,000 years ago. After prograding to the shelf margin, the delta was abandoned as the ancestral Brazos River shifted its course to the east and merged with the Trinity and Sabine rivers (Anderson et al., 1996).

Trinity–Sabine–Brazos Delta

Thomas and Anderson (1994) conducted a detailed study of the Trinity–Sabine incised fluvial valley on the inner shelf.

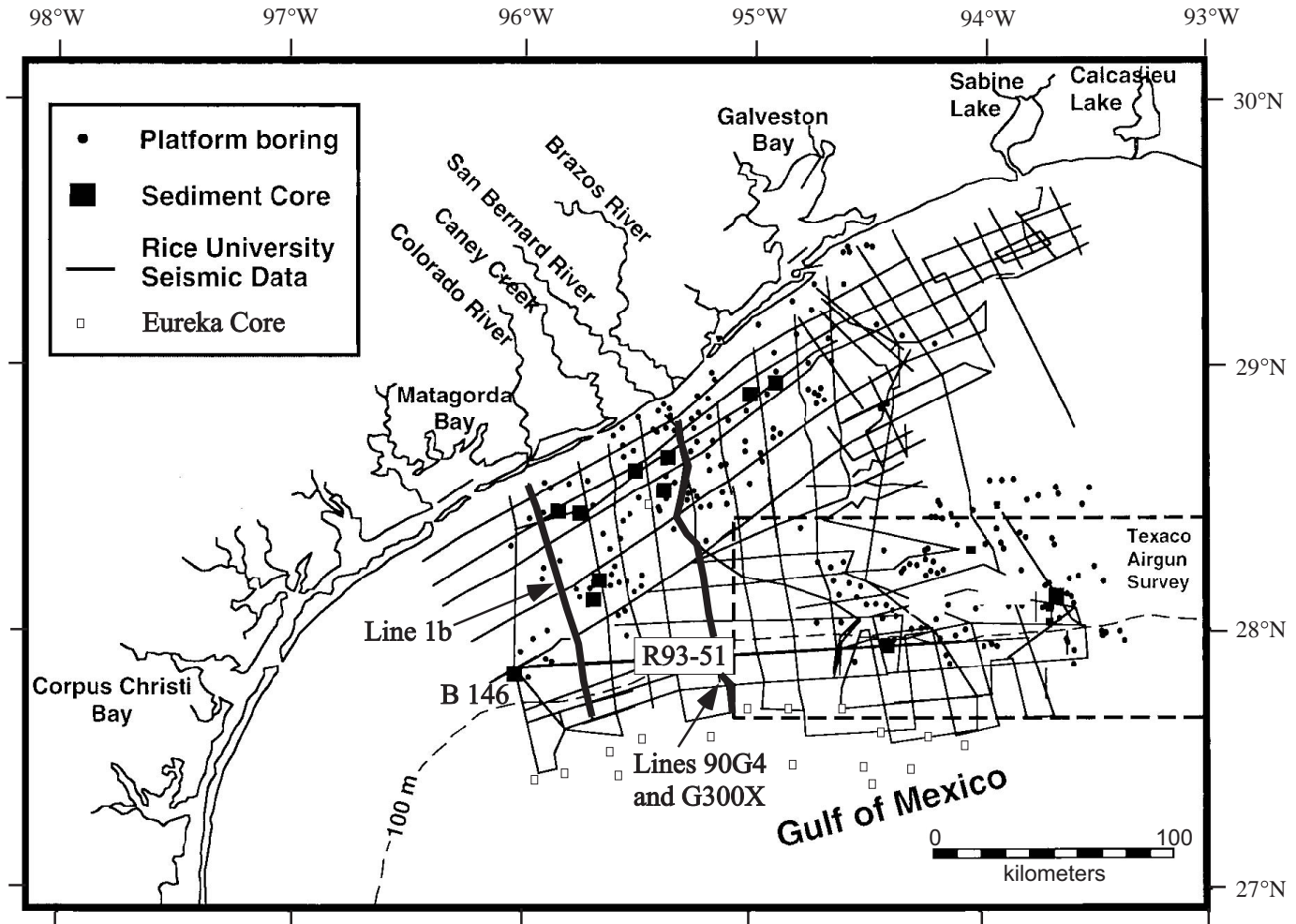


FIG. 9.—Data used by Fraticelli (2003) and Abdulah et al. (2004) to study the Colorado and Brazos deltas. The data set includes a dense grid of high-resolution seismic data provided by Texaco Oil Company and several long (average 300 meters) cores that sampled the upper continental slope (Eureka Project).

They concluded that the valley had been occupied throughout the fall in sea level (Stage 5 through Stage 2). The outer portion of the valley was later mapped by Anderson et al. (1996) and found to merge with the stage 2 Brazos valley. A recent investigation by Wellner et al. (2004) involved detailed seismic stratigraphic and chronostratigraphic analysis of the Trinity–Sabine–Brazos shelf-margin delta using an extensive data set (Fig. 14). A long core (B-343) through the delta was used for the chronostratigraphic analysis, which included radiocarbon dating.

During the Stage 5 through Stage 3 fall in sea level, the Trinity and Sabine rivers were confined to a single valley. Sediment supply to these rivers remained sufficiently small that they did not form a river-dominated delta. During the Stage 2 lowstand, the Brazos River shifted from its former location to the west and merged with the Trinity and Sabine rivers. After this merger took place, a prominent shelf-margin delta formed (Fig. 15).

Seismic profiles 29, 34, OS92-35, and G-410 are used to illustrate seismic facies and the stratigraphic architecture of the delta (Figs. 16–19). The Stage 2 sequence boundary identified in these profiles corresponds to the base of the Trinity, Sabine, and

Brazos incised valleys. Profile OS92-35 crossed the B-343 core site (Fig. 16). It is a uniboom profile and provides higher stratigraphic resolution than the other profiles. All of the profiles show the sigmoidal progradation that characterizes the delta. Lithologic descriptions from platform borings indicate that the delta is dominantly mud. Only within the incised valley were sands encountered. Seismic profile 34 (Fig. 17) is a dip line collected along the axis of the valley. It shows the incision of distributary channels into the muddy clinoforms of the delta followed by deposition of extensive mouth-bar deposits. Seven platform borings within the outer part of the valley (Fig. 15) penetrated sands near the seafloor that average 30 m in thickness.

