# CONTRASTING STYLES OF LATE NEOGENE DEEP-WATER SANDSTONE DEPOSITION, OFFSHORE TEXAS

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ABSTRACT

Middle Miocene and middle Pliocene deep-water reservoirs of the western Gulf Coast Basin are associated with failed shelf margins and subregional unconformities referred to as submarine pediments. The submarine pediments formed broad, convex-landward arcs along nondeltaic slopes and on the southwestern flanks of subjacent delta systems. They were created by retrogressive failure and were later enlarged by erosion during periods of lowered sea level. At times of lowered sea level, the deep embayments carved into the continental platform funneled nearshore sands downslope to basin-floor fans.

The pediments were first backfilled by deep-water mudstones deposited by mass transport processes. These slump blocks and high-energy turbidites exhibit mounded to chaotic seismic reflections that dip landward. Later, sand-rich channel-levee complexes were deposited above the basal mudstones and near the seismic facies transition from chaotic reflections to overlying horizontal or wavy reflections. The pre-entrenchment morphology of the shelf margin was finally restored by coalescence of small, prograding deltas that are recorded as clinoform reflections.

Unconfined lower slope and basin-floor fans associated with the submarine pediments are generally sand-poor. The sand-rich lowstand fan deposits are restricted to highly elongate, dip oriented leveed channels that mark the principal pathways of sediment transport.

Sandstones confined to leveed channels of the upper fan and pediment fill are the most prolific hydrocarbon reservoirs within each stratigraphic sequence. These channel sandstones exhibit high vertical continuity but low lateral continuity because interbedded turbidite mudstones increase away from the channel axes. Thin sandstones of the lower fan may exhibit high lateral continuity but they typically have poor reservoir properties because of high concentrations of original muddy matrix.

## INTRODUCTION

In many sedimentary basins worldwide hydrocarbon exploration is currently focused on deep-water deposits for several reasons. First the concepts of sea-level fluctuations and sequence stratigraphy (Vail et al. 1977; Posamentier et al. 1988) provide models that predict the potential for deposition of reservoir quality sandstones far basinward of the shelf margin and in depositional environments that are normally characterized by thick marine shale having no exploration potential. Furthermore, deep-water sandstones offer new frontiers for exploration in basins where drilling has reached the mature stage and where future drilling will be either (1) to test slope and abyssal plain facies of older rocks at great depths or (2) to explore for relatively young submarine fans and other turbidite deposits in present-day offshore areas.

Sandstones deposited in relatively deep water (> 200 m) typically exhibit complex lateral variability in facies and therefore have less predictable reservoir properties than sandstones deposited in relatively shallow water. As a result of this heterogeneity, deep-water sandstones have some of the lowest recovery efficiencies of any class of hydrocarbon reservoirs.

The differences in facies variability between shallow-water and deep-water deposits are generally related to hydrodynamics of the depositional environments and modes of sediment transport as well as temporal and spatial gradients of the physical processes. Waves and longshore currents in relatively shallow water combine to continuously concentrate sand within a long, but relatively narrow band near the contemporaneous shoreline. In contrast, sand deposition basinward of the shelf edge is sporadic and poorly constrained because slopes are unstable and sediment transport is mainly by turbidity currents or slumping (Bouma et al. 1985).

One of the most difficult tasks facing modern explorationists is predicting the location of reservoir-quality sandstones in deep-water deposits that were greatly influenced by the interaction of sea-level fluctuations and contemporaneous growth structures. An objective of this study is to document three-dimensional facies architecture of two late Neogene slope systems (Fig. 1) that were effected by changes in sea level and syndepositional deformation.

The two slope systems were selected because they represent two different physical settings that resulted in different depositional products. The middle Miocene example is a slightly faulted entrenched system that formed landward of the contemporaneous shelf edge. The deposits backfilling the entrenched system were laterally confined by relatively steep walls. In contrast, the middle Pliocene example emphasizes unconfined submarine deposition basinward of the shelf margin on a continental slope deformed by salt and shale diapirs.

In this study, megascopic (regional) and macroscopic (intraformational) scales of reservoir heterogeneity (Alpay 1972) are analyzed by jointly examining lithofacies and seismic facies patterns. Also emphasized are the recurring relationships between specific lithologies and seismic patterns that would indicate presence or absence of reservoir-quality sandstones.

## MIDDLE MIOCENE SLOPE SYSTEM

### *Regional geologic setting*

Middle Miocene deep-water deposits in the western Gulf Coast Basin (Fig. 1) include those sediments stratigraphically associated with the *Cibicides opima* foraminiferal assemblage (Fig. 2). They occur above the regional *Amphistegina* B stratigraphic marker and below the regional *Bigenerina humbeli* marker. Distal deltaic and strandplain sediments below the *Amphistegina* B stratigraphic marker (Figs. 3 and 4) represent a period of substantial progradation of the continental margin (Morton et al. 1985, Galloway et al. 1986). This period of platform construction was

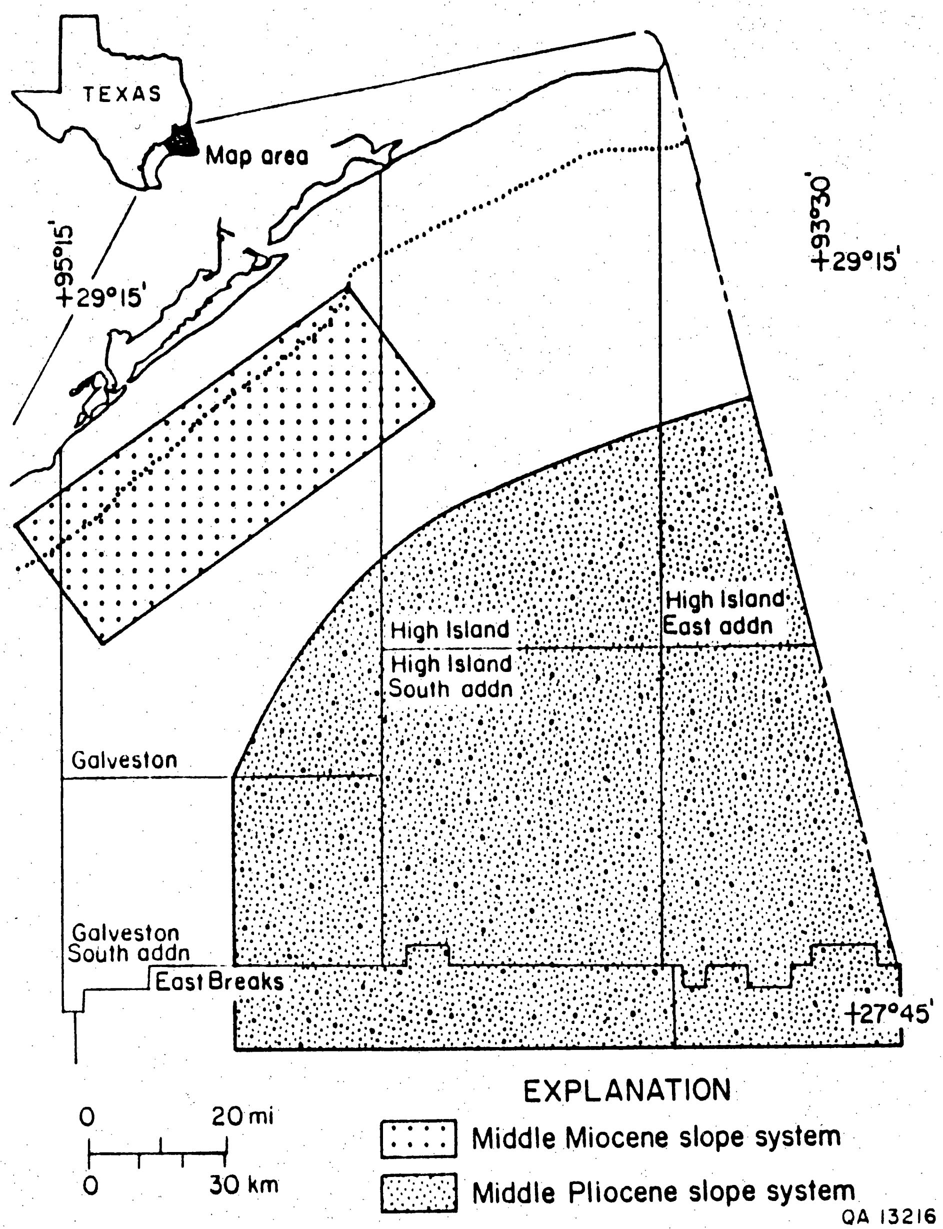


Figure 1. Index map of offshore Texas showing general locations of the middle Miocene and middle Pliocene deep-water deposits.

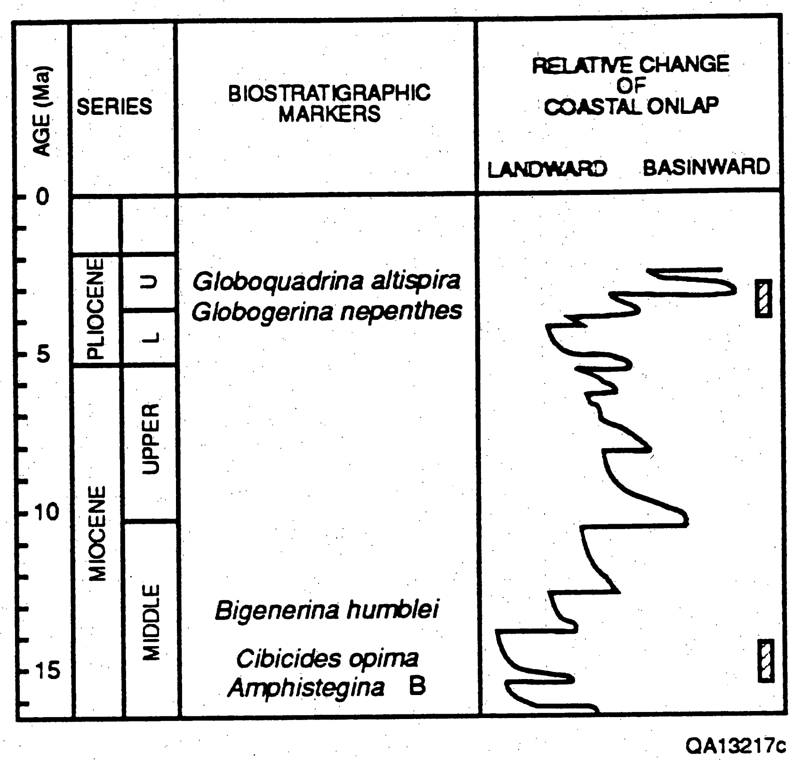


Figure 2. Stratigraphic chart illustrating late Neogene biostratigraphic and chronostratigraphic correlations for the western Gulf Coast Basin and the global curve of coastal onlap presented by Haq et al. (1987). Hachured columns show the stratigraphic intervals investigated in this study.

