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UNSTABLE PROGRADATIONAL CLASTIC SHELF MARGINS

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ABSTRACT

In some continental margin basins such as the northwestern Gulf of Mexico and the Niger Delta, large-scale slumping of the continental slope disturbs the topset-foreset geometry of the prograding shelf margin and thereby inhibits recognition of ancient shelfedges. As a result, concepts of shelf-margin dynamics have been underemphasized in explaining the structure and stratigraphy of such basins. Nonetheless, ancient unstable clastic shelf margins can be approximately located by criteria such as isopach maxima, timing of growth faulting, and the stratigraphic top of geopressure.

Gravity sliding of the continental slope creates a strongly extensional regime along the shelf margin, resulting in growth faulting and greatly enhanced subsidence rates. The corresponding compressional regime along the lower slope is important in initiating salt and shale structures; if the shelf margin progrades over these structures, diapiric activity can greatly complicate the style of growth faulting. High subsidence rates result in greatly expanded progradational cycles, which serve to distinguish shelf-margin deltaic sequences from deltas of the more stable shelf platform. Rapid fault movement along the shelf margin can hydraulically isolate shallow-water sandstones and juxtapose them against dewatering slope shales, thus allowing the development and maintenance of excess fluid pressure. These deep-water shales are probably a major source of both hydrocarbons and brines instrumental in diagenesis of geopressured deltaic sandstones.

INTRODUCTION

During the past two decades, a wealth of information has been acquired about the growth-faulted shelf margin of the northwestern Gulf of Mexico, primarily in the form of seismic reflection profiles. However, concepts of shelf-margin dynamics have not been applied widely to the interpretation of ancient analogs in the same basin, in contrast to the extensive application of models of deltaic sedimentation. For example, while numerous publications have mapped the distribution of various Tertiary and Cretaceous deltaic systems in the northwestern Gulf Basin, only a few generalized maps have been published of corresponding shelfedges (Hardin and Hardin, 1961; Woodbury et al., 1973; Martin, 1978). On the other hand, dynamics of shelf margins are closely related to principles of subsidence, growth faulting, diapirism, and excess fluid pressure (geopressure), subjects that have been discussed extensively in the literature. The main purpose of this paper is to review these subjects by using the unstable shelf margin as a unifying model and to speculate on possible implications of the model.

In the northwestern Gulf, the continental slope is a realm of gravity-driven sliding, slumping, and sediment transport on a wide range of scales, while the continental shelf is a realm of shallow-water deposition with a strong deltaic influence. The shelf margin represents the interface between these two realms, where the interaction between gravity-sliding and shallow-water sedimentation creates a unique association of structure and stratigraphy. Similar principles should apply to other continental margin clastic systems dominated by gravity tectonics, including the Niger Delta (Weber, 1971; Evamy et al., 1978; Girard, 1979), the MacKenzie Delta (Dailly, 1976; Lane and Jackson, 1980), the Baram Delta of eastern Malaysia (Scherer, 1980; Bol and van Hoorn, 1980), the Nile Delta (Ayout, 1980) and the adjacent continental slope of Sinai (Ben-Avrahim and Mart, 1981) and Israel (Almagor and Wiseman, 1977; Garfunkel et al., 1979), the Amazon Cone (Huff, 1980), and continental margin basins of West Africa (Todd and Mitchum, 1977) and Brazil (Brown and Fisher, 1977).

CLASSIFICATION OF CLASTIC SHELF MARGINS

Sedimentary sequences on continental margins can be classified according to shelf margin migration, i.e., prograding, aggrading, or retreating (Fig. 1). This classification reflects the rate of sediment influx relative to subsidence, and the apportionment of sediment to deep-water (slope) and shallow-water (shelf) facies. In the case of progradational clastic shelf margins an additional subdivision is useful, based on gravitational stability. In the unstable case, large-scale slumping of the continental slope disrupts the original depositional geometry. This phenomenon can generate local subsidence rates along the shelf margin much greater than the regional rate and greater than would be possible for