Seismic profile G-410 (Fig. 18) was collected at the western side of the delta and shows that, in this location, the Trinity–Sabine–Brazos Delta (units c through h) rests above the older Brazos Delta (unit b) (Fig. 3B). To the east, the Trinity–Sabine–Brazos Delta onlaps the older western Louisiana Delta. Seismic line 29 (Fig. 19) was collected near the center of the delta. At this location, deposition continued after sea level began to rise, as indicated by shallowing of the offlap break during deposition of units h through j. Chronostratigraphic

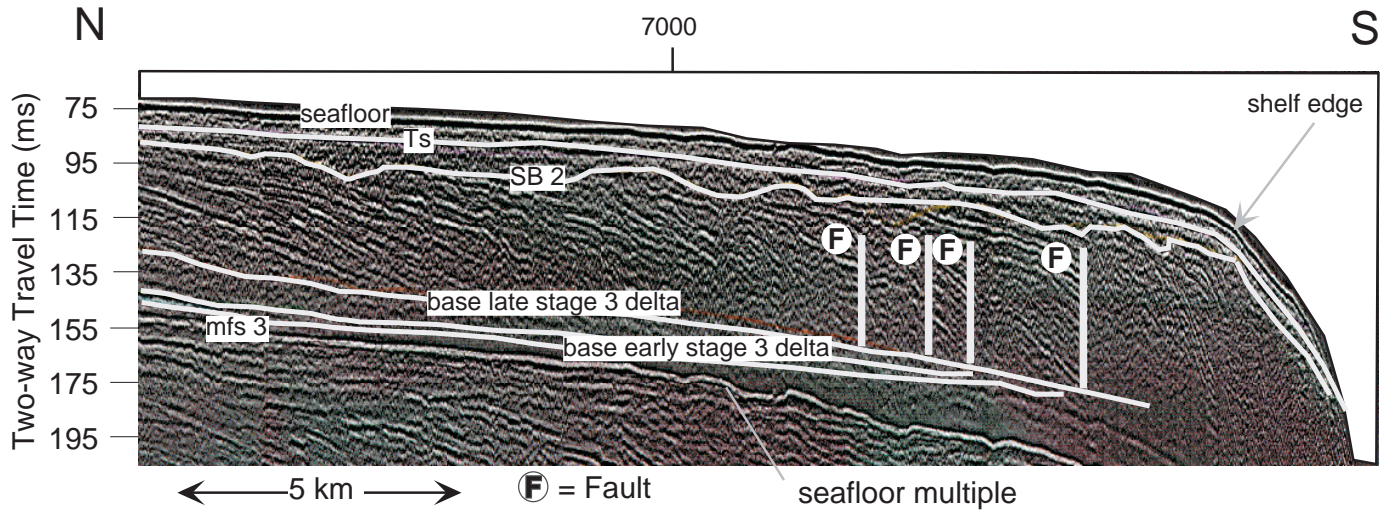


FIG. 10.—Seismic profile of dip line 1b is used to illustrate seismic facies and bounding surfaces of the Colorado shelf-margin delta. Ts = transgressive surface; SB2 = Stage 2 sequence boundary and associated correlative conformity; mfs 3 = Stage 3 flooding surface.

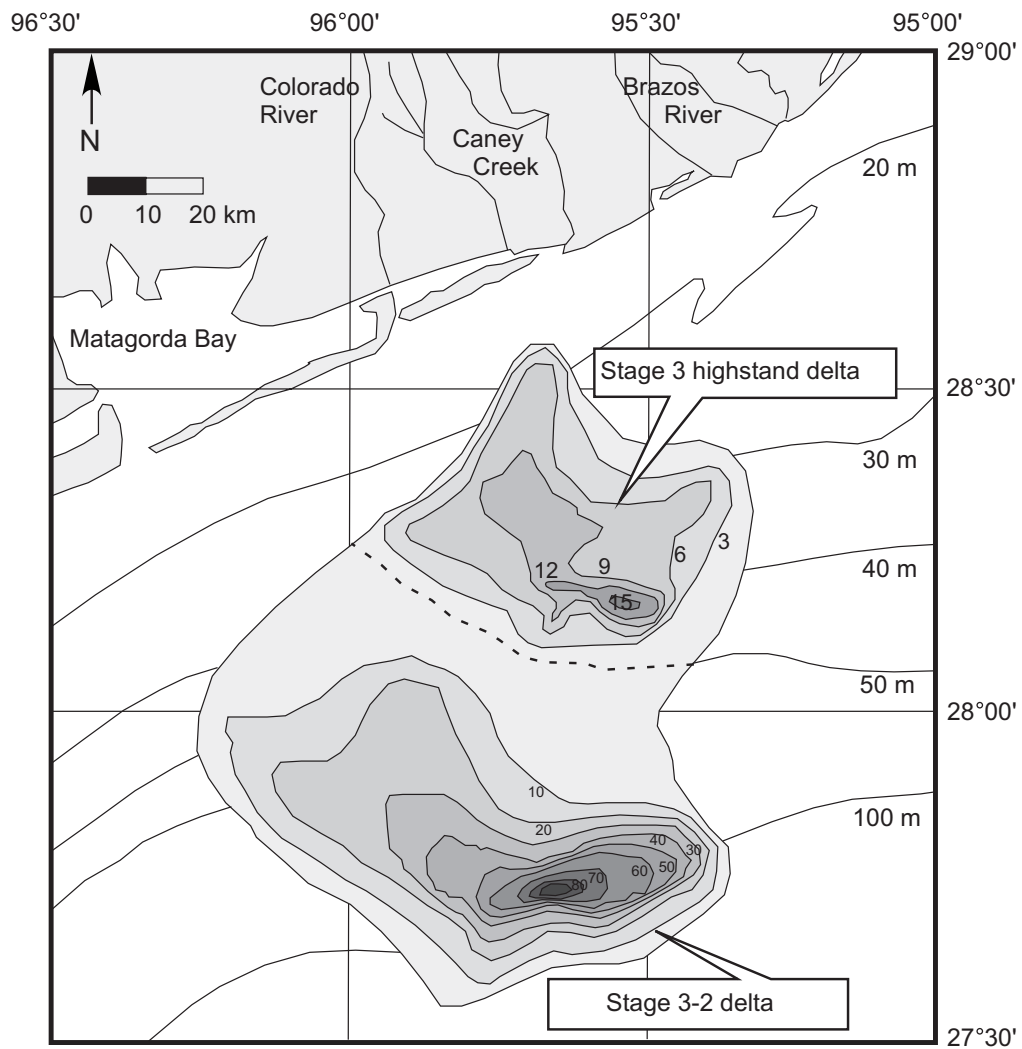


FIG. 11.—Isopach map of Colorado shelf-phase and shelf-margin deltas (modified from van Heijst et al., 2001).