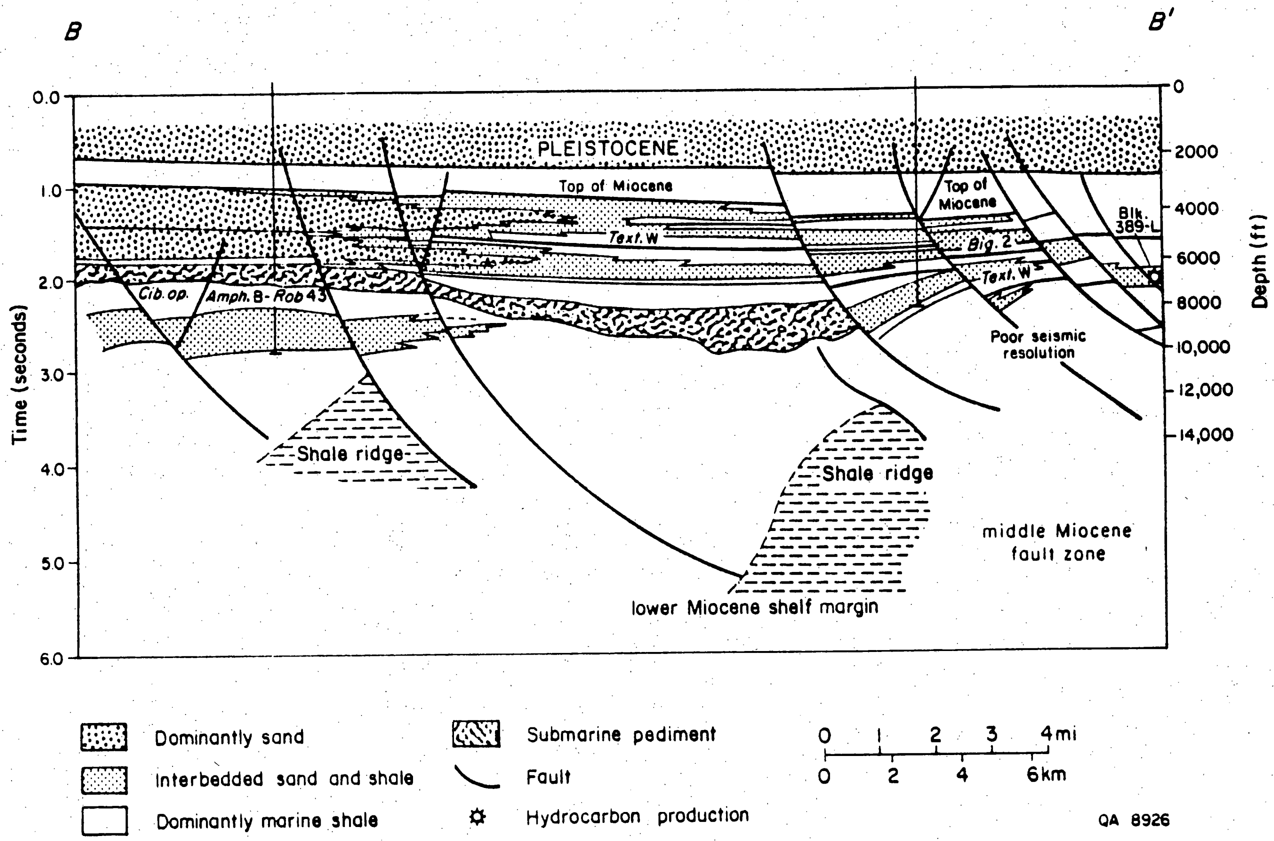


Figure 3. Structural cross section illustrating lithologies, biostratigraphic markers, and structural style in the Galveston Area, offshore Texas. Specific features include the submarine pediment and middle-Miocene expansion fault zone. Cross-section location, shown in Fig. 5, coincides with seismic line B-B′. From Morton et al. (1988).

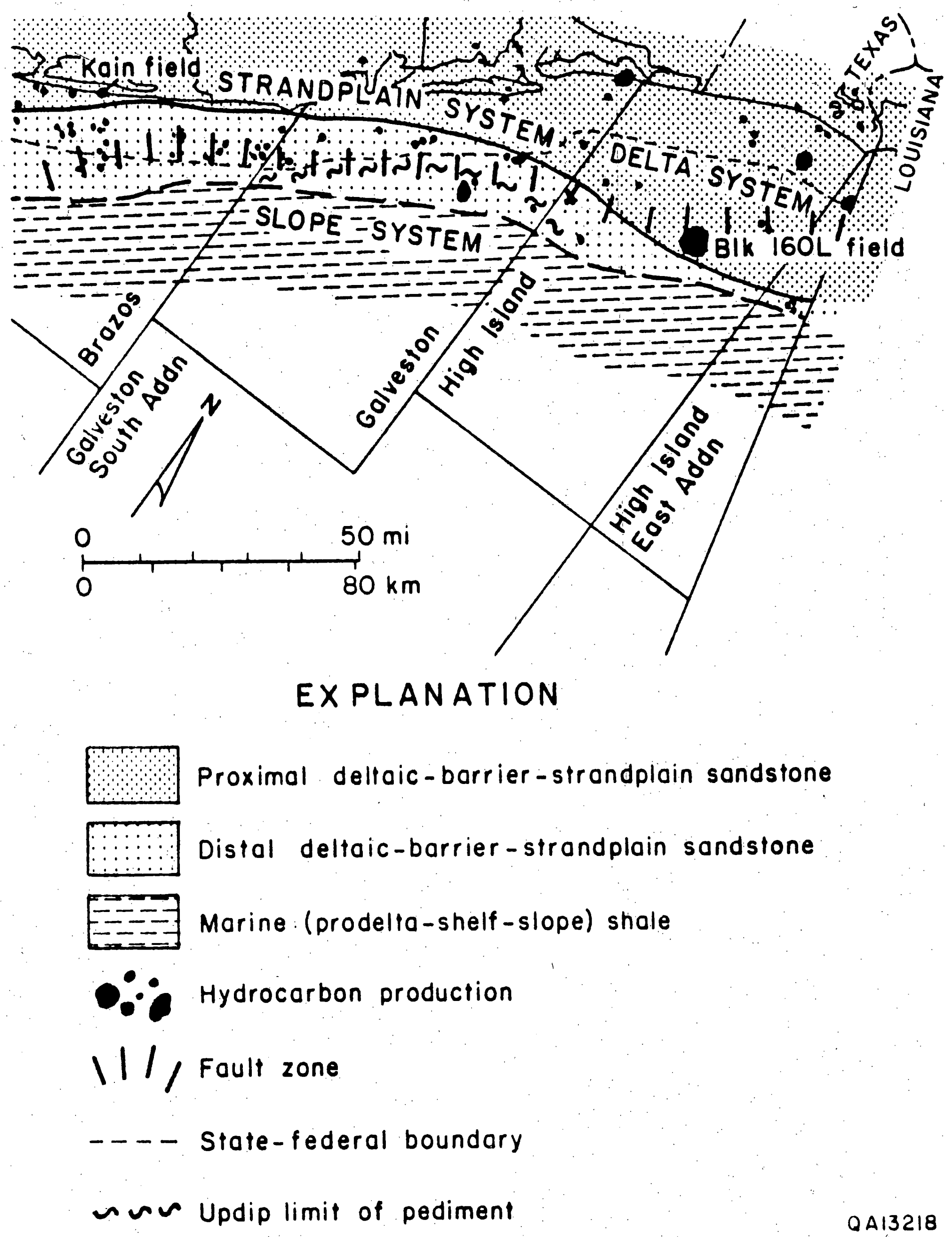


Figure 4. Regional geologic map of offshore Texas showing position of middle Miocene submarine pediment in relation to subjacent lower Miocene depositional systems. Map modified from Morton et al. (1985).

followed by a retrogradational phase of deposition that culminated in the basinwide *Amphistegina* B transgression and sea-level highstand. At the time of maximum flooding, the shoreline had retreated about 45 km landward of the shelf margin (Morton et al. 1988). The broad lower Miocene platform was inundated attendant with this pronounced landward shift in coastal onlap and the platform was subsequently buried by a thick succession of transgressive marine shale (Morton et al. 1985; 1988).

Primary features of the middle Miocene slope system are the submarine pediment and associated onlap wedge of deep-water deposits (Fig. 3) that have distinct sedimentologic and paleoecologic properties. Submarine pediment is a term used by Morton et al. (1988) to describe those nondeltaic failed shelf-margin features that are wider than they are long and that formed as a result of retrogressive slope failure and submarine erosion. Thus, they do not fit the standard morphological or genetic definition of a deep, relatively narrow incised valley and canyon formed at the shelf margin by river entrenchment as a result of lowered sea level.

The middle Miocene submarine pediment forms a broad convex-landward arc that is about 100 km wide parallel to paleostrike and about 20 km long parallel to paleodip (Figs. 4 and 5). The pediment occupies a broad zone bounded on its basinward edge by the lower Miocene shelf/slope transition (Fig. 4) and on its flanks by sandy wave-dominated deltaic and barrier/strandplain systems (Morton et al. 1985; Galloway et al. 1986). These prominent constructional features and the preexisting indention of the shelf margin probably influenced the position of the pediment (Fig. 4); however, the pediment is younger than all the subjacent shorezone systems. Thus, it formed in an interdeltaic setting rather than at the mouth of a major river as is commonly envisaged for entrenched valleys and canyons near the shelf margin (Vail et al. 1977; Nelson and Nilsen 1984; Posamentier et al. 1988; Steffens 1988).

The *Cibicides opima* submarine pediment extended approximately 20 km landward of the shelf margin or about one-half the width of the continental shelf inundated by the *Amphistegina* B regional transgression. Landward extent of the embayment was controlled by the magnitude of lowered sea level and by steepness of the continental shelf. The length of the pediment is greatest across the low-gradient shelf whereas it is considerably less extensive along steeper slopes such as near the former shelf margin and seaward of the delta system. The pediment is mostly confined to downthrown fault blocks basinward of the lower Miocene fault zone (Fig. 5). This relationship suggests that contemporaneous faults influenced or directly controlled the locations and steepness of some walls of the entrenched system.

Cross sections (Figs. 6-8), seismic profiles (Fig. 9), and benthic foram assemblages show that slope and shelf deposits backfilled the pediment. The pediment fill, which is 500 to 600 m thick, forms a basinward thickening wedge that terminates updip near the lower Miocene fault zone (Fig. 5). The wedge is obscured by the shadow zone beneath the middle Miocene faults (Fig. 3)

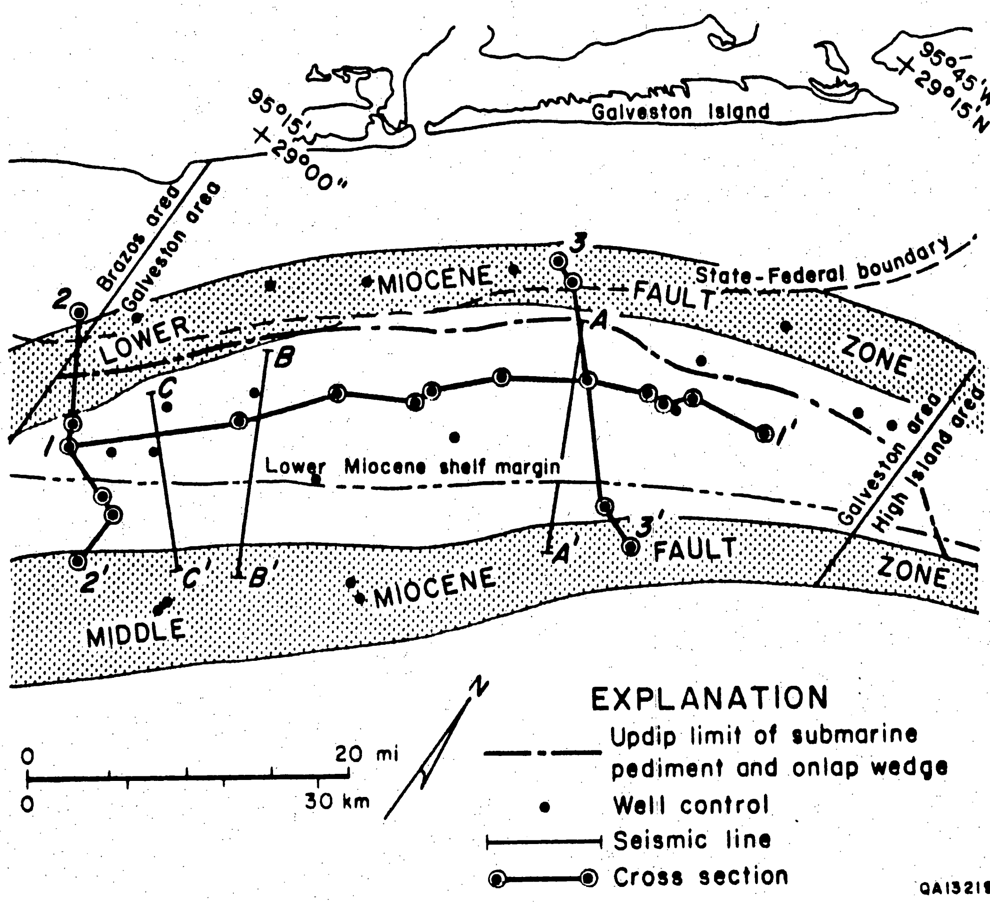


Figure 5. Principal geologic features and locations of seismic lines and wells penetrating the middle Miocene submarine pediment in the Galveston Area, offshore Texas.