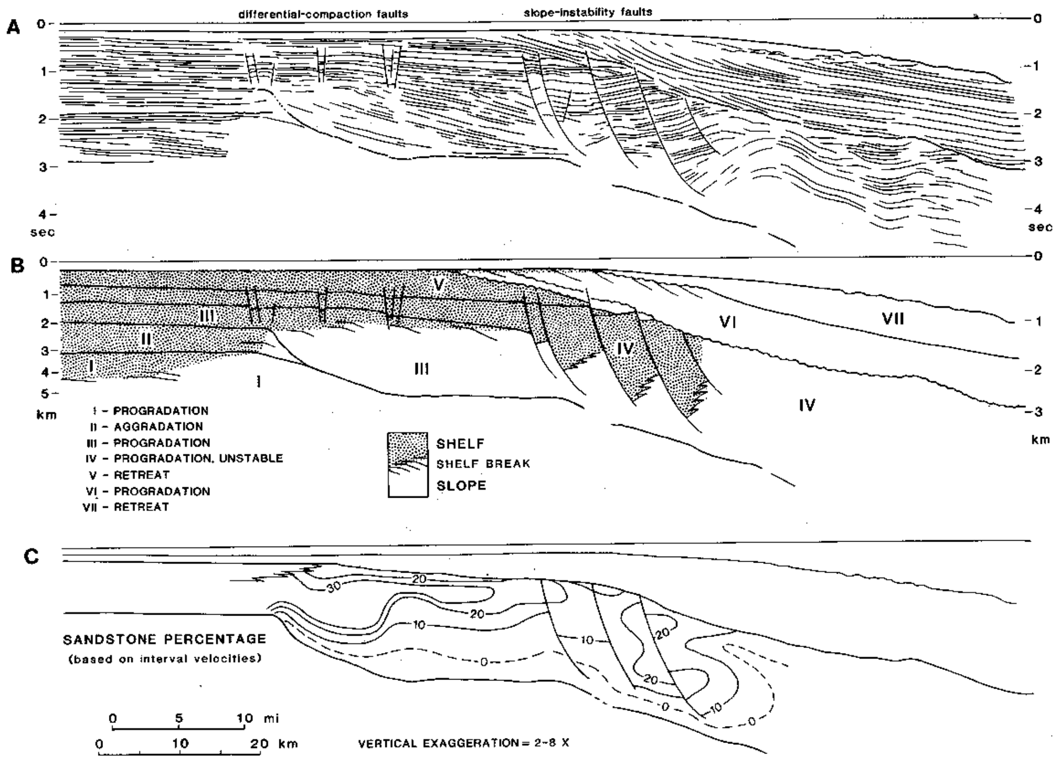


FIG. 1.—Interpretation of a seismic dip section from offshore West Africa (for original section, see Todd and Mitchum, 1977, their Fig. 9). *A*, Tracing of reflectors and interpreted faults. Faults generated by gravitational instability of slope are listric, and predominantly down-to-basin, and associated with contemporaneous compressional structures downdip. Faults generated by differential compaction of high-shale section (Sequence III) over carbonate bank and slope (Sequence II) are higher-angle, more symmetrically distributed, and not listric; displacement decreases to zero at depth. *B*, Interpretation of shelf and slope facies and classification of seismic sequences according to migration of the shelfedge. Exact position of shelfedge in growth-faulted sequence is speculative. Sequence IV demonstrates the initiation phase of unstable progradation, juxtaposing shallow-water sandstones against deep-water shale. Progradation did not proceed far enough for diapir-override phase (compare with Fig. 6 where diapir-override is well developed). Also compare with interpretation by Mitchum and Vail, (1977, their Fig. 3). *C*, Sandstone percentage (after Gralka et al., 1980), reflects high subsidence rate and rapid accumulation of shallow-water sediments deposited near the shelf margin. Net-sandstone map of Sequence IV would show major thickening across growth faults; percent-sandstone map should more accurately depict deltaic lobes (compare with Fig. 9).

a stable progradational margin. Consequently, in unstable progradational systems (unlike stable systems), sediments deposited near the shelf margin are a volumetrically substantial part of the total basin-fill and can be considered as a distinct megafacies. A seismic section from offshore West Africa (Fig. 1) illustrates the application of this classification scheme to seismic sequences and the contrasting geometry of stable and unstable prograding system. The potential for accumulation of great thicknesses of shallow water sediments in a short period of time is clearly evident.

RECOGNITION OF ANCIENT UNSTABLE SHELF MARGINS

Disturbance of the large-scale geometry of shelf topsets and slope foresets inhibits recognition of ancient unstable shelfedges by seismic stratigraphy or well-log correlation. Primarily for this reason, little mention has been made of them in the literature on such basins as the Gulf of Mexico and Niger Delta. However, it has been widely recognized that: (1) these basins have been filled by offlapping depocenters migrating basinward (Wilhelm and Ewing, 1972; Antoine et al., 1974; Martin, 1978; Evamy et al., 1978; Weber, 1971); (2) the timing of maximum activity of regional contemporaneous faults becomes progressively later in a basinward direction (Thorsen, 1963; Dailly, 1976; Evamy et al., 1978); and (3) the stratigraphic top of geopressure also becomes progressively younger basinward (Dickinson, 1953; Harkins and Baugher, 1969; Stuart, 1970). These phenomena are related to progradation of the shelf margin and can provide alternate criteria for shelf margin recognition when more conventional criteria such as clinoform stratification, sedimentary structures, and faunal assemblages cannot be used due to inadequate or ambiguous data (Table 1).

Not surprisingly, there is a trade-off between accuracy of locating the shelfbreak and availability of the necessary data. Therefore, the less precise criteria tend to be more useful for regional mapping (Fig. 2), although they may be inappropriate for prospect-scale mapping. Along the modern shelf margin (Fig. 3), maximum displacements, expansion ratios of growth faults, and maximum thicknesses of progradational deltaic sequences typically occur within a few miles of the shelfbreak (Lehner, 1969). Harkins and Baugher (1969) demonstrated a close correspondence, with a similar degree of precision, between the shelfbreak and the updip limit of geopressure in the Miocene *Bigenerina* 'A' zone, offshore Louisiana. Weaver (1955) proposed that a flexure, defined as a change in regional dip and an increase in the rate of basinward thickening, represents the paleo-shelfbreak, although our experience is that the flexure usually occurs several miles updip of the corresponding shelfbreak.

Using these criteria, it is possible to map regional shelf margin trends of the northwestern Gulf of Mexico (Fig. 2) and the Niger Delta, primarily on the basis of published studies and data. Although