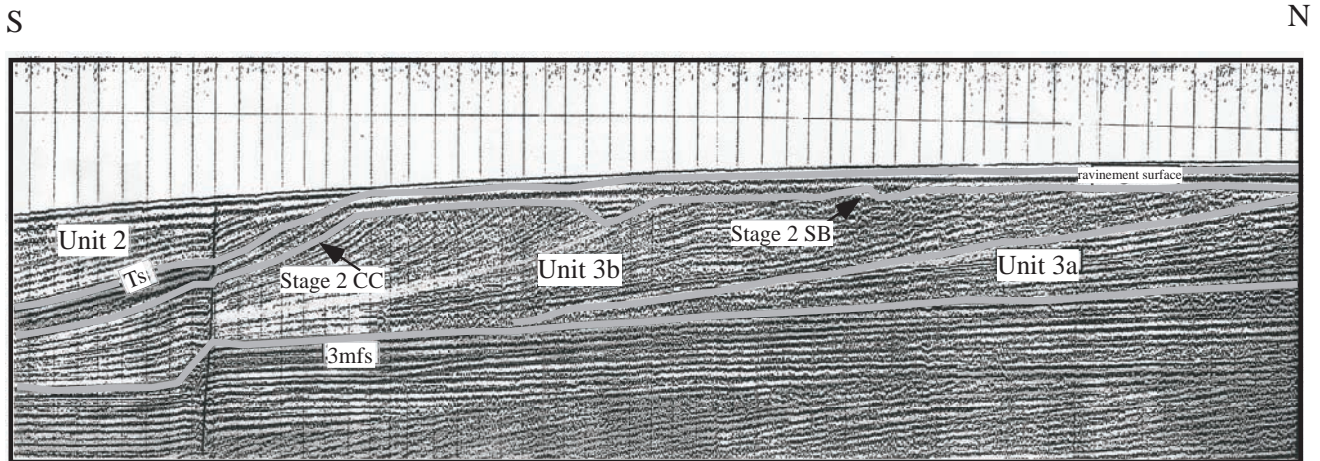


FIG. 12.—Seismic Line 340X is used to illustrate the change in clinoform geometries used by Fraticelli (2003) to map individual lobes of the Brazos shelf-margin deltas (Fig. 13). The unit 3a flooding surface (FS) separates lobes 3a and 3b, and the unit 3b flooding surface separates lobes 3b and 3c. TS is the transgressive surface and the lower bounding surface of unit 2 transgressive deposits. 3 mfs = Stage 3 flooding surface and cc = Stage 2 correlative conformity.

constraints for the age of the Trinity–Sabine–Brazos delta come from core B343 (Figs. 14, 16) and from correlation of the Stage 2 sequence boundary to adjacent study areas (Wellner et al., 2004; Abdulah et al., 2004). The sequence boundary in core B343 is marked by a silty unit that contains a sparse, low-

diversity foraminiferal assemblage indicative of bay or shoreface environments (Abdulah et al., 2004). A sample from below the sequence boundary (65 m) in core B343 yielded an age of 26.360 ka. Above this surface there is an increase in faunal abundance and diversity indicative of

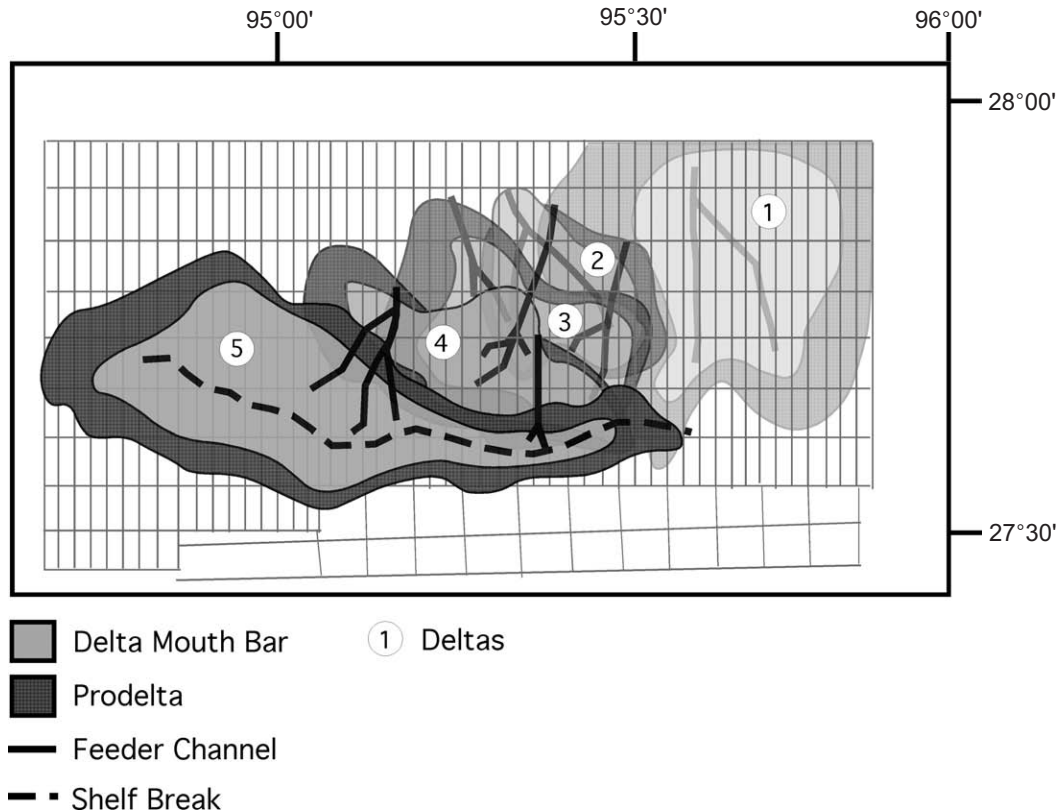


FIG. 13.—Paleogeographic maps showing the evolution of the Brazos shelf-margin delta during the late fall in sea level (Stage 5 through 3) (modified from Fraticelli, 2003).