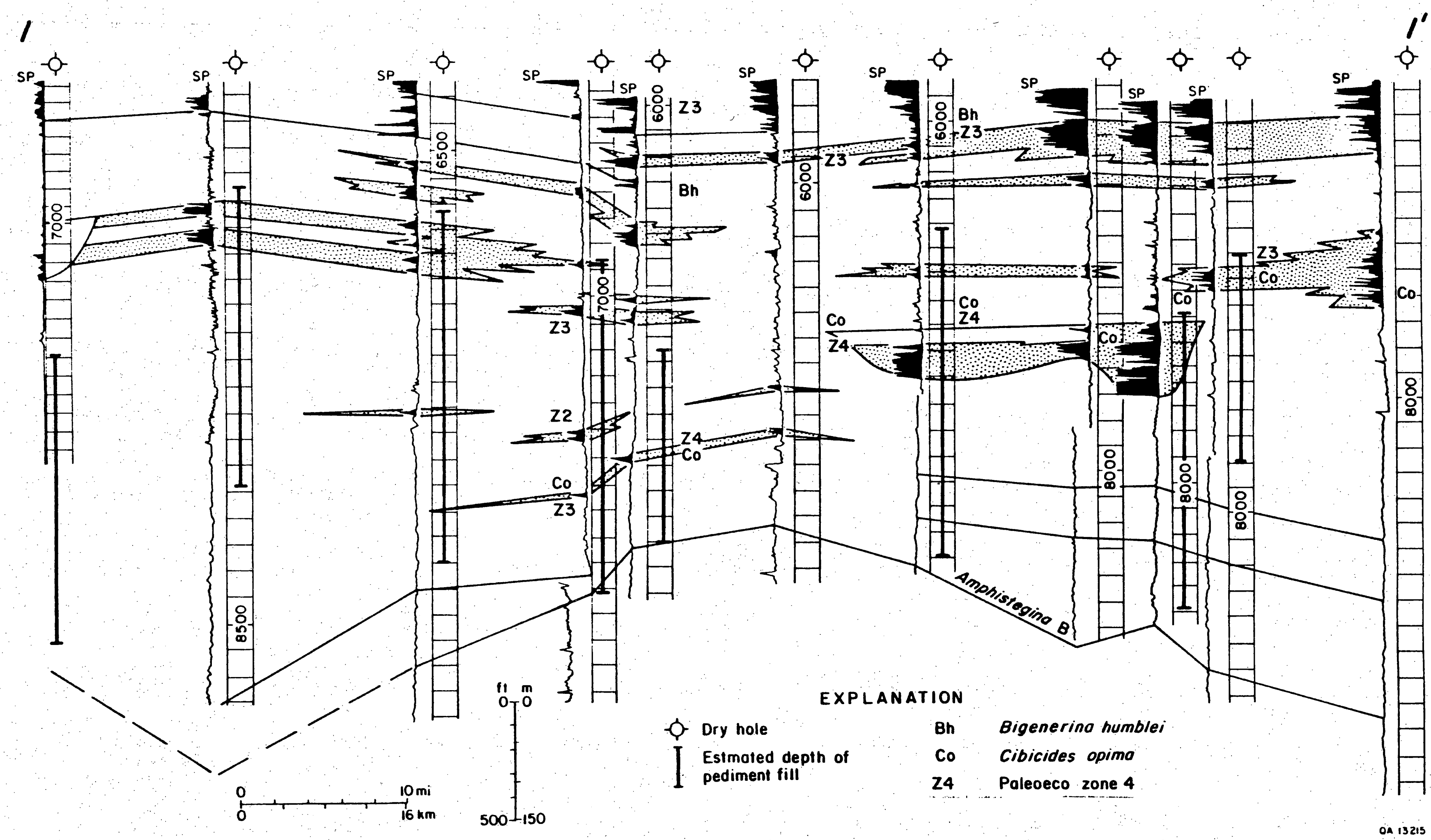


Figure 6. Stratigraphic strike section 1-1′ illustrating middle Miocene lithofacies, last occurrence of benthic foraminifers, and paleoecozones. Location shown on Fig. 5.

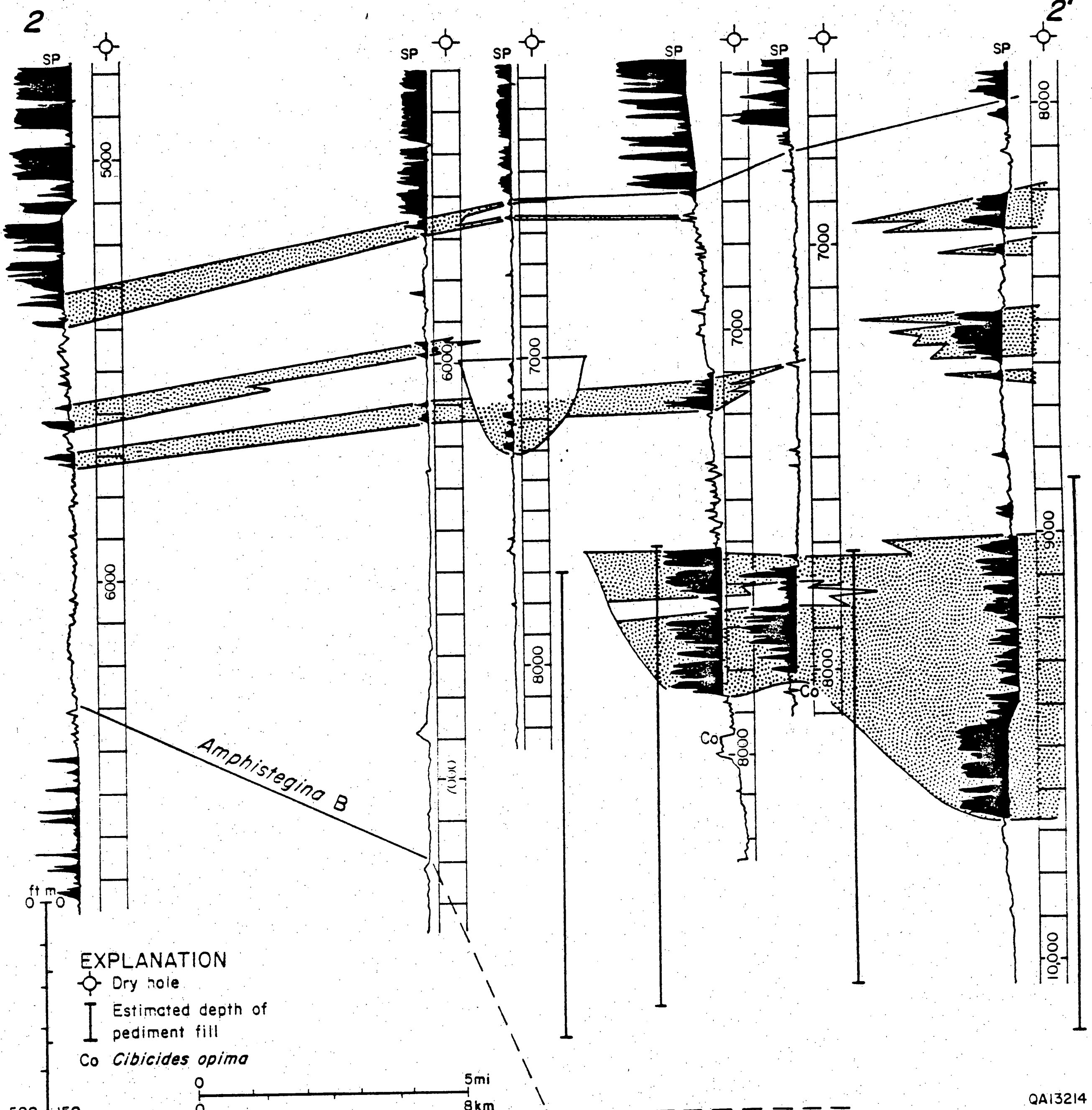


Figure 7. Stratigraphic dip section 2-2′ illustrating middle Miocene lithofacies, last occurrence of benthic foraminifers, and paleoecozones. Location shown on Fig. 5.

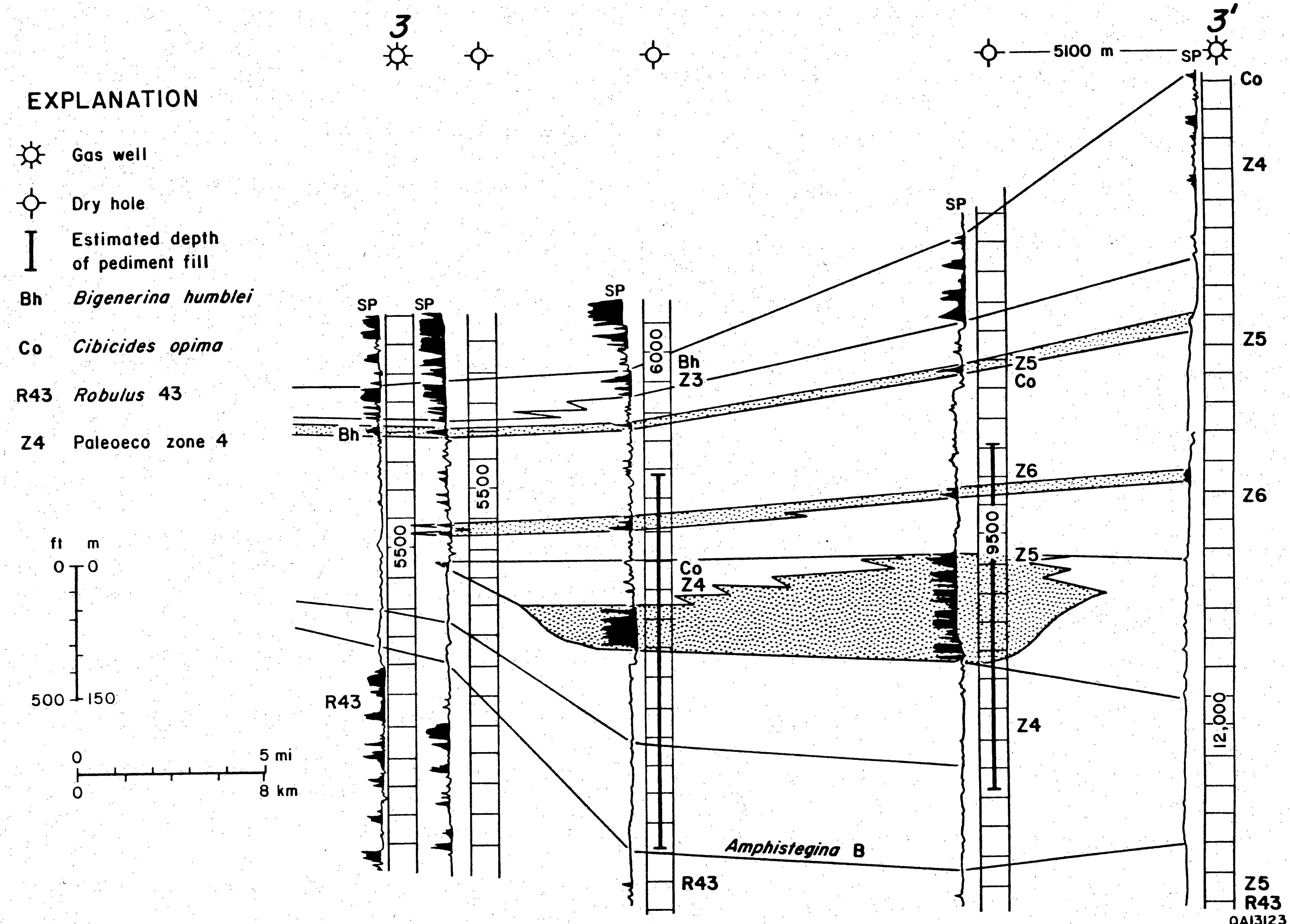


Figure 8. Stratigraphic dip section 3-3′ illustrating middle Miocene lithofacies, last occurrence of benthic foraminifers, and paleoecozones. Location shown on Fig. 5.