TABLE 1.—CRITERIA FOR LOCATING ANCIENT SHELF EDGES IN UNSTABLE PROGRADATIONAL SYSTEMS

	Criterion	Principle	Observed in: Quaternary	Ancient	Figure and Literature References	Comments
(Most Precise)	Topset-foreset geometry	Stratification represents depositional relief of shelf and slope	X		Figs. 1, 3, C–F	Usually obscured by contemporaneous structural growth; below resolution of conventional seismic reflection data
	Lithofacies	Turbidites (sandstones) and disrupted, chaotic bedding (shales) characterize slope sediments	X	X	Berg, 1981	Ancient slope sediments seldom cored in this type of basin; "deep-water" sedimentary structures may occur in fairly shallow water
	Microfaunal assemblages	Neritic-bathyal transition marks shelfbreak	X	X	Woodbury et al., 1978; Stude, 1978; Biel & Buck, 1978	Faunas can mix and interfinger; neritic fauna may be reworked into slope sediments; species may change environmental range with time; disagreement among paleontologists
	Isopach maximum	Maximum sedimentation and subsidence rates occur at the shelfbreak	X	X	Fig. 3; Woodbury et al., 1973; Poag & Valentine, 1976	Usually insufficient downdip data to see thinning basinward of shelfbreak
	Maximum rate of growth faulting	Maximum extension rate and growth ratios occur at shelfbreak	X	X	Fig. 3; Lehner, 1969; Thorsen, 1963	Usually insufficient deep data to observe pre-maximum fault growth
(Least Precise)	Stratigraphic top of geopressure	Geopressure results from hydraulic isolation of shallow-water sandstones faulted against older slope shales		X	Fig. 5; Harkins & Baugher, 1969; Dickinson, 1953	Relationship fairly circumstantial and poorly documented, but can be used in areas of very sparse data (mud bights and paleo-tops)
	"Flexure"	Sharp increase in regional dip marks relict shelfedge		X	Weaver, 1955; Hardin & Hardin, 1961	In subsurface, "flexure" usually occurs several miles updip of shelf break; may be poorly defined

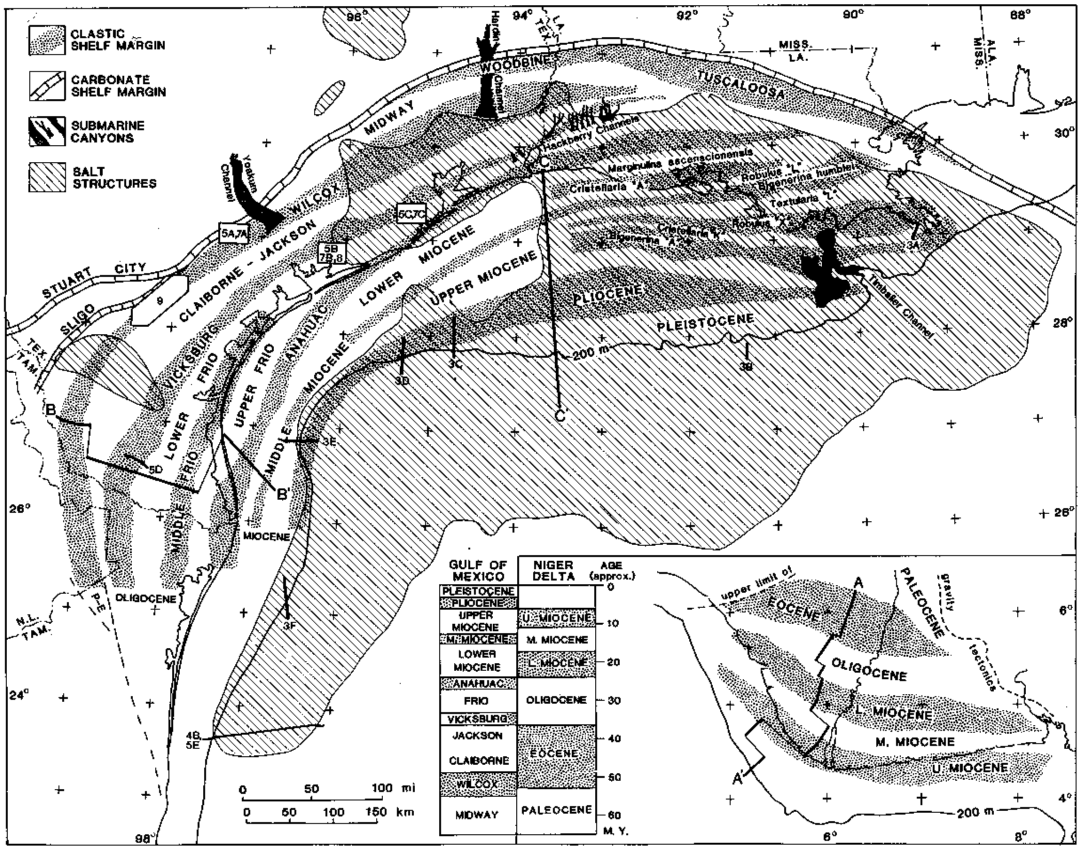


FIG. 2.—Regional shelf margin trends of the northwestern Gulf of Mexico and Niger Delta, based on isopach maxima, flexures (particularly in Niger Delta), timing of maximum growth-fault activity (particularly in Texas and northeast Mexico), and stratigraphic top of geopressure (particularly in Louisiana). Where necessary, shelf margin trends are extrapolated along regional growth-fault trends (particularly in Niger Delta). In Gulf Basin, Midway and Woodbine represent stable progradation; all other clastic sequences represent unstable progradation. Ages of submarine canyons are: Yoakum and Hardin, mid-Wilcox; Hackberry, mid-Frio; Timbalier, Pleistocene. Gulf Basin exhibits major shifts in progradation rates, whereas Niger Delta exhibits fairly steady progradation. Time scales and correlations between basins are approximate. (Based on Bebout et al., 1979; Busch, 1973, 1975; Christina and Martin, 1979; Dailly, 1976; Dickinson, 1953; Edwards, 1980, 1981; Evamy et al., 1978; Foss, 1979; Girard, 1979; Gregory, 1966; Hardin and Hardin, 1961; Harkins and Baugher, 1969; Hickey et al., 1972; Hoyt, 1959; Jones, 1975; Khan et al., 1975a, 1975b; Martin, 1978, 1980; Paine, 1968; Poag and Valentine, 1976; Thorsen, 1963; Woodbury et al., 1973, 1978; file data at University of Texas, Bureau of Economic Geology).