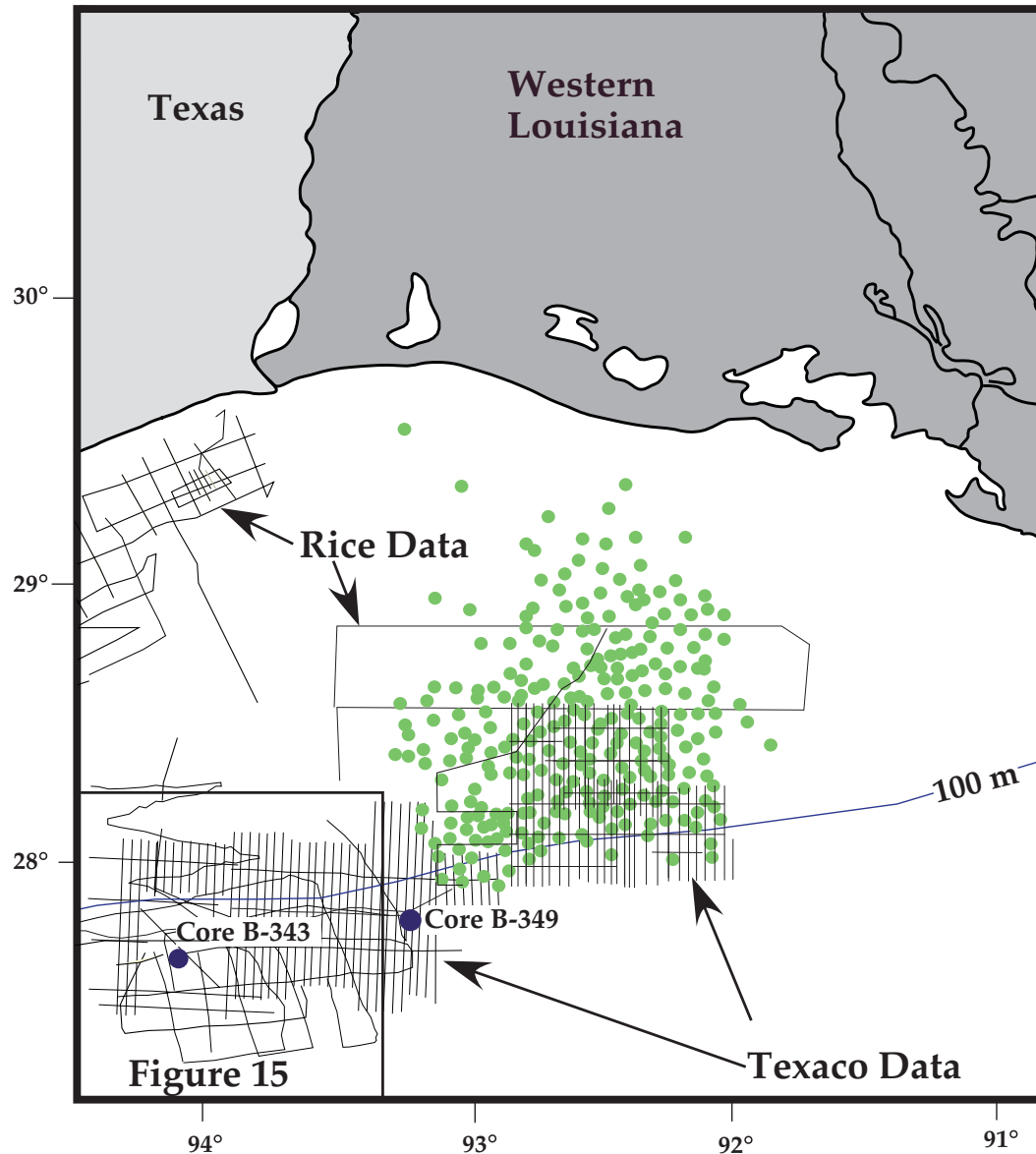


FIG. 14.—Seismic data and platform borings (dots) used to study the Trinity–Sabine–Brazos and western Louisiana shelf-margin deltas.

marginal-marine to inner-neritic conditions (Wellner et al., 2004). Two radiocarbon dates from the clinoform package above the sequence boundary yielded ages in the range of 14.370 to 13.025 ka (16,640 and 14,820 cal BP). Hence, the delta was deposited after the Stage 2 lowstand and significant progradation occurred well after sea level began to rise. During the lowstand, significant sediment bypass of the shelf occurred and sediments were transported downslope into slope minibasins (Beaubouef and Friedmann, 2000; Anderson and Rodriguez, 2001) (Figs. 15, 18).

Western Louisiana Delta

Initial work on the western Louisiana Delta was conducted by Lewis (1984) and Suter and Berryhill (1985), with later studies conducted by Sarzalejo (1993), Anderson et al. (1996), Morton and

Suter (1996), and Wellner et al. (2004). The most recent study, by Wellner et al. (2004), was based on a dense grid of seismic data and more than a hundred platform boring descriptions (Fig. 14). This later study was also based on a robust chronostratigraphic framework.

During the previous interglacial highstand, large rivers flowed across the western Louisiana continental shelf, forming a network of fluvial valleys on the shelf (Berryhill et al., 1987). Sediment supply to the shelf was sufficient to fill all accommodation created by subsidence and sea-level rise (Wellner et al., 2004). This implies that at least a portion of that sediment was derived from the ancestral Mississippi River and Red River. During the late stages of falling sea level (Stage 3), a large shelf-margin delta, the western Louisiana Delta (WLD), prograded across the western Louisiana shelf. Sarzalejo's (1993) detailed map of the delta shows the distribu-

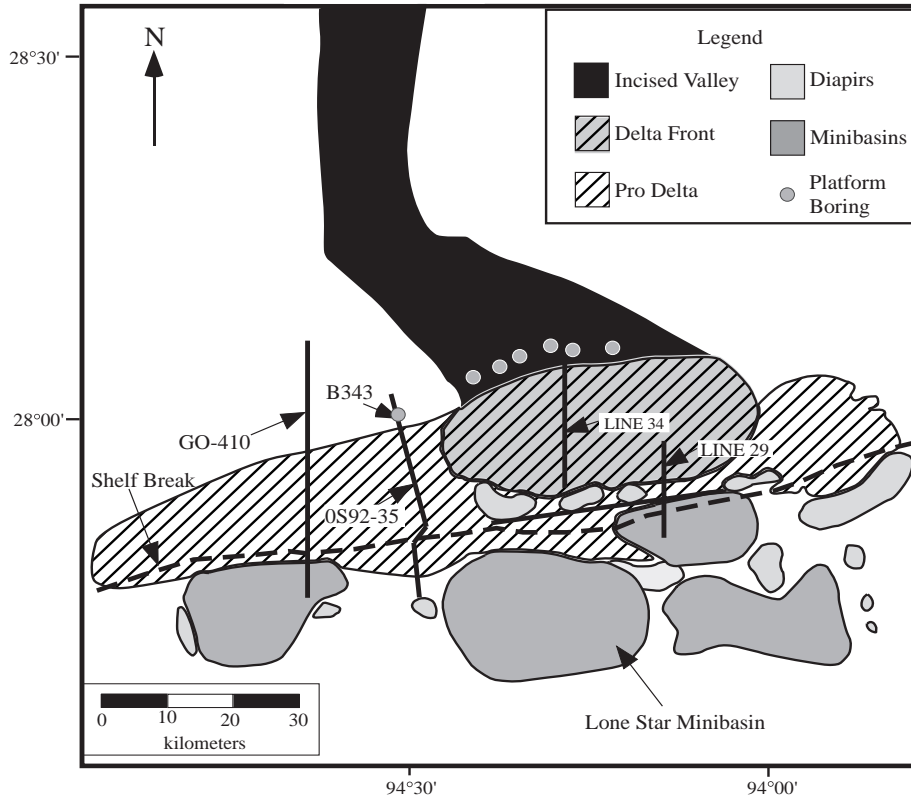


FIG. 15.—Paleogeographic map of the Trinity–Sabine–Brazos shelf-margin delta. Also shown are the locations of seismic profiles Line 29, Line 34, OS 92-35, and G-410.