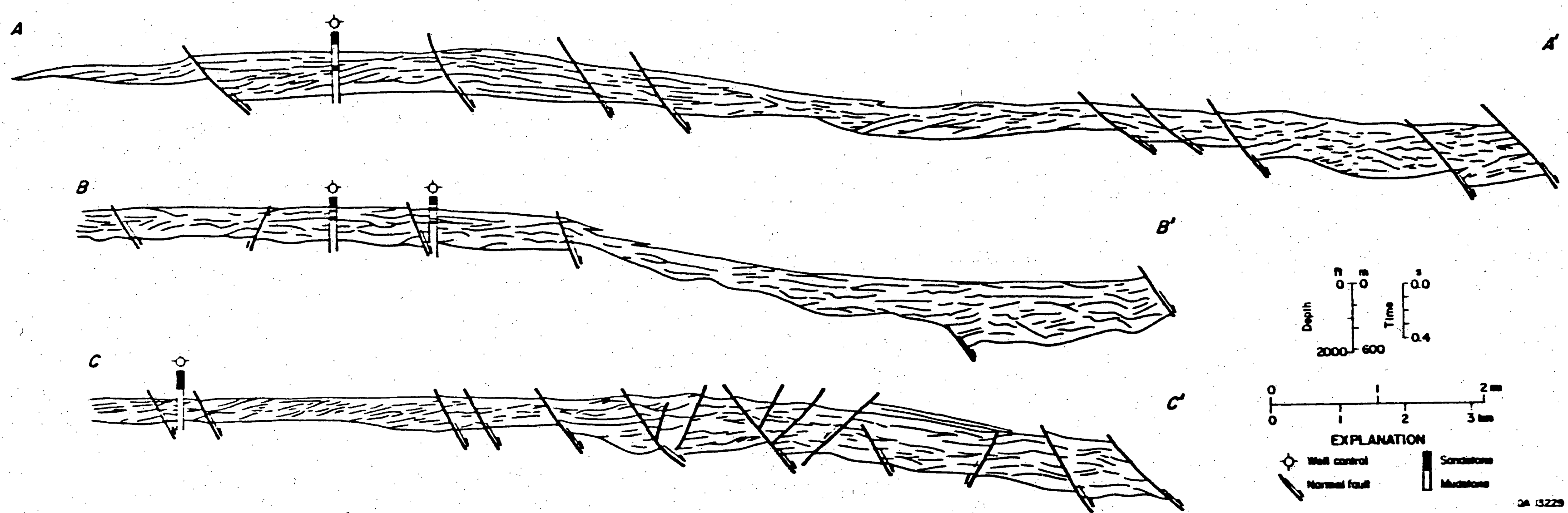


Figure 9. Line drawing of interpreted seismic profiles illustrating two-dimensional geometry and reflection characteristics of the middle Miocene onlap wedge. These dip-aligned profiles are only partly reconstructed (along fault planes). They are not decompacted or adjusted for non-faulting deformation. Locations shown on Fig. 5.

and becomes indistinguishable from progradational and aggradational slope deposits along the middle Miocene slope. The largest offshore field in Texas produces from these middle-Miocene slope deposits (Fig. 8) and other reservoirs deposited near the shelf margin (Morton et al. 1988).

*Lithostratigraphic correlations and paleoenvironments*

Sediments overlying the erosional unconformity at the base of the onlap wedge comprise a vertical succession of interbedded sandstones and mudstones (Figs. 6-8). The lowermost part of the wedge is composed of a thick section of mudstone deposited in upper slope and lower slope environments (zone 4 and 5) (Fig. 8). Simple landward thinning and possible onlap in the basal shale are indicated by electric-log correlations whereas seismic reflections typically reveal more complex stratal patterns (compare Figs. 8 and 9A). Lithologies of the middle to upper part of the onlap wedge are more irregular and may be composed of either mudstone or interbedded mudstone and sandstone (Figs. 6-8).

Sandstone beds are concentrated on the eastern and western flanks of the entrenched system (Fig. 10) and they pinch out near the margins (Figs. 6-8). Most wells encounter net sandstone thicknesses of 30 m or less, but as much as 120 m of net sandstone has been penetrated. The axes of greatest sandstone thickness are aligned in roughly north-south trends (Fig. 10). However, these trends actually form oblique southwesterly angles when compared to the regional trend of depositional strike. This preferential southwesterly orientation also is displayed by younger incised channels cut into the broad shelf (Berryhill 1987).

The middle Miocene strata contain arenaceous benthic foraminifers that lived in outer shelf to abyssal plain environments (zones 3 to 6). The species are indicators of cold bottom water containing high concentrations of suspended sediment (Echols and Curtis 1973) like that produced by turbidity currents flowing down the continental slope. Furthermore, the middle Miocene turbid-water assemblage is similar to those contained in other turbidites deposited in both older and younger Tertiary Gulf Coast embayments (Stuckey 1964). Thus, the electric-log patterns (Selley 1978), faunal evidence, and paleogeographic setting demonstrate that these deep-water sediments were deposited within the entrenched system by slumps and by small, restricted submarine channels and fans.

Unconfined submarine fans, which extend basinward of the lower Miocene shelf margin, represent a second style of deep-water deposition associated with the Galveston slope system (Morton et al. 1988). Few wells have penetrated these submarine fans because of their great depths seaward of the fault zone. Therefore, they are not included in this study. The narrow apron of muddy fans seaward of the interdeltaic embayment were supplied by sediments excavated from the entrenched system and by slumping and other gravity-induced processes operating along the unstable slope. Precise correlation between the basin-floor fans and slightly younger backfilled

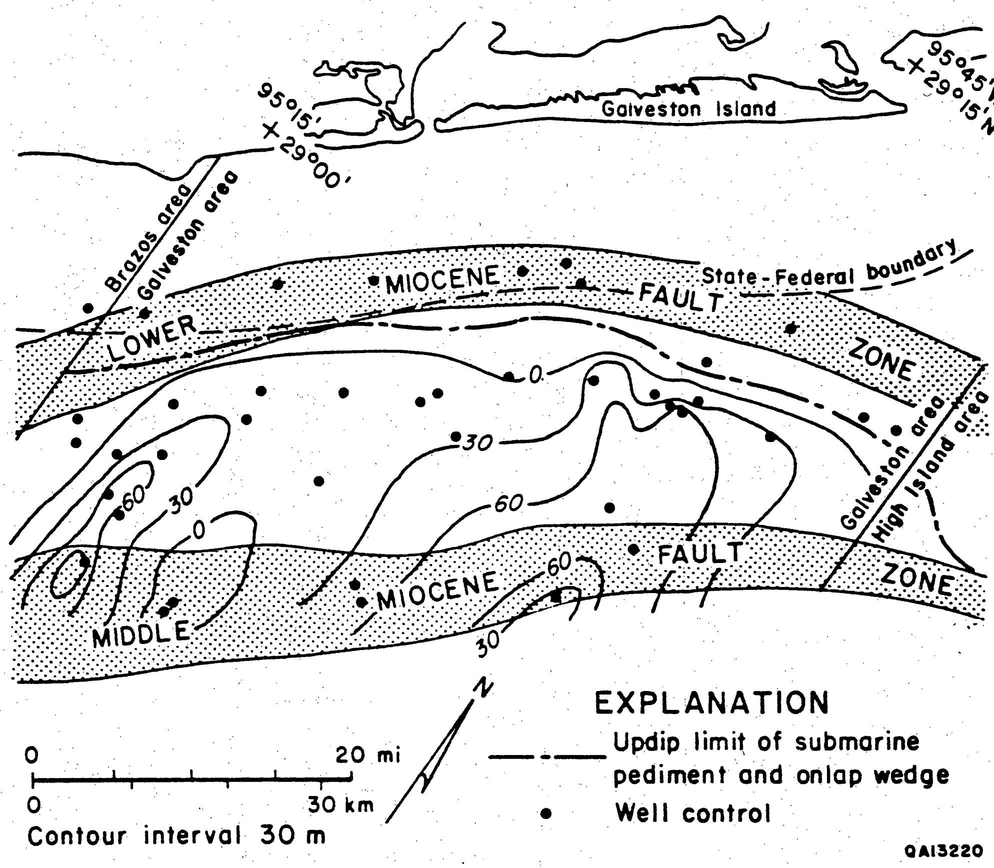


Figure 10. Net thickness of sandstones within the middle Miocene onlap wedge. Stratigraphic datum is a resistivity correlation marker below the base of the sand-rich section.

deposits is prevented by large stratigraphic displacements across the middle Miocene growth faults (Figs. 3 and 5).

The reported top of the *Cibicides opima* faunal zone is inconsistent when compared to stratigraphic correlations made on the basis of electric logs and seismic profiles (Figs. 6-8). These lithostratigraphic and biostratigraphic discrepancies can be explained by environmental controls on the benthic population and possible reworking of sediments containing the extinct species. The last appearance of the *Cibicides opima* fauna climbs in the section where subsidence rates were greater and deeper water depths were maintained for a longer period (Figs. 6 and 8). Furthermore, submarine erosion and subsequent redeposition of older sediments may account for the appearance of biostratigraphic markers both above and below the sandstone facies in different wells (Figs. 6-8).

Paleoecological zones at a particular stratigraphic horizon generally indicate systematic landward decreases in water depth as expected (Fig. 8). However, the range of water depths (approximately 1,500 m) exceeds the apparent accommodation space indicating sea-level fluctuations as well as a steep seafloor gradient.

### *Seismic facies*

A broad, thick zone of irregular seismic reflections located above and landward of the lower Miocene continental platform (Figs. 3 and 9) and near the *Cibicides opima* stratigraphic horizon identify the submarine pediment and depositional apron on seismic lines. An approximate reconstruction of the submarine pediment and overlying onlap wedge provides a more accurate representation of pre-deformational continuity and attitudes of internal seismic reflections (Fig. 9). As shown by this reconstruction, the basal pediment surface exhibits a step-like longitudinal profile, especially along its basinward limit. Step length decreases headward but step height may either increase or decrease in the same direction (Fig. 9).

Seismic reflections of the pediment fill are discontinuous, have highly variable dips and amplitudes, and are not arranged in simple geometric patterns. Despite the lack of systematic order, some generalizations can be made about the stacking geometries of seismic reflections. Reflections are mostly mounded, landward dipping, or chaotic in the deepest and most seaward part of the onlap wedge. The disconnected hummocky and chaotic patterns suggest disorganized mass movement and redeposition of sediment derived from the shelf (Lehner, 1969) whereas the other patterns portray original depositional surfaces.

Sets of reflections dipping landward typically occur immediately above and terminate near or against the basal unconformity (Fig. 9). These landward dipping reflections have apparent dips of as much as 10 degrees; slightly greater paleodips would be calculated if the profiles were adjusted for basinward tilt. Minor listric faults and rotation of slump blocks explain some, but not all, of the landward dipping sets of reflections (Fig. 9). These small landslides appear to be concentrated in the deepest part of the entrenched system. Apparently the erosional unconformity acted as a detachment surface along which basinward slip occurred, or conversely, the shallow fault plane created the basal discontinuity at some locations. The predominance of landward dips without fault rotation suggests lateral accretion processes with sediment being supplied by sources parallel to depositional strike.

Basinward dipping sets of reflections are most common in middip areas near the inflection zone where clinoforms and reflections subparallel to the upper boundary characterize the uppermost part of the wedge (Figs. 9A and 9C). The clinoform reflections record progradation of a muddy shelf and slope that produced an upward-shoaling facies architecture.

Some sets of landward dipping reflections are overlain by seaward dipping reflections. In those cases, the sets of divergent reflections are commonly separated by a single reflector or set of horizontal to wavy reflectors. Some of the wavy reflectors appear to be levees associated with channels of a submarine fan complex.

If present, a complete vertical succession of seismic stratal patterns consists of: (1) landward dipping, mounded, or chaotic, (2) sub-horizontal or wavy, and (3) seaward dipping reflections (Fig. 9). Some sets of landward and basinward dipping reflections form bidirectional downlapping mounds that may outline extremely small lobes of submarine fans (Mitchum 1985).

### *Facies architecture, sandstone continuity, and reservoir potential*

Sea level fluctuations and attendant changes in facies architecture controlled the position and thickness of middle Miocene sandstones, their continuity, and their potential as hydrocarbon reservoirs. Paleoecological assemblages record initial upward-deepening, then substantial submergence, and finally a prolonged period of upward-shoaling (Figs. 6 and 8). The initial upward deepening accompanied a relative rise in sea level and highstand that resulted in the *Amphistegina* B regional transgression. Hemipelagic mudstone drapes and extremely thin turbidites were deposited in outer shelf to lower slope environments (zones 3-5) by transgressive and highstand systems tracts, using the terminology of Posamentier et al. (1988). The basinal mudstones contain no sandstone or only extremely rare sandstone beds (Figs. 6-8) because the site was far from the shoreline and active zone of sand deposition.

The next significant event was abrupt deepening caused by degradation of the shelf margin and erosion of the unconformity. At that time fine-grained sediment was slumped and removed from the continental platform and transferred to the slope as mud-rich submarine fans. The few interbedded sandstones deposited as pediment fill are less than 6 m thick, limited in areal extent, and discontinuous (Fig. 6). Mudstones make up at least half of the section observed on electric logs and account for nearly all the interval in updip wells (Figs. 7 and 8).