FIG. 3.—Dip sections of Quaternary shelf margin and vicinity, northwestern Gulf of Mexico. Locations of sections are shown in Fig. 2. *A*, Sand geometry typical of growth-faulted Tertiary deltas (compare section AA′, Fig. 8) as observed in the modern Mississippi Delta. The modern Mississippi has not yet reached the shelfedge, but is closer to a true shelf margin delta than other Holocene models (after Friedman and Sanders, 1978, based on data from J. M. Coleman). *B*, Mixing and interfingering of shallow-water and deep-water fauna near present shelfedge may reflect downslope reworking of shallow-water fauna or oscillation of shelfbreak over several miles (after Woodbury and others, 1978). *C*, Tracing of a mini-sparker profile of late Pleistocene shelf margin delta (after Winker, 1980). *D–F*, Tracings of sparker profiles (KANE survey) of shelf margin deltas formed during late Pleistocene low-stands of sea-level. Note close association in most cases of shelfbreak with isopach maxima of time-stratigraphic units, maximum rate of fault movement, maximum thickness of progradational cycles, and maximum steepness of clinoforms. Section F is a rare example of a modern system cut by predominantly up-to-basin ("counterregional") faults (compare with Fig. 6). Depth conversion: 1 second = 2500–3000 ft.

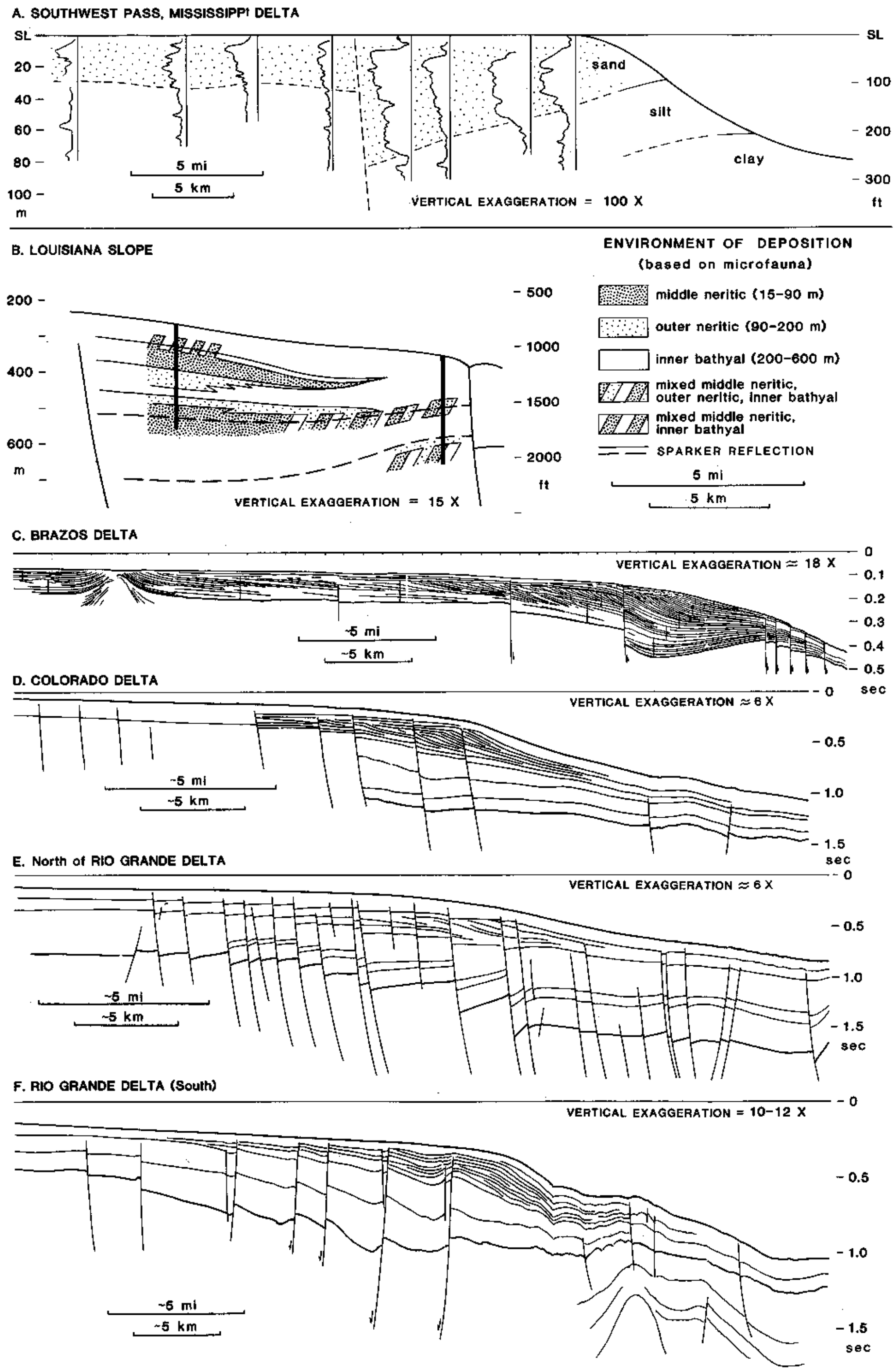

A. SOUTHWEST PASS, MISSISSIPPI DELTA
SL
20
40
60
80
100
m
sand
silt
clay
5 mi
5 km
VERTICAL EXAGGERATION = 100 X
100
200
300
ft
B. LOUISIANA SLOPE
200
400
600
m
500
1000
1500
2000
ft
VERTICAL EXAGGERATION = 15 X
ENVIRONMENT OF DEPOSITION
(based on microfauna)
middle neritic (15-90 m)
outer neritic (90-200 m)
inner bathyal (200-600 m)
mixed middle neritic, outer neritic, inner bathyal
mixed middle neritic, inner bathyal
SPARKER REFLECTION
5 mi
5 km
C. BRAZOS DELTA
VERTICAL EXAGGERATION ≈ 18 X
~5 mi
~5 km
0
0.1
0.2
0.3
0.4
0.5
sec
D. COLORADO DELTA
VERTICAL EXAGGERATION ≈ 6 X
~5 mi
~5 km
0
0.5
1.0
1.5
sec
E. North of RIO GRANDE DELTA
VERTICAL EXAGGERATION ≈ 6 X
~5 mi
~5 km
0
0.5
1.0
1.5
sec
F. RIO GRANDE DELTA (South)
VERTICAL EXAGGERATION = 10-12 X
~5 mi
~5 km
0
0.5
1.0
1.5
sec