tary channels and mouth bars that constituted the delta (Fig. 20). The prodelta of the WLD extends to the west, where it is buried beneath the younger Trinity–Sabine–Brazos delta (Fig. 3B). Platform borings through the delta sampled prodelta muds that are overlain and in sharp contact with sandy channel-mouth-bar and distributary-channel deposits (Wellner et

al., 2004). A series of diapiric uplifts, which extend along the shelf margin, prevented the delta from prograding across the shelf break (Anderson et al., 1996).

The WLD shelf-margin delta is characterized by low-angle clinoforms that steepen to more than 3° toward the west and are tangential with the underlying Stage 5e maximum flooding sur-

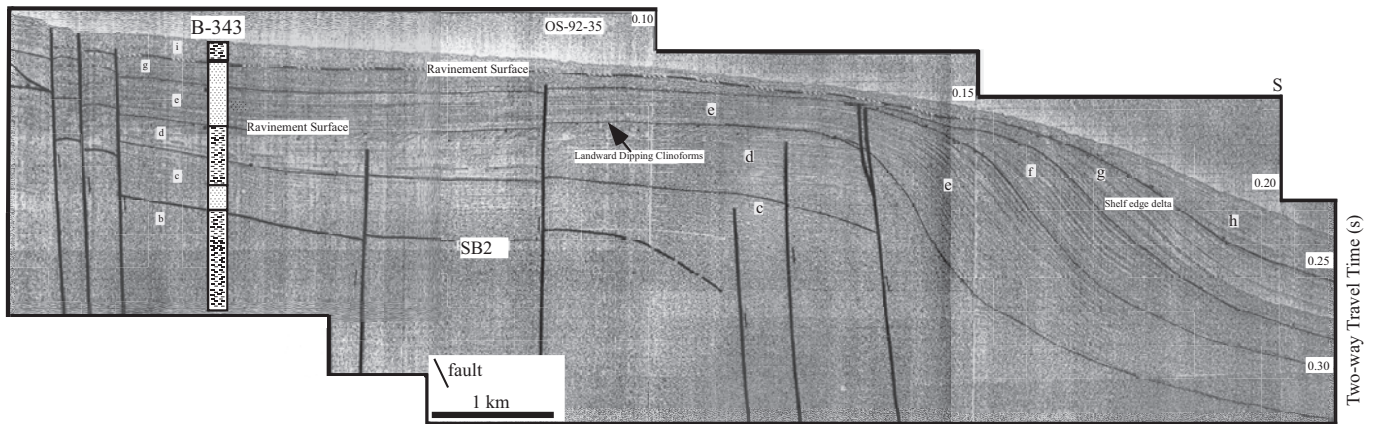


FIG. 16.—Seismic profile OS92-35 is a uniboom profile collected near the center of the Trinity–Sabine–Brazos delta, which crosses the B-343 core site. Seismic units are labeled b–h. SB2 = Stage 2 sequence boundary. Radiocarbon dates from core B-343 provide constraints on the Stage 2 sequence boundary and indicate that units e–h of the shelf margin delta are younger than approximately 16,640 kyr BP, so they were deposited during the initial stage of transgression.

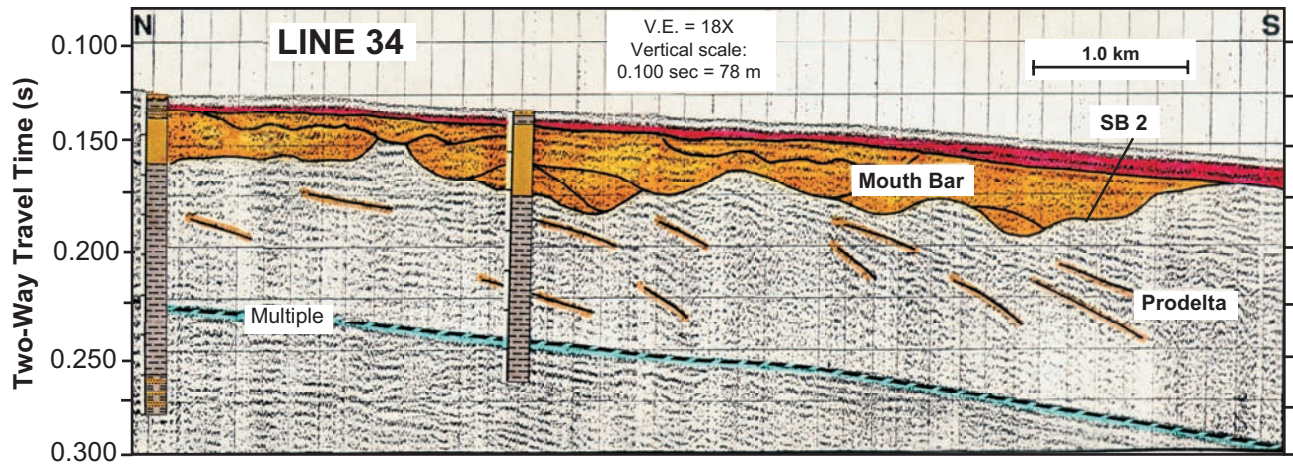


FIG. 17.—Seismic profile 34 was acquired down the depositional axis of the Trinity, Sabine, and Brazos shelf-margin delta. This line shows sandy distributary-channel and mouth-bar facies (shaded) that downcut into muddy prodelta deposits. The two platform borings provide lithological descriptions for these facies.

face (Fig. 21). The clinoforms are deeply incised by distributary channels with chaotic seismic facies (Fig. 21).

Core 349-B (Fig. 14) was used for micropaleontological analysis and to constrain the WLD delta (Wellner et al., 2004). This core site occurs near the western margin of the delta and sampled nearly 20 meters of sandy distributary-mouth-bar deposits resting on prodelta muds. Clinoform thickness indicates that the delta prograded into water depths up to 50 meters and the distributary-mouth-bar facies in core 349-B contains inner-neritic to outer-neritic foraminifera (Wellner et al., 2004). These sandy deposits also contain glauconite, which is not observed in any of the other shelf-margin deltas.