The upward-shoaling phase of deposition was initiated by a lowstand systems tract, which deposited mud-rich fans as well as overlying channel-fill sandstones with subordinate interbedded mudstones. The thickest concentrations of sandstone (Fig. 10) coincide with these sharped-based sandstones that display overall upward-fining and upward-thinning profiles (Figs. 6-8). Paleoecological zonations indicate that these channel-fill sandstones were deposited in upper and lower slope environments (zones 4 and 5). Individual sandstone packages of the channel fill are less than 20 m thick. They have mixed blocky, upward-coarsening and upward-fining profiles, are separated by mudstones that are commonly 3 to 5 m thick, and are laterally separated from other sand-filled channels by the thin mudstones. These sand-filled channels near the tops of the submarine fans and attached sand lobes are the primary hydrocarbon reservoirs in the section. The interval of channel sandstones is relatively continuous, but individual sand bodies are highly compartmentalized by numerous shale beds that reflect turbidite deposition.

As deposition continued, the seafloor was eventually restored to a position comparable to that before the pediment surface was eroded. Sandstone deposition diminished as the relative rise in sea level counteracted the supply of coarse clastic sediments. At that time, the transgressive systems tract deposited mudstones and thin, highly discontinuous sandstones above the sand-prone interval, at the top of the pediment fill, and immediately above the pediment fill. Despite being deposited mainly in outer shelf environments (zone 3), this lithofacies exhibits highly variable three-dimensional architectures that are not repeated in nearby wells (Fig. 6).

The final phase of upward-shoaling was related to another highstand in sea level and renewed construction of the shelf margin. The highstand systems tract prograded across the surface of maximum flooding depositing sand-rich nearshore sediments. The dominantly sandstone lithofacies consistently forms upward-coarsening and upward-shoaling profiles at the top of the section (Figs. 6-8). These sandstones and subjacent mudstones were deposited in outer shelf environments (zone 3, Figs. 6 and 8). Individual sandstone beds are very thin (1 to 3 m) and are separated by mudstones of comparable thicknesses (Figs. 6-8). These well-sorted progradational sandstones are highly continuous and productive in nearby fields (Fig. 8).

Time-to-depth conversions between seismic profiles and electric logs reveal the relationships between facies architecture and seismic stratal patterns (Fig. 9). The basal mounded, landward dipping, and chaotic reflections are the seismic signatures of resedimented slumps or deep-water mudstones deposited as turbidites. The slumps were locally derived from the floor and walls of the pediment but remained after the upper layers were transported downslope. These residual slumps are overlain by muddy turbidites derived from more distant sources such as the shelf or headward erosion of the entrenched system. The sand-filled submarine channels occur above the mounded and landward dipping reflections near the transition with overlying horizontal to wavy reflections

(Fig. 9). The stratigraphically highest sets of seaward dipping reflections coincide with the upward-shoaling and upward-coarsening progradational succession of shallow-water mudstones and sandstones.

## MIDDLE PLIOCENE SLOPE SYSTEM

### *Regional setting*

Middle Pliocene strata investigated in this study (Fig. 1) include those sediments bracketed by the regional extinction horizons of the *Globogerina nepenthes* and *Globoquadrina altispira* faunal assemblages (Fig. 2). This stratigraphic interval records the influence of sea-level fluctuations and growth structures on deep-water sedimentation both landward and basinward of the paleoshelf margin. Emphasis, however, is placed on the submarine channels and fans deposited on the lower slope and basin floor.

The early Pliocene geologic history of the southeast Texas continental shelf and slope began with basinwide progradation and platform construction (Fig. 2). During this period of shoreline regression, deltaic depocenters rapidly advanced the continental margin of offshore Louisiana while the Texas shelf subsided and remained a nondeltaic margin. Progradation of the delta-flank margin was limited because it received only minor amounts of mud supplied by the Louisiana deltas (Morton et al. 1990). Later, during the middle Pliocene, the monotonous deposition of progressively deeper water mudstones in Texas was interrupted by an abrupt influx of coarse terrigenous clastics onto the slope and basin floor (Fig. 11).

The source and conduit for these coarse clastics was a broad submarine pediment (Figs. 12 and 13) eroded into the continental shelf on the southwestern flank of a lower Pliocene delta. Sand and mud excavated from and bypassed through the entrenched system was deposited on the slope and basin floor as coeval submarine channels and fans (Fig. 14). The pediment was subsequently backfilled and later the shelf margin was reestablished by small, coalescing deltas.

The middle Pliocene submarine pediment is also a convex-landward feature that is about 150 km wide and 50 km long (Figs. 12 and 13). The basal unconformity displays more than 600 m of total relief, which decreases landward. Retrogressive failure and erosion of subjacent strata are indicated by intraformational slumping and internal reflections having the same seismic expression as channel cut-and-fill. Sediments backfilling the unconformity form an onlap wedge that thickens basinward (Fig. 13). The wedge terminates updip near the upper Miocene shelf margin (Fig. 14) and it passes downdip into conformable slope deposits that are disrupted by growth faults and salt domes (Fig. 11). Some of the largest Plio-Pleistocene fields in the western Gulf Coast Basin produce from deep-water sandstones associated with these or similar slope deposits (Morton et al. 1990).

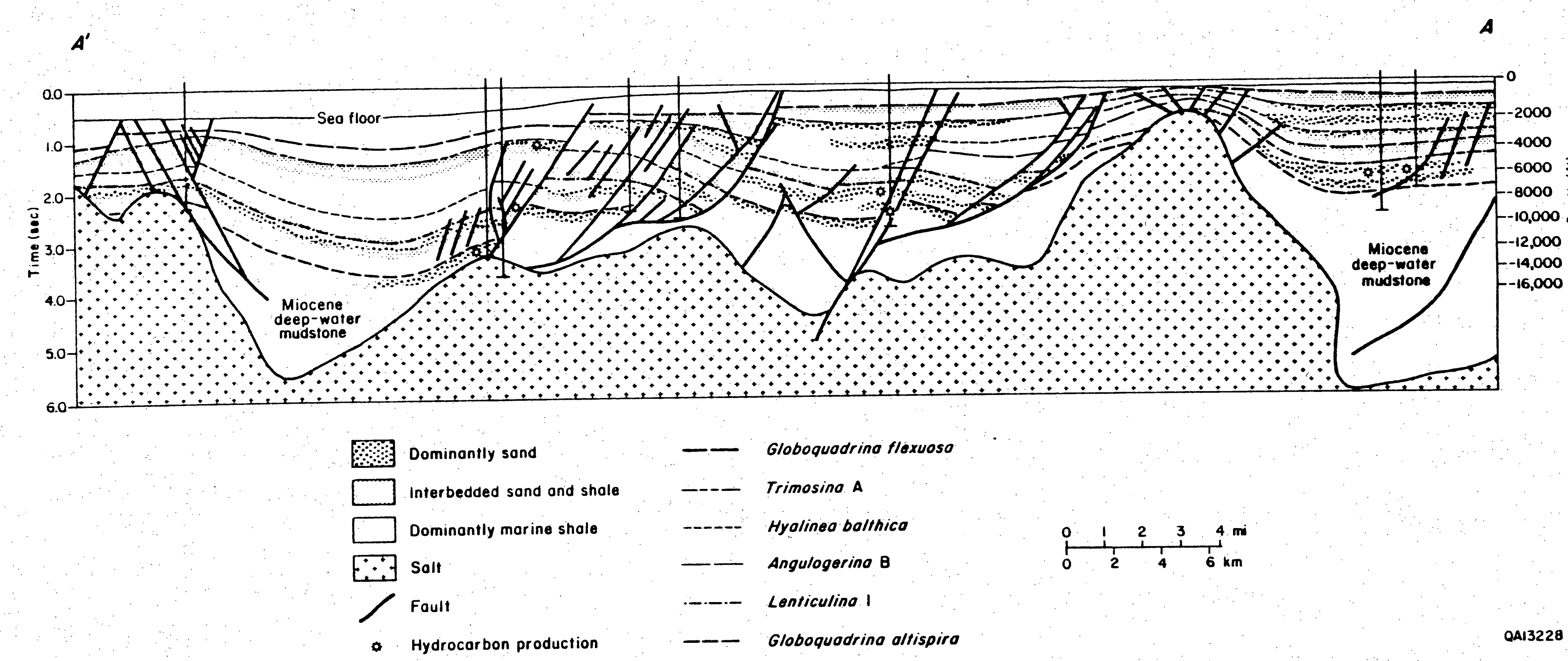


Figure 11. Seismic profile and interpreted structural cross section illustrating lithologies, biostratigraphic markers, and structural style of Plio-Pleistocene sediments, offshore Texas. Specific features include major expansion faults, salt diapirs, and withdrawal synclines. Vertical lines represent nearby well control Location shown on Figure 12. Modified from Morton et al. (1990).

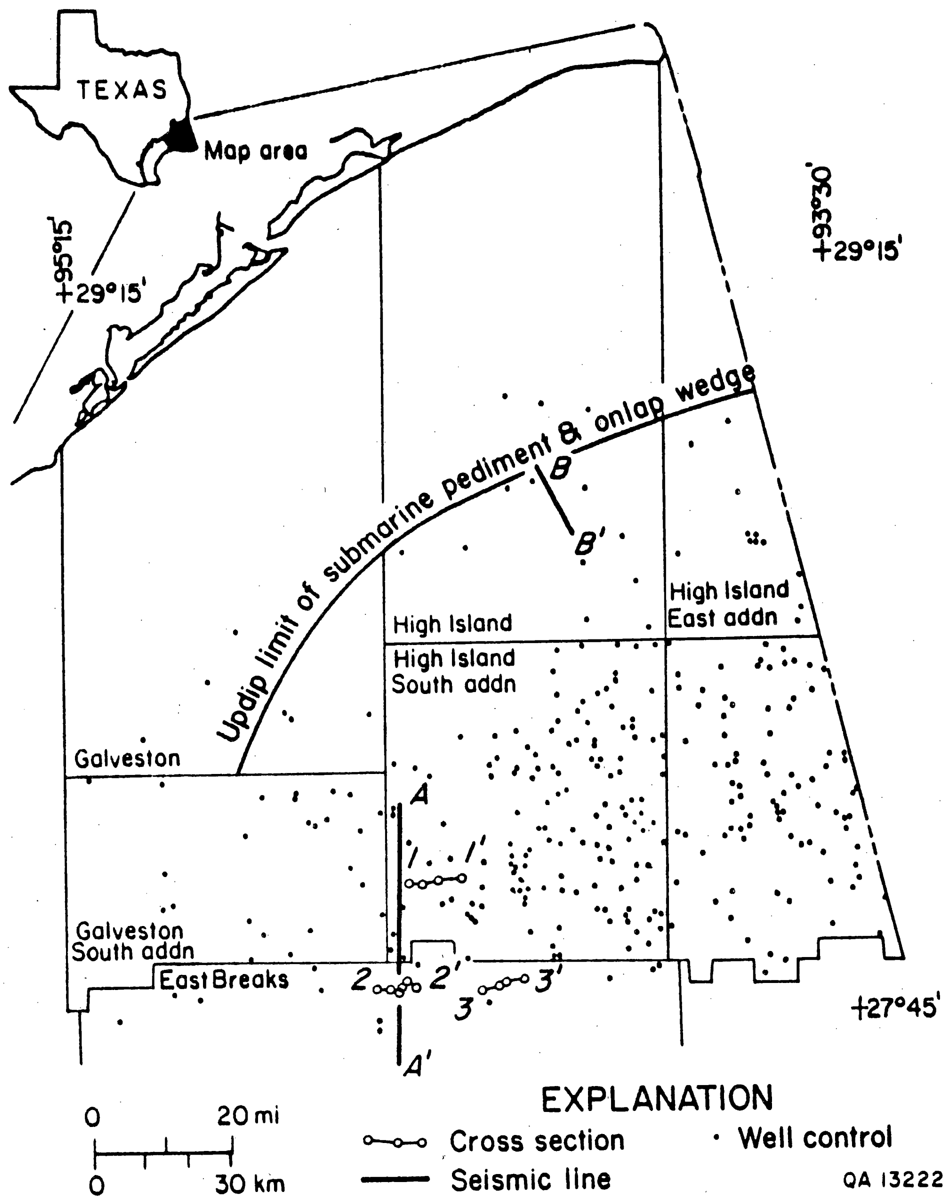


Figure 12. Locations of well control, seismic lines, and stratigraphic cross sections used to interpret middle Pliocene deep-water deposits of offshore Texas.