TABLE 2.—PROPOSED MECHANISMS FOR GULF COAST STYLE GROWTH FAULTING

Mechanism	References	Comments
Slope instability; gravitational creep	Rettger, 1935 Bornhauser, 1958 Cloos, 1968 Bruce, 1973 Crans et al., 1980	Difficult to document in ancient record because paleobathymetric relief and toe structures not well preserved
Sand loading on shale	Bruce, 1973	Does not explain growth faulting in all-shale sequences, or occurrence of toe structures far downdip of sand pinchout; may be important positive-feedback mechanism in some cases
Differential compaction	Carver, 1968 Bruce, 1973	Does not account for large extensional component or listric geometry; may cause faulting in some cases (Fig. 1)
Uplift of salt or shale ridges	Quarles, 1953 Ocamb, 1961	Does not account for asymmetry (predominantly down-to-basin) of most growth-fault systems; does not predict large extensional component of major faults; useful in explaining crestal and up-to-basin faults (Fig. 3F, 6)

these maps are too generalized for locating ancient shelfbreaks in prospect-scale work, they do reveal major changes in the rate of sediment influx. For example, they reveal major shifts in depocenters in the Gulf of Mexico in contrast to the regular progradation of a single depocenter in the Niger Delta.

STRUCTURAL MECHANISMS

In order to explain the circumstantial relationship of structural geometry to the shelf margin, it is useful to consider the mechanisms of growth faulting. Although a number of mechanisms have been proposed (Table 2), large-scale slope instability (also referred to as sliding, slumping, or creep) best explains the following features of regional growth-fault systems: (1) asymmetry (predominantly down-to-basin); (2) listric geometry, rollover, and large extensional component, all indicative of decollement; (3) contemporaneous faulting in all-shale sequences; and (4) localization of maximum extension rates along the contemporaneous shelf margin. Faults attributable to differential compaction (Fig. 1) or diapiric uplift have distinctly different geometries.

Slope instability involves three overlapping regimes: *translation* of the slope over a decollement surface or zone; *extension* along the top of the slope; and *compression* along the lower slope. Typical structural styles associated with these regimes are evident on seismic sections of the continental slope off northeastern Mexico (Fig. 4). Infinite-slope analysis, which deals with the translational regime, has been successfully applied to shallow-seated submarine slope failures (Prior and Suhayda, 1979; Almagor and Wiseman, 1977; Watkins and Kraft, 1979). A major implication of this analysis is the role of pore pressure in reducing effective stress, thus permitting failure of very low slopes (approximately 1°) typical of the continental slope of the northwestern Gulf. Similar analysis can be applied to larger-scale slope instability, but with qualifications:

1. The slope cannot be assumed to be infinitely long; buttressing effects at the toe are probably important.
2. Slumping does not occur as a single instantaneous failure, as predicted by infinite-slope analysis, but rather as a slow creep which is continuously active for millions of years. This suggests that the decollement is not a discrete surface of brittle failure but rather a zone of ductile or viscous deformation (Kehle, 1970).
3. Superimposed effects of "diapiric" structures driven by density inversion are not taken into account.

STRUCTURAL EVOLUTION

Regional Scale

Structural evolution can be considered on two scales: first, the regional evolution of shelf margin structural styles as the slope progrades into the basin, and second, the local evolution of structural styles as a specific area evolves from a slope environment to a shelf margin environment and finally a stable platform environment. On a regional scale, three phases can potentially develop if sufficient progradation takes place.

1. A *stable phase* is characterized by preservation of slope clinoforms (Figs. 1, 5A). In the Gulf Basin this phase is represented by the Woodbine (Upper Cretaceous) and Midway (Paleocene) trends (Fig. 2).
2. An *initiation phase* is characterized by closely and evenly spaced down-to-basin regional faults, usually without the complication of contemporaneous diapirs (Figs. 1, 5A, 6). In the Gulf Basin, this phase is represented by the Tuscaloosa (Upper

Cretaceous) and Wilcox (Paleocene-Eocene) trends (Fig. 2). Thrust faults and ridges or domes cored by salt or shale originate along the lower slope as compressional structures (Watkins and others, 1978; Buffler et al., 1979; Humphris, 1979).

3. A *diapir-override phase* begins when the shelf margin progrades over shale or salt domes formed during the initiation phase. This phase is represented by the Frio and younger trends in the Gulf of Mexico and post-Eocene trends in the Niger Delta (Fig. 6), but did not develop in the West Africa example because of insufficient progradation (Fig. 1).