A radiocarbon age of 48 ka (radiocarbon dead) was acquired just beneath the delta, and a sample from the top of the delta yielded an age of 33 ka. Thus, the delta was deposited prior to the Stage 2 maximum lowstand. These dates confirm earlier interpretations by Sarzalejo (1993) and Anderson et al. (1996) that placed the sequence boundary above the delta (Fig. 3B), therefore placing the delta in the highstand systems tract. The sequence boundary in this case is not the surface of maximum stream incision, but rather is a relatively smooth surface that in a landward direction amalgamates with the transgressive surface (Fig. 21). This led Anderson et al. (1996) to conclude that its main fluvial feeder

abandoned the WLD prior to the maximum lowstand, similarly to the Brazos delta.

DISCUSSION

Eustasy and Delta Evolution

The shelf-margin deltas of the northwestern Gulf of Mexico margin show a complex pattern of progradation and aggradation that varies from one delta to the next. This complexity reflects the different intervals of the eustatic cycle over which these deltas were constructed. During the Stage 5 interglacial high-sea-level episode, large fluvial deltas associated with the ancestral Rio Grande, Colorado, Brazos, and western Louisiana rivers prograded across the shelf (Banfield and Anderson, 2004; Abdulah et al. 2004; Wellner et al., 2004). As these deltas advanced seaward, their updip portions suffered considerable erosion by rivers and streams and by waves (regressive shoreface erosion). As a result, the upper, sand-prone portions of these deltas were eroded, leaving mostly muddy distal bar and prodelta deposits on the inner shelf.

Approximately 70,000 years ago, sea level fell then rose rapidly, culminating in the Stage 3 flooding event (Fig. 2). Following

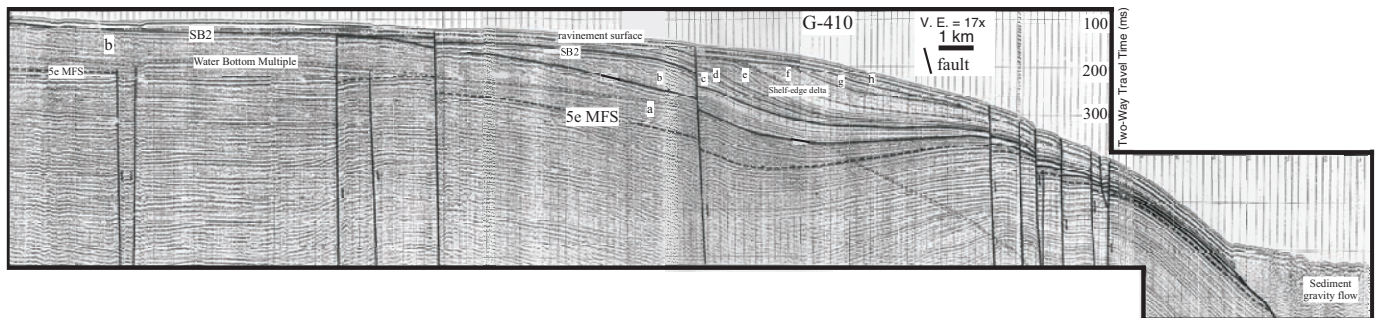


FIG. 18.—Seismic profile G-410 is used to illustrate the stratigraphic architecture of the Trinity–Sabine–Brazos shelf-margin delta and upper-slope mini-basin fill. Seismic units are the same as in Figure 16. 5e MFS = Stage 5e maximum flooding surface; SB2 = Stage 2 sequence boundary and correlative conformity.

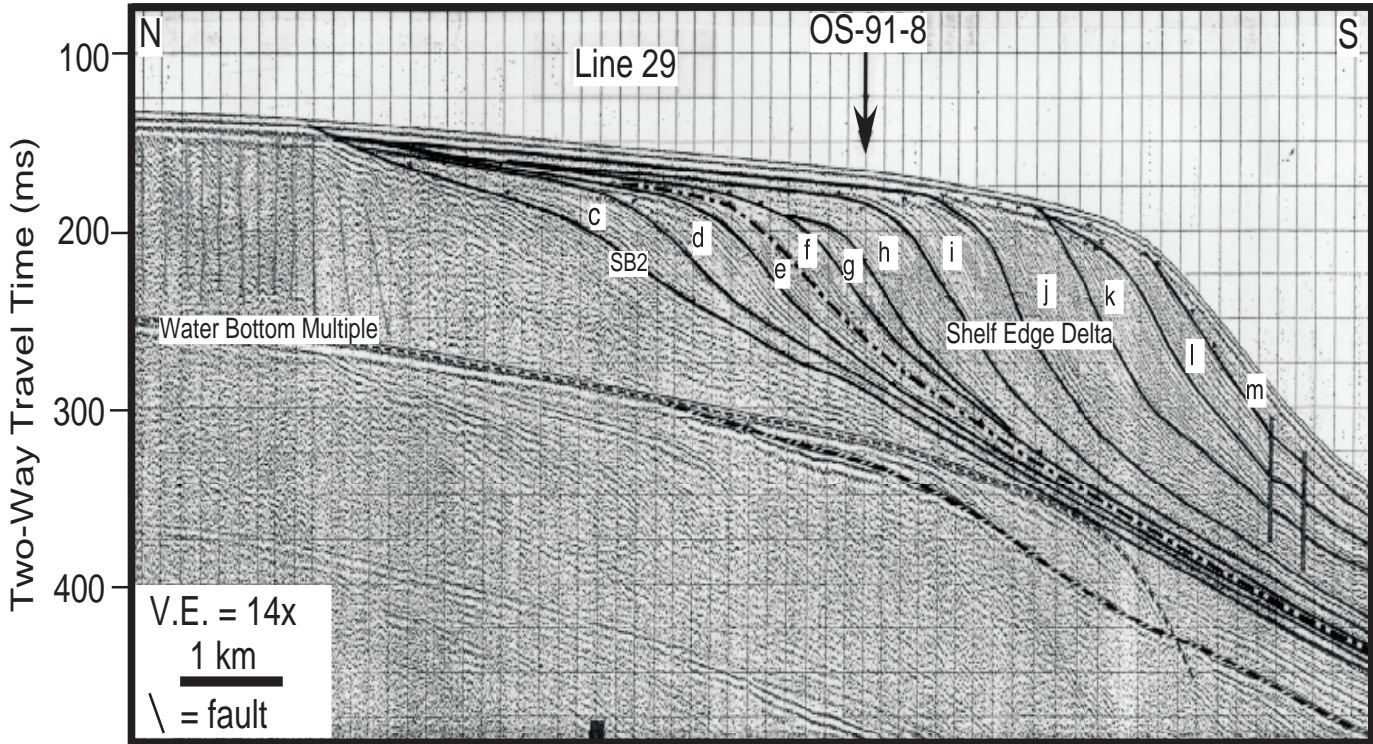


FIG. 19.—Seismic profile 29 is used to illustrate the transgressive aggradational clinoforms of the Trinity–Sabine–Brazos shelf-margin delta. Seismic units are the same as in Figures 15 and 17. SB2 = Stage 2 sequence boundary and correlative conformity.