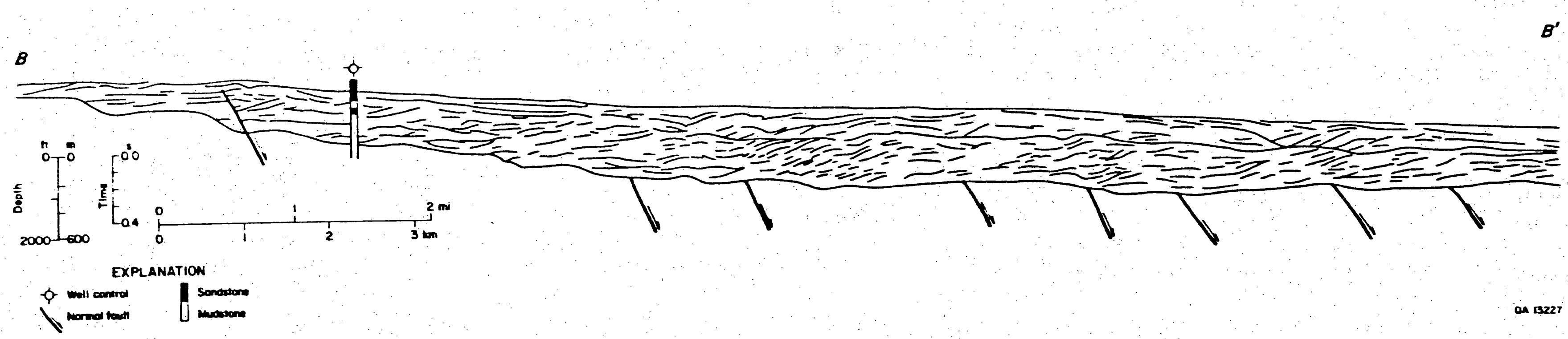


Figure 13. Line drawing of interpreted seismic profile illustrating two-dimensional geometry and reflection characteristics of middle Pliocene deep-water deposits. This dip-aligned profile is not adjusted for sediment decompaction or non-faulting deformation. Location shown on Fig. 12.

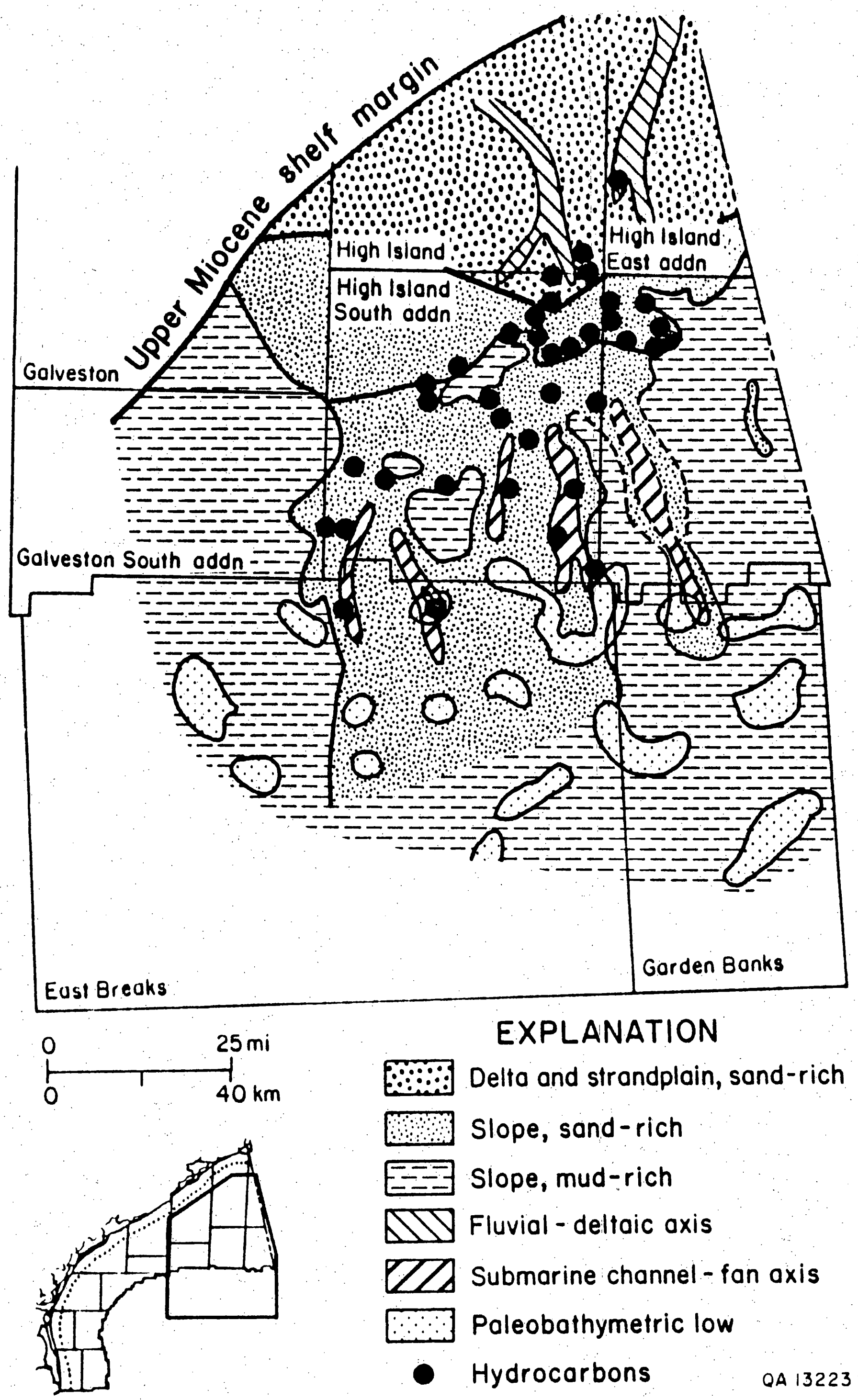


Figure 14. Principal depositional systems of the *Globoquadrina altispira* genetic sequence in the western Gulf Coast Basin. The map represents a composite of subjacent lowstand systems tracts, transgressive systems tracts, and suprajacent highstand systems tracts. Modified from Morton et al. (1990).

*Lithostratigraphic correlations and paleoenvironments*

The middle Pliocene stratigraphic interval is composed of framework sandstones with interbedded mudstones surrounded by mudstones of variable thickness that separate the sandstone packages (Figs. 15-17). The interval can be subdivided into four units on the basis of lithofacies and stratigraphic position. Thick mudstones deposited in lower slope and abyssal environments comprise the basal unit (Figs. 15 and 17). Overlying these mudstones are amalgamated sandstones deposited in upper slope environments. These sandstones are widely distributed within the middle part of the stratigraphic sequence, but three-dimensional continuity of individual sand bodies is highly variable. The third lithofacies unit overlies the sand-prone section and is characterized by mudstones and interbedded sandstones of variables thickness. The uppermost unit, like the basal unit, is also composed of lower slope and abyssal plain mudstones that record a return to deeper-water conditions. Together the paleobathymetries, sandbody geometries, and stratification types indicate that these deep-water sediments were deposited by a submarine channel and fan complex.

The sand-rich submarine channels and fans that dominate the basinal part of the genetic sequence form a broad band about 80 km wide (Fig. 18). They abruptly pinch out to the west because they were deposited downslope of the entrenched system and were not reworked by oceanic currents flowing subparallel to bathymetric contours. Except for local channel-fill deposits, sandstone abundance decreases landward where the sequence onlaps the basal unconformity. The principal axes of abundant sandstone are highly elongate, dip oriented, and 7 to 10 km wide (Fig. 18). They exhibit southerly alignments that are parallel to the primary direction of sediment transport. A secondary axis of sandstone deposition is postulated in the eastern part of the study area where well control is sparse. This inferred depositional axis cannot be traced updip because younger sequences are extremely thick and few wells have been drilled deep enough to penetrate the *Globoquadrina altispira* sequence.

Most wells penetrating depositional axes encounter from 30 to 90 m of net sandstone and a few wells penetrate as much as 180 m of net sandstone (Fig. 18). Sandstone thickness is greatest toward the basinward terminus of each depositional axis, in paleobathymetric lows, and around young diapirs that post-date sandstone deposition (Morton et al. 1990). Faults and salt structures on the slope exerted local control on sandstone distribution that is reflected in local facies variability around producing structures. Some large emergent structures trapped the coarse bedload of turbidity currents and prevented deposition farther downslope. Still other bathymetric highs merely deflected the organized feeder systems and focused their discharge of sand between growing structures. Reduction or absence of sandstones around some domes indicates that syndepositional salt structures diverted flow and created downcurrent shadow zones. This interference with sediment transport caused local thinning and shale out of some potential sandstone reservoirs (Fig. 15).

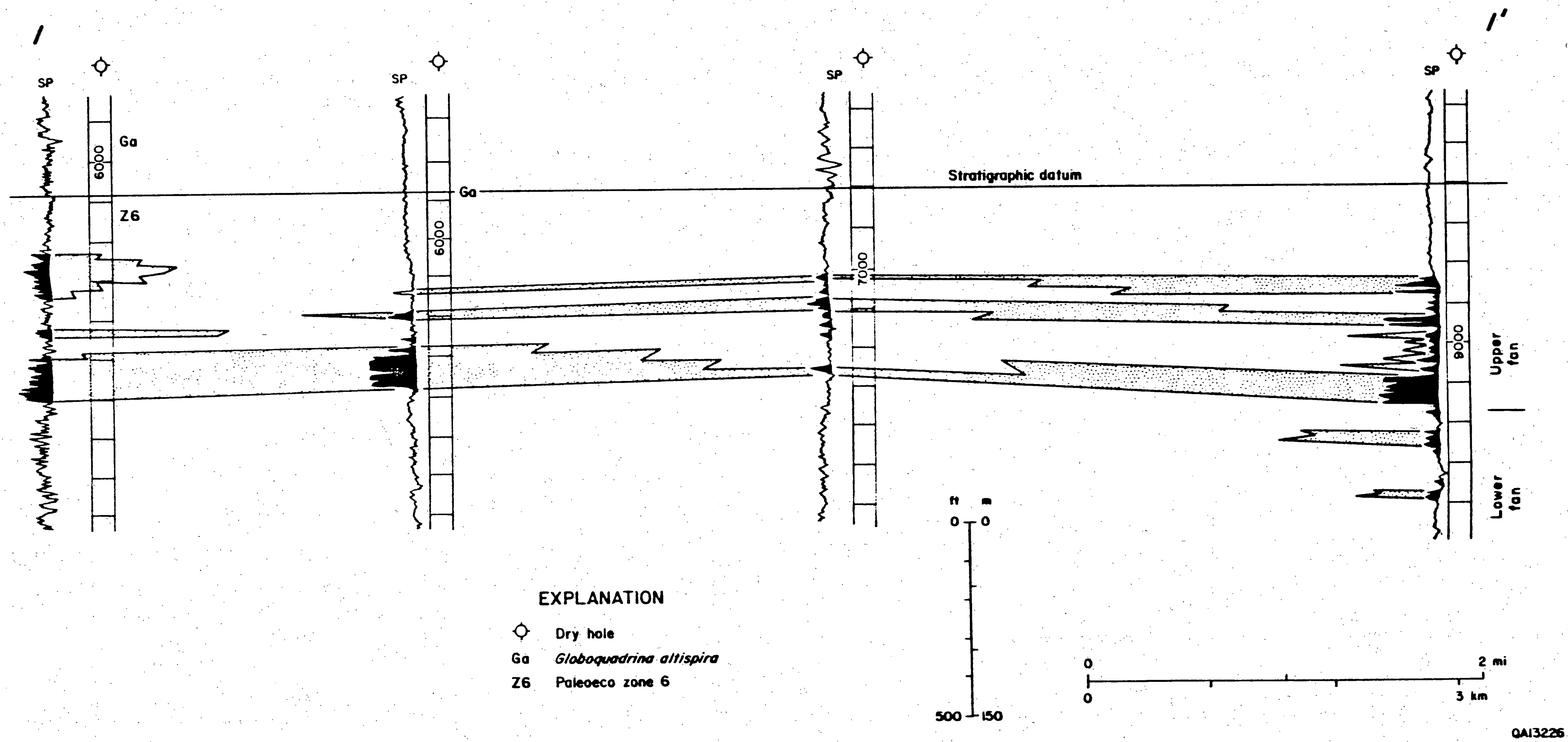


Figure 15. Stratigraphic strike section 1-1′ illustrating middle Pliocene lithofacies, last occurrence of planktonic foraminifers, and paleoecozones. Location shown on Fig. 12.