The principal characteristic of the diapir-override phase is increasing structural complexity, caused by the interaction of regional horizontal extension and local uplifts. Previously formed diapirs tend to control the position of growth faults and thus cause more complex (strongly sinuous or arcuate) fault patterns in plan view than the evenly-spaced, subparallel patterns which typify the initiation phase. Crestal faults tend to develop over diapirs, and up-to-basin faults commonly develop on the landward side of shale ridges. Up-to-basin faults (Figs. 3F, 6) may be essentially symmetrical with down-to-basin faults ("back-to-back" faults of Evamy et al., 1978), or they may be the major structure-forming faults ("counter-regional" faults of Evamy et al., 1978; also see Spindler, 1977). As a general rule, the complexity and variety of shelf margin structural styles increases as progradation proceeds into the basin and increasingly mobile diapirs are overridden; a great variety of styles can be observed along modern unstable margins (Figs. 3, 4).

Local Scale

On a local scale, structural evolution can be reconstructed with a series of isopach maps if the appropriate paleobathymetric corrections are made. In the case of shallow water deposition where depositional relief is much less than the magnitude of contemporaneous structural relief, these corrections are not necessary for a first approximation (Fig. 7).

The first stage of local structural evolution, the compressional regime (Fig. 3), cannot usually be reconstructed because later deformation severely

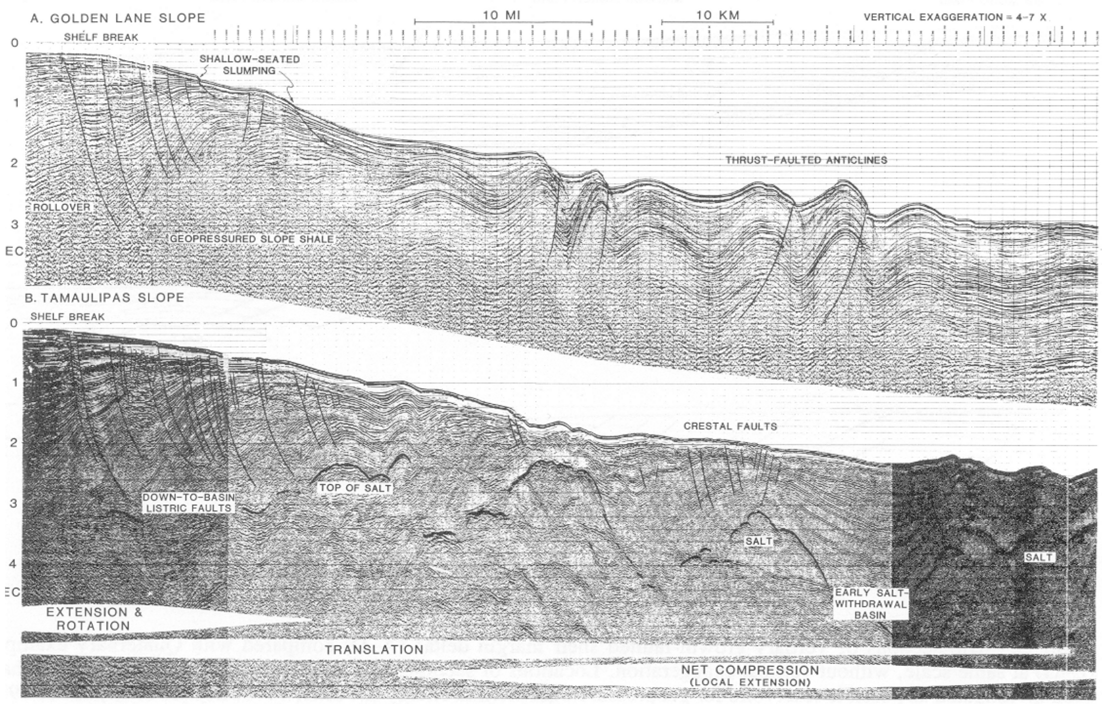


FIG. 4.—Seismic dip sections of the continental slope, western Gulf of Mexico (for original sections, see Watkins et al., 1976; Buffler et al., 1979). Sections illustrate origin of contemporaneous structures through deep-seated slumping of continental slope. Growth faults originate in tensional regime along top of slope; decollement is in undercompacted shale (A) or salt (B). Ridges cored by shale (A) or salt (B) originate in compressional regime along lower slope. These ridges may evolve into diapirs as shelf margin progrades over them. Most of the compression is probably accommodated by thrust faulting (which is rarely seen due to poor seismic penetration through salt and shale structures) rather than by folding. Location of section B is shown in Fig. 2. Approximate depth conversion: 1 sec = 2500 to 3500 ft.