the flooding episode, sea level fell more or less continuously. The Rio Grande, Colorado, Brazos, and western Louisiana deltas experienced nearly continuous growth during the Stage 3 sea-level fall (Fig. 1). These deltas were all situated in a shelf-margin position long before the maximum lowstand. However, the times at which individual deltas reached the shelf margin vary across the region, reflecting the different long-term sediment discharge of the rivers (Fig. 3B).

The Rio Grande, Brazos, and western Louisiana deltas were the first to reach the shelf margin. These late highstand or falling-stage deltas were similar to the modern Mississippi Delta in that they prograded into water depths of several tens of meters, maintaining low fluvial gradients as sea level fell. There was considerable accommodation on the flanks of these deltas. Ultimately, the Brazos and western Louisiana deltas shifted their locations to fill accommodation on the adjacent shelf. The fluvial feeder of the western Louisiana delta, possibly the Red River, shifted to a location far to the east. The Brazos River shifted to the eastern flank of its late highstand delta. As a result of these avulsion events and associated delta abandonment, the SB/CC is situated above the Brazos and western Louisiana shelf-margin deltas. Because they were abandoned, neither the ancestral Brazos nor the western Louisiana fluvial–deltaic systems nourished deep-water fans. Indeed, the cores acquired downslope of these shelf-margin deltas sampled relatively thin clays whose ages span the late highstand and lowstand (Anderson et al., 1996; Fraticelli and Anderson, 2003).

The sands delivered to the margin by the Brazos and western Louisiana fluvial system during the overall fall in sea level (Stage 5 through 2) are, for the most part, sequestered on the outer shelf in fluvial channels and in widespread and thick mouth-bar

deposits. These sand bodies occur at the tops of clinoforms, and they rest in sharp contact on prodelta muds. This stratigraphic association results from incision of distributary channels during sea-level fall, but this incision occurred prior to the maximum lowstand (Figs. 12, 17).

The Colorado and Rio Grande deltas span the Stage 3 fall through the lowstand. Both rivers remained relatively fixed in their locations throughout the late sea-level fall, resulting in broad channels that subsequently were incised during the maximum lowstand. These incised valleys deepen offshore, cutting into late highstand deposits. This indicates that these valleys experienced headward erosion during the maximum lowstand. Flume experiments by van Heijst et al. (2001) demonstrated how this headward erosion might have occurred. Both the Rio Grande and the Colorado rivers nourished slope fans during the lowstand (Anderson et al., 1996; Banfield and Anderson, 2004). The SB/CC of the Rio Grande and Colorado shelf-margin deltas is situated within these deltas (Figs. 8A, 3B). Seismic profile R93-51 best illustrates the different stratigraphic positions of the sequence boundary relative to the Colorado, Trinity–Sabine–Brazos, and WLD shelf-margin deltas (Fig. 3B).

The Trinity and Sabine rivers have occupied the same valleys throughout the eustatic cycle. During the lowstand, the Brazos River merged with the Trinity–Sabine rivers on the outer shelf. Only then was the sediment supply to the valley large enough to create a shelf-margin delta. The Trinity, Sabine, and Brazos delta was nourished during the lowstand and a significant part of the transgression. Much of the sediment transported through the system bypassed the shelf and ended up in slope minibasins. Indeed, sediment bypass during repeated eustatic

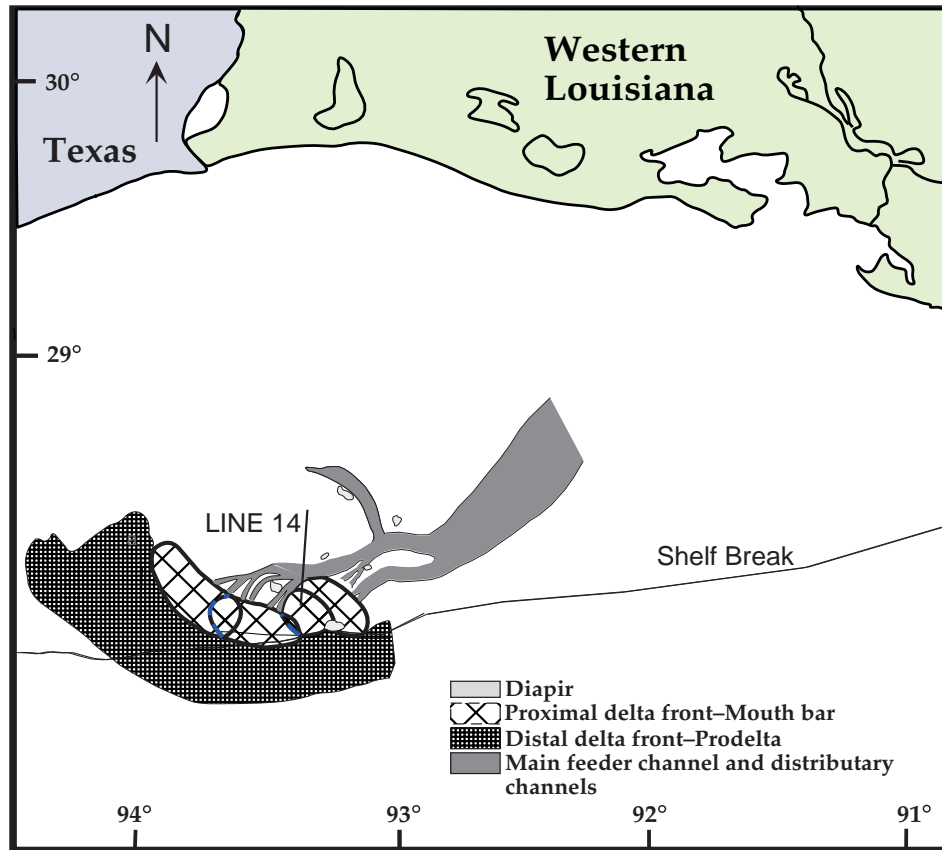


FIG. 20.—Paleogeographic map of western Louisiana shelf-margin delta, showing depositional environments (modified from Anderson et al., 1996). Also shown is the location of seismic Line 14, which is used to illustrate seismic units and seismic facies (Fig. 21).

lowstands has nourished fans within slope minibasins (Anderson and Rodriguez, 2001).