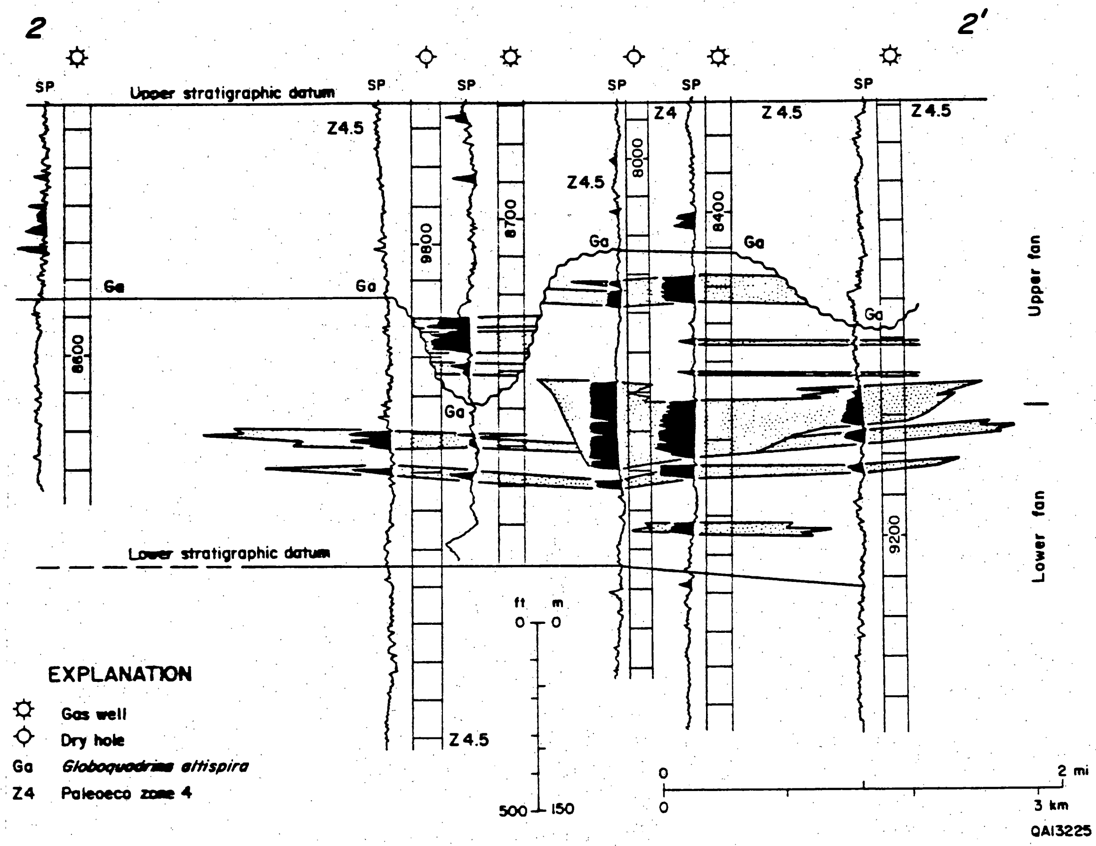


Figure 16. Stratigraphic strike section 2-2′ illustrating middle Pliocene lithofacies, last occurrence of planktonic foraminifers, and paleoecozones. Location shown on Fig. 12.

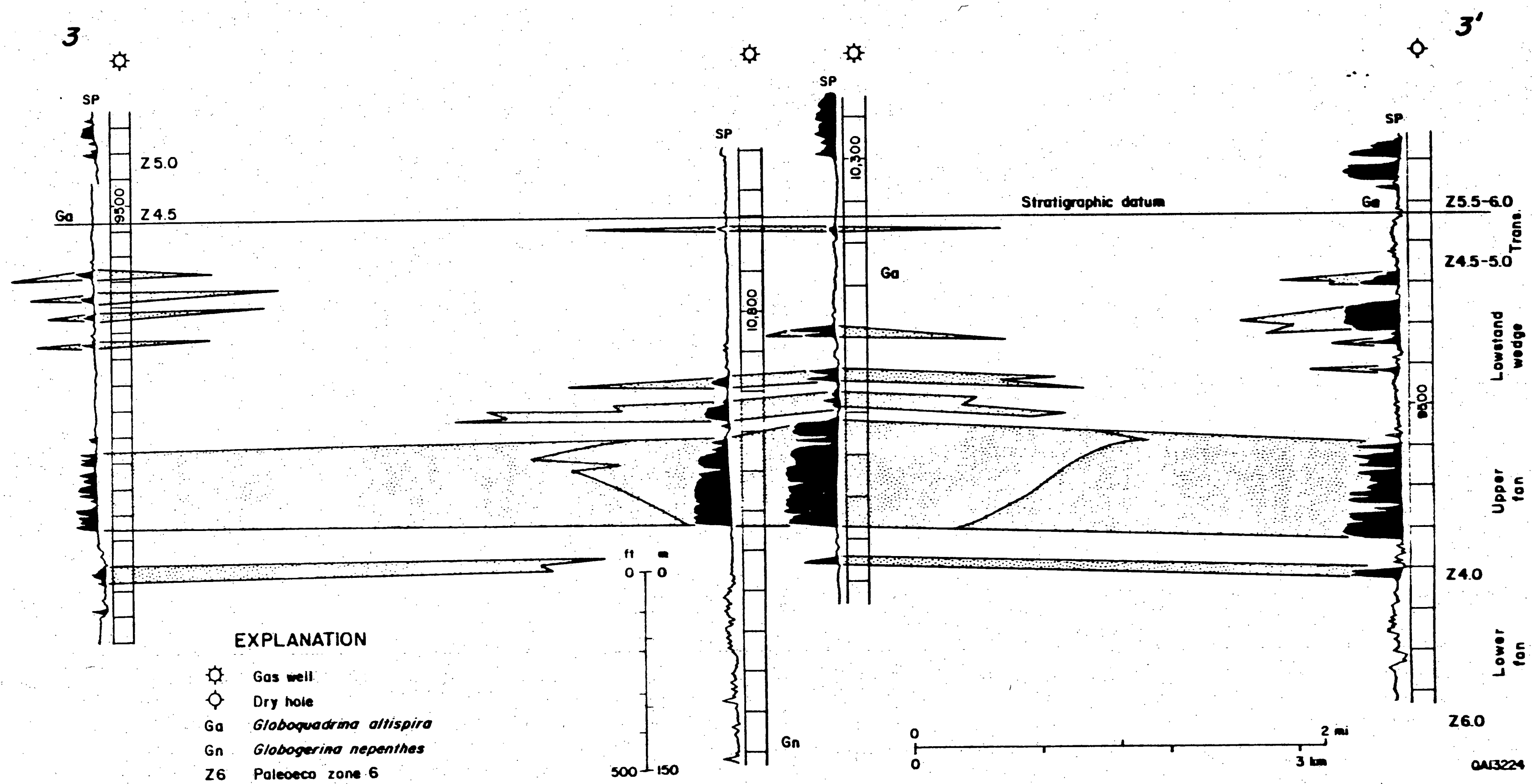


Figure 17. Stratigraphic strike section 3-3′ illustrating middle Pliocene lithofacies, last occurrence of planktonic foraminifers, and paleoecozones. Location shown on Fig. 12.

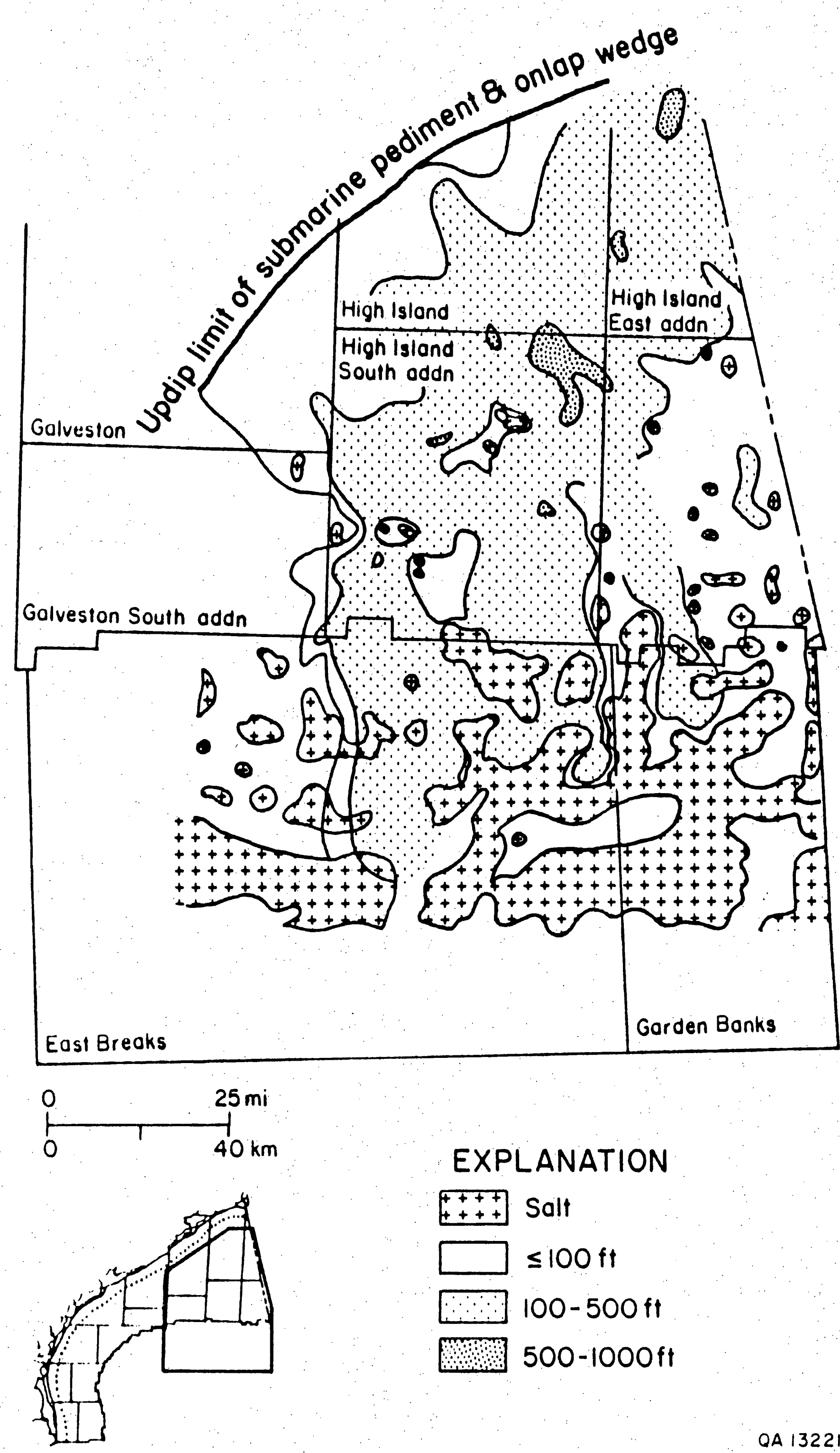


Figure 18. Composite net thickness of *Globoquadrina altispira* sandstones. Modified from Morton et al. (1990).

The sand-poor middle part of the slope system is composed of thin interbedded sandstones and mudstones deposited in outer shelf and upper slope environments by shelf-edge deltas and small submarine fans. The fans overlap and coalesce immediately basinward of the shelf/slope break forming a long but narrow apron (Fig. 14).

The most updip part of the wedge, which coincides with the submarine pediment (Fig. 13), is composed mostly of mudstone. The few discontinuous lenticular sandstone packages, which are interbedded with mudstones, consist of resedimented outer shelf to lower slope deposits (zones 3 to 5). In updip positions and toward the top of the wedge, sandstones become thicker, more continuous, and display upward-coarsening patterns that reflect deposition in progressively shallower water.

### *Seismic facies*

Seismic facies patterns of the *Globoquadrina altispira* stratigraphic sequence can be grouped into three distinct zones on the basis of reflection strength, continuity, and concordance. The most landward zone, which coincides with the submarine pediment (Fig. 13), consists of high-amplitude, discontinuous, and divergent reflections that unconformably overlie and truncate high-amplitude, continuous reflections. Some pediment-fill reflections are mounded or wavy and many dip landward.

Basinward-dipping clinoforms are not well developed in the middle Pliocene sequence and are restricted to updip areas within the entrenched system. Where present, clinoforms occur near the top of the interval and downlap onto the divergent and hummocky reflections. These irregular seismic patterns and geometric arrangements are similar to those observed in the middle Miocene pediment fill (Figs. 9 and 13).

Divergent reflections of the pediment fill are replaced basinward by alternating high- and low-amplitude, parallel, continuous reflections. In turn, these seismic patterns grade laterally and basinward into either low-amplitude, parallel and continuous reflections or a thin zone (0.2 sec) of moderate-amplitude, discontinuous, hummocky to wavy reflections. The zone of discontinuous, divergent reflections also contains local slump features and areas of chaotic reflections indicating mass movement of sediment.