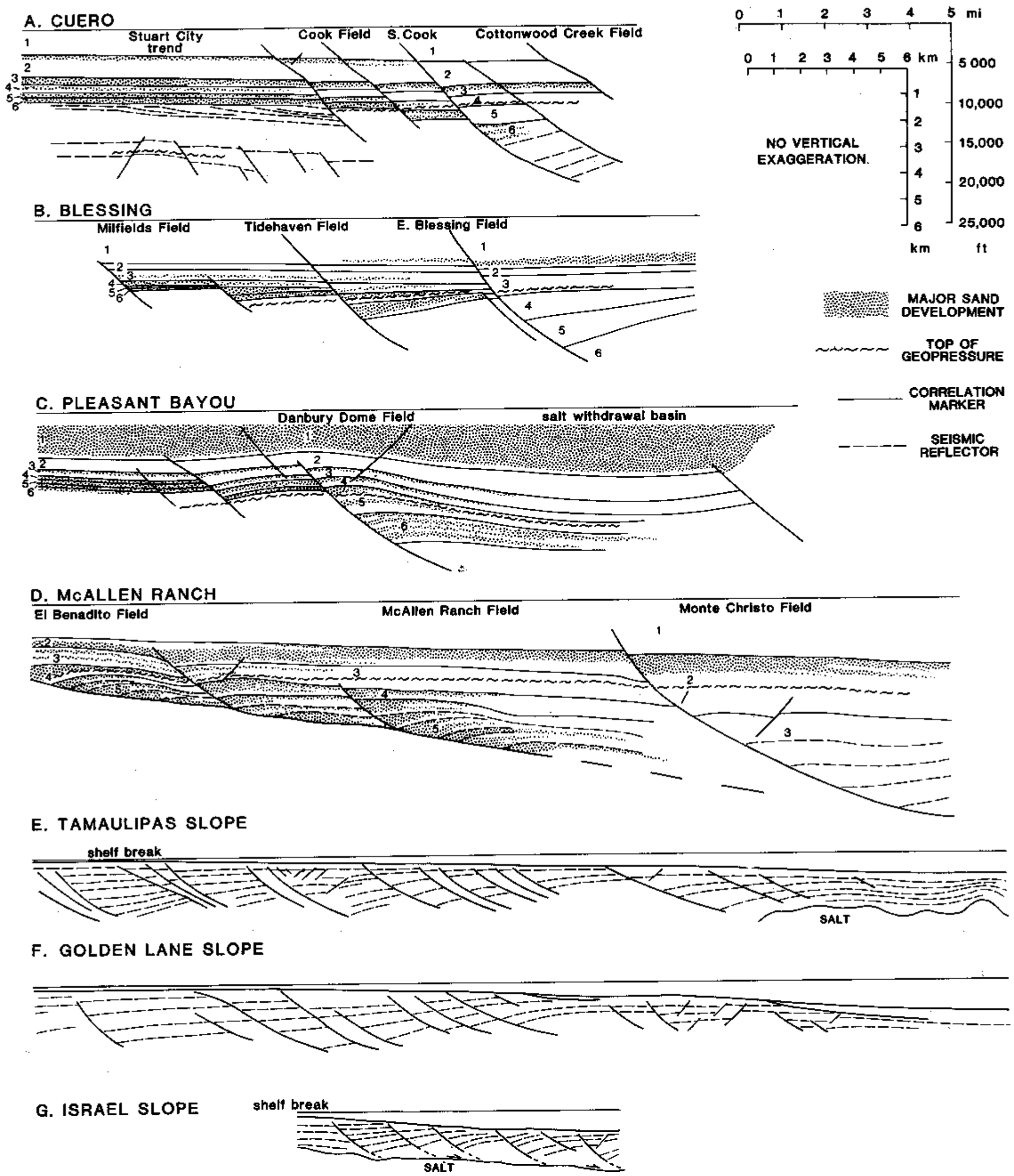


FIG. 5.—Dip sections of Tertiary growth-faulted shelf margin deltas (A–D) compared with Quaternary examples (E–G) at same scale, without vertical exaggeration. Locations of sections A–E are shown in Fig. 2. Areas A–D have been investigated as possible reservoirs for geopressured geothermal energy (Loucks, 1978; Bebout et al., 1978, 1979; Winker et al., 1981a, 1981b). Numbers in sections A–C correspond to isopach units in Fig. 7; highest numbered units are believed to represent deltaic sequences deposited closest to shelfedge; only these sequences are geopressured. In each case, geopressured sandstones are bounded landward by major growth faults, basinward by pinch outs, and above by transgressive shale wedges or sand-shale sequences. *A*, Transition from stable progradation, with clinoform stratification (Midway, immediately below unit 6) to initiation phase of unstable progradation (Lower Wilcox, unit 6). *B*, Fault spacing, rollover, and growth ratios for Frio trend are typically greater than for Wilcox trend. *C*, Diapir-override phase with late growth of Danbury salt dome. *D*, Shallow decollement is typical of Vicksburg trend in south Texas (Berg et al., 1979; Ashford, 1972). *E–G*, Analogous structures in modern upper-slope settings, interpreted from seismic sections. (E and F are based on section in Fig. 4; G is based on Garfunkel et al., 1979).

disturbs the early structures, because the lower-slope deposits are not usually penetrated by drilling, and because they are usually seismically transparent or absorbent. Consequently, the initiation of salt and shale structures is difficult to understand without studying modern examples (Lehner, 1969; Humphris, 1979; Buffler et al., 1979).

In contrast, the second stage, or extensional regime, is well known in the ancient record, and an extensive literature exists on the subject of growth faults (Table 2). The typical style is down-to-basin contemporaneous listric faults with "rollover" (reversal of dip from regional trend). In the absence of time-calibration of stratigraphy, relative rates of fault growth can be quantified by the *growth ratio* or *expansion index,* defined as the ratio of the downthrown thickness to upthrown thickness (Thorsen, 1963). With most growth faults, the largest growth ratios are observed in the deepest structures penetrated and decline steadily up-section (Fig. 7).

The final stage of local structural evolution is that of platform-style deposition, still within an extensional regime but a much weaker one. Most growth faults continue to move, but at a much-reduced rate (Fig. 7). This slower movement is still sufficient in many cases to create structural closure, however, even with simultaneous regional basinward tilting (Fig. 7A and B). Growth of salt structures (domes and withdrawal basins) is most apparent during this stage. In the case of salt tectonics, the structures formed during platform-style deposition may be entirely different from those formed near the shelf margin, as in the Frio trend of Brazoria County, Texas (Fig. 7C).