Those rivers that flowed across the ramp-like central Texas shelf (i.e., Nueces, San Antonio) formed wave-dominated deltas that were mostly reworked into the prograding shoreline (Eckles et al., 2004). No shelf-margin deltas have been identified on this portion of the shelf. This is due to the relatively small sediment supply of central Texas rivers.

Sequence Stratigraphic Implications

The advent of sequence stratigraphy has resulted in reevaluation of the methods used for stratigraphic interpretation. It has also resulted in a proliferation of conceptual models and differences of opinion about these models. One lingering controversy concerns the relationship between the major bounding surfaces and systems tracts to sea level (see Nystuen, 1998, and Posamentier and Allen, 1999, for reviews). The data set presented in this paper allows direct comparison of depositional units and bounding surfaces to the well established sea-level curve of the last glacial-eustatic cycle so that these relationships can be documented.

The earliest sequence stratigraphic models assumed that little preservation of falling-stage strata occurs. The data presented in this paper demonstrate clearly that this is not the case. Even though the rate of sea-level fall during the late Quaternary eustatic cycles was fast in comparison to pre-Pleistocene glacial-eustatic cycles, delta progradation across the shelf was relatively

continuous and interrupted only by the rapid fall and rise that occurred during oxygen isotope stages 4 and 3 (Fig. 2). Although fluvial incision did occur throughout the overall fall in sea level, from Stage 5e to Stage 2, by far the most prominent surface of erosion on the shelf is associated with the maximum fall during Stage 2. Hence, the Stage 2 surface of erosion is the only real candidate for a sequence boundary.

Now let us address the long-standing debate as to where to place the sequence boundary and associated correlative conformity relative to the sediment wedge formed during the falling limb of sea level (e.g., Vail et al., 1977; Hunt and Tucker, 1992; Kolla et al., 1995; Van Wagoner, 1995; Posamentier and Allen, 1999). This is a nontrivial problem for exploration geologists in search of deep-water reservoirs because it bears on the existence and stratigraphic location of sands within shelf-margin deltas and associated deep-water fan deposits, relative to the sequence boundary. The results of this study have shown that the position of the sequence boundary (surface of subaerial exposure and erosion) is at the top of the deltas deposited during the late stages of sea-level fall. The stratigraphic position of the correlative conformity, on the other hand, varies across the shelf, depending on when deltas reached the shelf margin and how long they remained fixed in their locations on the outer shelf. Given this result, I am inclined to agree with Nystuen (1998), who stated that "Instead of forcing the available data into a rigid classification system, the geologically most reasonable and practical solution should be chosen." (Nystuen, 1998, p. 98).

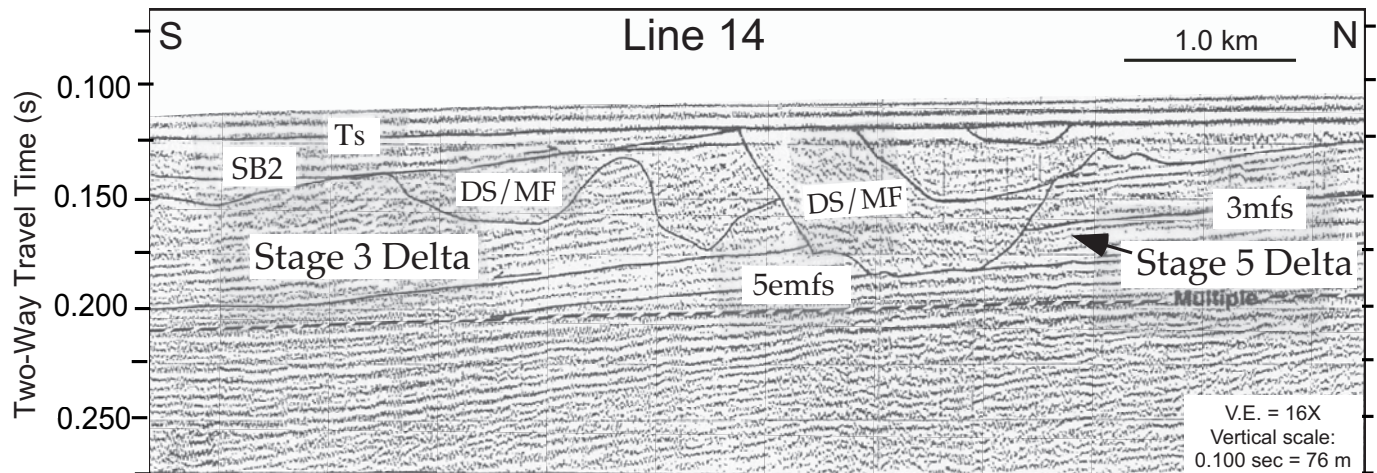


FIG. 21.—Seismic Line 14 is used to illustrate seismic facies and the stratal architecture of the western Louisiana shelf-margin delta. Ts = transgressive surface; SB2 = Stage 2 sequence boundary; 3mfs = Stage 3 maximum flooding surface; 5mfs = Stage 5 maximum flooding surface; DS/MF = distributary channels and channel-mouth bar facies.

CONCLUSIONS

1. Five different delta complexes existed on the outer shelf of the northwestern Gulf of Mexico during the last glacioeustatic cycle. These include the Rio Grande, Colorado, Brazos, Trinity–Sabine–Brazos, and western Louisiana deltas.
2. The shelf-margin deltas of the northwestern Gulf formed at different times during the late fall, lowstand, and early transgression. Hence, the location of the sequence boundary and correlative conformity (SB/CC) within these deltas differs. The Brazos and western Louisiana deltas reached the shelf margin during the late fall in sea level and were abandoned prior to the maximum lowstand. The SB/CC is the upper bounding surface for these deltas. The Rio Grande and Colorado deltas maintained a shelf-margin position throughout the late fall, lowstand, and early transgression. Hence the correlative unconformity occurs within these delta packages. The Trinity, Sabine, and Brazos delta is the only system that fits the classic sequence stratigraphic model (the Exxon model of Vail et al., 1977) in that it began to form only after sea level reached the shelf margin. The delta continued to grow well into the transgression. Hence, it overlies the correlative conformity.
3. Of the five deltas that existed on the outer shelf, three of them (Rio Grande, Colorado, and Trinity–Sabine–Brazos) nourished lowstand fans. Two of the largest deltas, the Brazos and the western Louisiana deltas, do not have linked lowstand fans because these rivers avulsed prior to the maximum lowstand.

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