The most basinward seismic facies patterns consist of low- to moderate-amplitude, mostly discontinuous reflections. A few high-amplitude continuous reflections commonly both underlie and drape over the groups of discontinuous, variable amplitude reflections. Post-depositional deformation obscures any external geometries such as bidirectional downlap of reflections that would indicate submarine fan lobes (Mitchum 1985).

*Facies architecture, sandstone continuity, and reservoir potential*

Facies architecture and sandstone continuity within the middle Pliocene slope deposits are highly variable owing to fluctuations in sea level and shifting sites of turbidite deposition. The three-dimensional sandstone heterogenieties are primarily related to the principal components of the slope system. From oldest to youngest they are: lobes of the lower submarine fan, submarine channels and levees of the upper fan, and the submarine pediment fill including minor shelf margin deltas. Sandstone discontinuities may also be caused by erosional unconformities that locally remove as much as 120 m (400 ft) of section (Fig. 16).

Paleobathymetry of the *Globoquadrina altispira* sequence records a series of alternating upward-deepening and upward-shoaling events (Figs. 15 and 17). Lower-slope and abyssal plain mudstones at the base of the interval and immediately above the *Globogerina nepenthes* marker record systematic deepening of the slope. This upward-deepening phase of hemipelagic mudstone deposition was related to a regional rise in sea level and highstand (Fig. 2). Thus, these mudstones are products of transgressive and highstand systems tracts.

The overlying sand-prone submarine channels and fans, which were deposited in upper to middle slope environments (zones 4 and 4.5), represent a sudden upward-shoaling (Fig. 17) caused by lowering of sea level coupled with slope aggradation that exceeded rates of subsidence. The facies architecture of the lower lowstand fan consists of sandstones 6 to 15 m thick that have irregular, spikey to upward-coarsening log profiles (Figs. 15-17). Highest intrawell continuity is exhibited by these thin sandstones beds of the lower fan lobes.

In contrast to the lower fan, facies architecture of the upper fan is characterized by aggradational and retrogradational sandstone packages 20 to 60 m thick having blocky or irregular SP responses that exhibit an overall upward-fining and upward-thinning profile (Figs. 16 and 17). These log patterns represent sand aggradation within the upper-fan channels followed by diminished supply of the coarse fraction. The basal sandstones in these packages commonly eroded into underlying mudstones of the lower fan (Figs. 16 and 17). At the regional scale of mapping (Fig. 18), axes of primary feeder systems can be identified; however, the positions of individual channel-levee complexes cannot be predicted with great accuracy.

The channel-fill facies has the greatest vertical sandstone continuity but the lowest lateral continuity (Figs. 16-17). Sandstone continuity decreases toward the margins of the primary axis where the number and thickness of mudstone interbeds increases. The inter-channel deposits exhibit irregular to serrate log responses reflecting the greater abundance of mudstone turbidites that accumulated in overbank and levee environments (Figs. 15 and 17). Mudstones of the channel-fan complex are thick enough to isolate the sandstone beds creating separate hydrocarbon reservoirs as indicated by variable hydrocarbon/water contacts even within the same well.

The lowstand submarine channel-fan deposits may have onlapped the paleoslope and pinched out before reaching the contemporaneous shelf margin, but such a relationship is not indicated by composite sandstone continuity (Fig. 18). Seismic facies analysis is also inconclusive as to whether or not the slope sandstones extend updip and intersect feeder channels as an attached fan system.

Landward of the lowstand channels and fans is a zone of progradational sandstones interpreted to be a lowstand wedge, using the terminology of Posamentier et al. (1988). The facies architecture of the lowstand wedge consists of aggradational, upward-coarsening sandstones, which are 3 to 9 m thick. The boundary between these upward-coarsening sandstones and the more basinward upward-fining sandstones closely approximates the paleomargin (Fig. 12). Nearly all middip wells encounter sandstone lenses, but sandstone thickness and concentration are highly variable (Fig. 15). The sand-prone intervals are moderately continuous because of overlapping lobes and the vertical-offset stacking arrangement of sandy facies.

The return to lower slope and abyssal water depths (zones 5 and 6, Figs. 15 and 17) and concomitant hemipelagic mudstone deposition at the top of the sequence was related to a relative rise in sea level. These deep-water mudstones, which contain the regional *Globoquadrina altispira* extinction horizon (Figs. 15-17), represent deposits of a transgressive systems tract.

The facies architecture that characterizes the pediment fill (not shown) consists of stacked sandstone packages having mixed irregular upward-coarsening and upward-fining profiles (Morton et al. 1990). Thicknesses of these aggradational deposits typically range from 10 to 45 m, but they may be as thick as 105 m. Updip components of the onlap wedge are backfilling and aggradational lower slope to upper slope mudstones above the submarine pediment surface. These residual slump deposits and turbidites are overlain by thin, outer-shelf deltaic deposits representing minor progradation of the "shelf margin" within the entrenched system. Together the mixed upward-fining and upward-coarsening sandstones record submarine entrenchment, slope aggradation, and deltaic progradation across the continental platform.

The slump and turbidite mudstones at the base of the pediment fill correspond to the mounded and hummocky seismic reflections, the thin irregular sandstones occur above these divergent reflections, and the upward-coarsening interval coincides with the clinoforms at the top of the pediment fill (Fig. 13). These seismic facies and lithofacies relationships are similar to those of the middle Miocene pediment fill (Figs. 9 and 13).

The principal middle Pliocene depositional systems responsible for transporting reservoir-quality sandstones to the slope were a lowstand submarine fan complex and a lowstand shelf-edge delta. The sandstones are composed of fine- to very fine-grained quartz with some mica and feldspar grains. These were the coarsest grain sizes available because they were derived from multicycle coastal plain sediments and were deposited far from sources of first cycle sediments.

Sorting of the sand fraction can be moderate to poor depending on energy of the turbidity currents and opportunities for removal of the muddy matrix. Even the thickest sandstone beds contain substantial amounts of primary matrix. Despite the lack of uniform sorting, these unconsolidated sandstones have excellent pore properties because most have been buried less than 3 km and have not been diagenetically altered. As a result of these favorable conditions, porosities commonly range from 30 to 35 percent and permeabilities range from several hundred to several thousand millidarcies.

Initial rates of production from individual wells can exceed 500 $m^3$ of oil and 135,000 $m^3$ of gas per day. Development wells completed in the channel-fill typically maintain better reservoir pressures and have higher yields and total recovery than wells completed in the fan lobes or levees where reservoir heterogenieties cause incomplete drainage and disrupt communication between wells.

## DISCUSSION AND CONCLUSIONS

Many modern and ancient submarine fans were deposited along active plate margins where high topographic relief and steep seafloor gradients between the source and basin floor contribute to the construction of coarse-grained radial fans and debris aprons (Walker, 1978; Nelson and Nilsen, 1984). Clearly the late Neogene slope deposits of the western Gulf Coast Basin are products of (1) unstable slopes that were reduced between source and depositional site by shelf-margin failure and creation of submarine pediments, (2) deposition of mud-rich elongate fans, and (3) formation of inter-fan channels confined by levees that promoted downslope transportion of sand great distances from the shelf margin.

There are distinct similarities between the middle Miocene and middle Pliocene submarine pediments and deep-water deposits. Both submarine pediments are wider than the shelf embayed part of the Mississippi Canyon (Coleman et al. 1983) eventhough they were not formed by principal rivers of continental drainage systems. The two pediment surfaces represent the most prominent and extensive erosional unconformities observed in the late Neogene basin fill of the western Gulf Coast Basin. Both unconformities were eroded after regional marine transgressions flooded the continental platform, depositing thick blankets of deep-water shale. Both unconformities formed broad, crescent shaped submarine pediments along nondeltaic slopes and on the southwestern flanks of subjacent delta systems rather than at the mouths of major rivers. The submarine pediments spread landward across the submerged continental platforms by retrogresssive failure of the shelf margin and prolonged collapse of steep, unstable slopes such as those described by Farre et al. (1984) and Prior and Coleman (1978).

The deep embayments carved into the platform funnelled nearshore sediments downslope to mud-rich basin-floor fans. Sandstones associated with submarine channel-levee complexes are the most prolific hydrocarbon reservoirs within each depositional sequence. Each backfilled wedge above the unconformity and updip of the basin-floor fans is also composed of deep-water deposits (slumps, fans, and channel-levee complexes). These slightly younger slope deposits also include some sandstones of reservoir quality. The sand-prone interval is generally located near the basinward part of the onlap wedge in the middle of the zone of irregular seismic reflections, rather than at the base as would be expected for incision by fluvial channels. The updip sand-prone facies occurs above the basal mounded seismic reflections and near the transition with overlying horizontal or clinoform reflections.

Unconfined fans deposited basinward of the shelf edge are generally sand-poor. Sandstones associated with lower fan deposits may exhibit high lateral continuity but they are generally thin and may have low permeabilities because of poor sorting. In contrast, confined channels of the middle and upper fan account for the highest sandstone concentrations and best pore properties, but the lowest lateral continuity (Figs. 16 and 17).

Components of both middle Miocene and middle Pliocene slope systems consist of (1) normal upward-deepening slope deposits, (2) a submarine erosional unconformity, (3) submarine channels and fans and slightly younger slope deposits that onlap and backfill the unconformity, and (4) progradational deltas that reconstructed the shelf margin. Sandstones associated with submarine channel-levee complexes are the most prolific hydrocarbon reservoirs within each depositional sequence. At the regional scale of exploration, axes of primary feeder systems can be identified (Fig. 18); however, the positions of individual channel-levee complexes cannot be accurately predicted.

The late Neogene deep-water sandstones are ideal targets for deep basin exploration because, in their respective areas, they are the oldest permeable beds with seals that can be charged with hydrocarbons. Thus, they represent the first available traps for oil and gas migrating out of the basin. These submarine channel and fan deposits are similar to those of the middle Frio Hackberry Embayment (Tyler and Reistiffe, this volume) and other deep-water embayments that occur throughout the Tertiary of the Gulf Coast Basin. However, the middle Miocene and late Pliocene submarine pediments and onlap wedges had briefer histories and less relief, which resulted in thinner successions of deep-water sandstones.

In summary, submarine pediments are a unique type of unstable shelf-margin feature. They resemble submarine canyons on seismic profiles but are different in their size, morphology, origin and hydrocarbon exploration potential. Submarine pediments are wider than they are long, inscribe convex-landward arcs in plan view, and typically form along interdeltaic or nondeltaic shelf margins. They are initially created by retrogressive failure near the shelf edge, partly excavated by shelf and slope currents during periods of lowered sea level, and later filled by a combination of slope aggradation and subsequent shelf margin progradation. Thus, they do not fit the standard morphological or genetic definition of a deep, relatively narrow incised valley/canyon formed at the shelf margin by entrenchment of a major river system. Landward pediment extent is commonly controlled by shelf gradient and contemporaneous faults. Pediment length is greatest across broad, low-gradient shelves and least along steep gradients such as the paleomargin and basinward of delta systems.

A broad, thick zone of irregular seismic reflections (disturbed sediments) identify the submarine pediment and depositional apron on seismic lines. Seismic reflections are discontinuous, have highly variable dips and amplitudes, and are not arranged in simple geometric patterns. Predominant reflections are mostly landward-dipping, mounded, hummocky, or chaotic in the deepest and most seaward part of the onlap wedge. Together these reflections are similar to channel-fill patterns. Overlying but subordinate reflections are sub-horizontal or wavy and seaward-dipping. The disconnected hummocky and chaotic patterns suggest disorganized mass movement and redeposition of sediment derived from the shelf and slope, whereas the other reflection attitudes indicate original depositional surfaces.

The pediment fill forms a basinward-thickening wedge that becomes obscure beneath the shadow zone of major extensional faults near the paleoshelf margin. The lowermost part of the wedge is composed of a thick section of mudstone deposited in upper slope and lower slope environments. Lithologies of the middle to upper part of the onlap wedge are more variable and may be composed of either mudstone or interbedded mudstone and sandstone. Most sandstones within the pediment fill are highly discontinuous. These predominantly slope sediments contain foraminiferal assemblages that are indicative of outer shelf to lower slope environments. The deep-water sediments were deposited within the embayment by slumping and as small submarine fans emanating from restricted channels. Unconfined basinfloor fans deposited seaward of the pediment are also mud-rich but contain substantial quantities of reservoir-quality sandstone concentrated within dip-oriented feeder systems.

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