Shelf Margin Deltas

Attempts to develop models of deltaic sedimentation at the shelf margin are hampered by a lack of modern analogs, with the arguable exception of the modern lobe of the Mississippi Delta (Fig. 3A). Even this model does not explain many of the features observed in Tertiary deltaic sequences believed to be formed at the shelf margin. To a large extent we are dependent on studies of late Pleistocene deposition during low stands of sealevel (Leh-

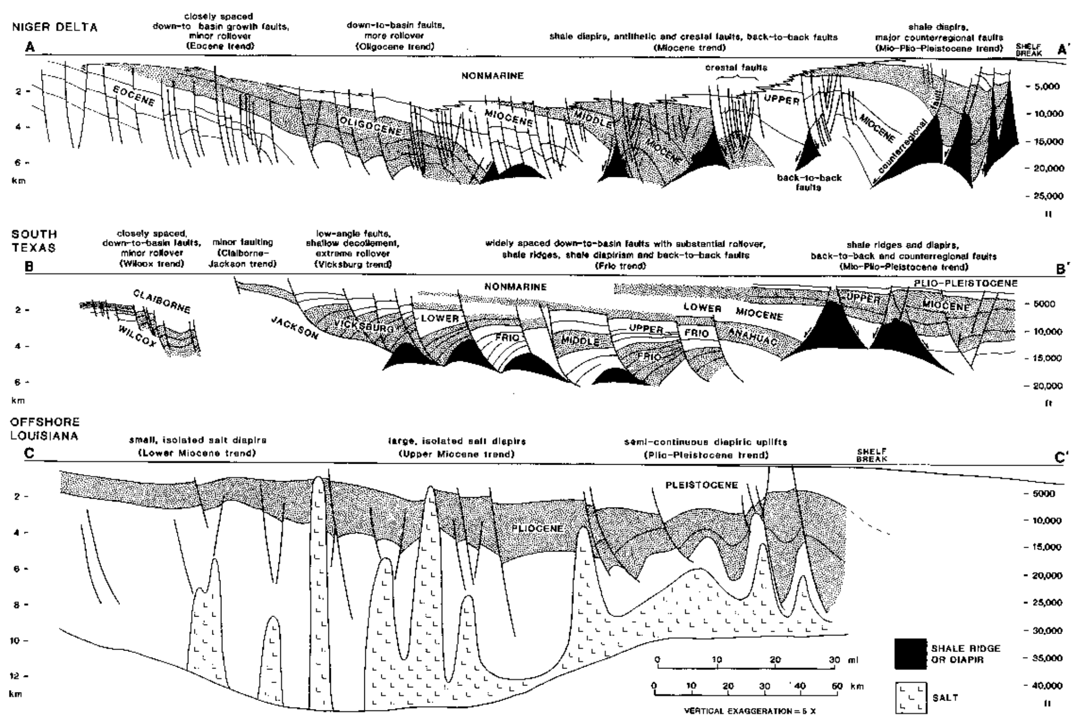


FIG. 6.—Generalized composite regional dip sections of northwestern Gulf of Mexico and Niger Delta, illustrating progressive changes in structural style associated with progradation of shelf margin (after Bebout et al., 1979; Evamy et al., 1978; Jones, 1975; Khan et al., 1975a; Woodbury et al., 1973). Locations of sections shown in Fig. 2. For each time-stratigraphic unit, shallow-water sediments form a basinward-thickening wedge, shelf margin position corresponds with maximum thickness, and slope sediments are mobilized into diapirs or "sheath" around salt domes. Closely spaced down-to-basin faults are typical of the initiation phase of growth faulting; contemporaneous shale ridges presumably formed approximately 50 mi downdip along the lower slope and were later overridden.

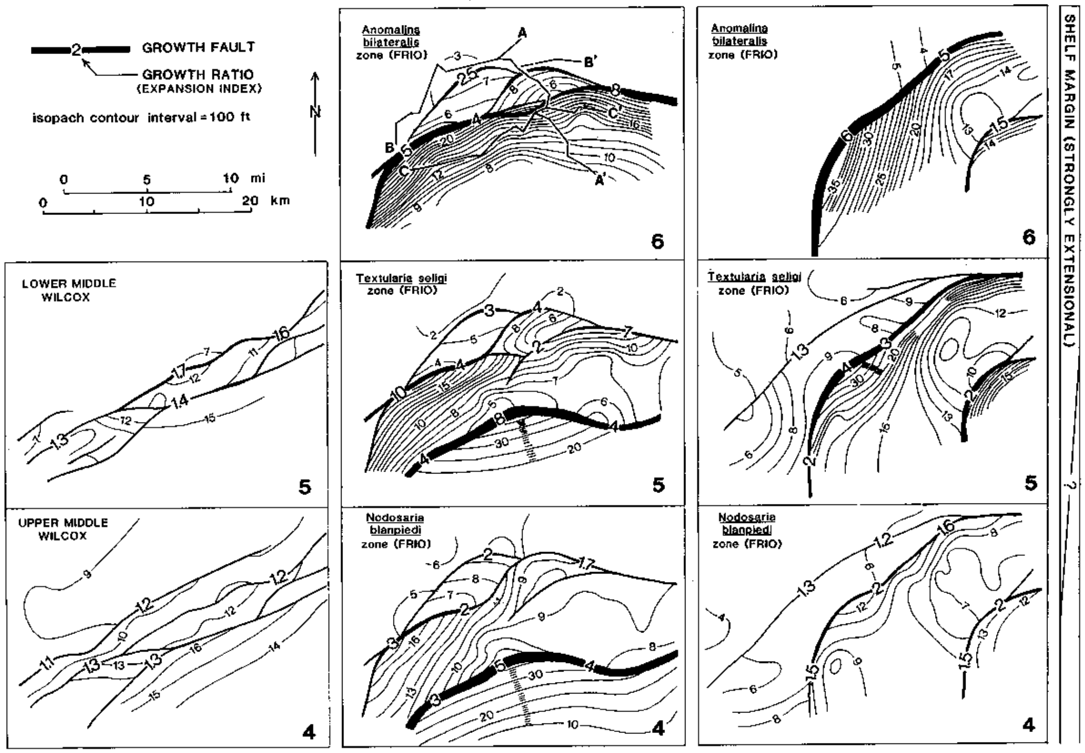


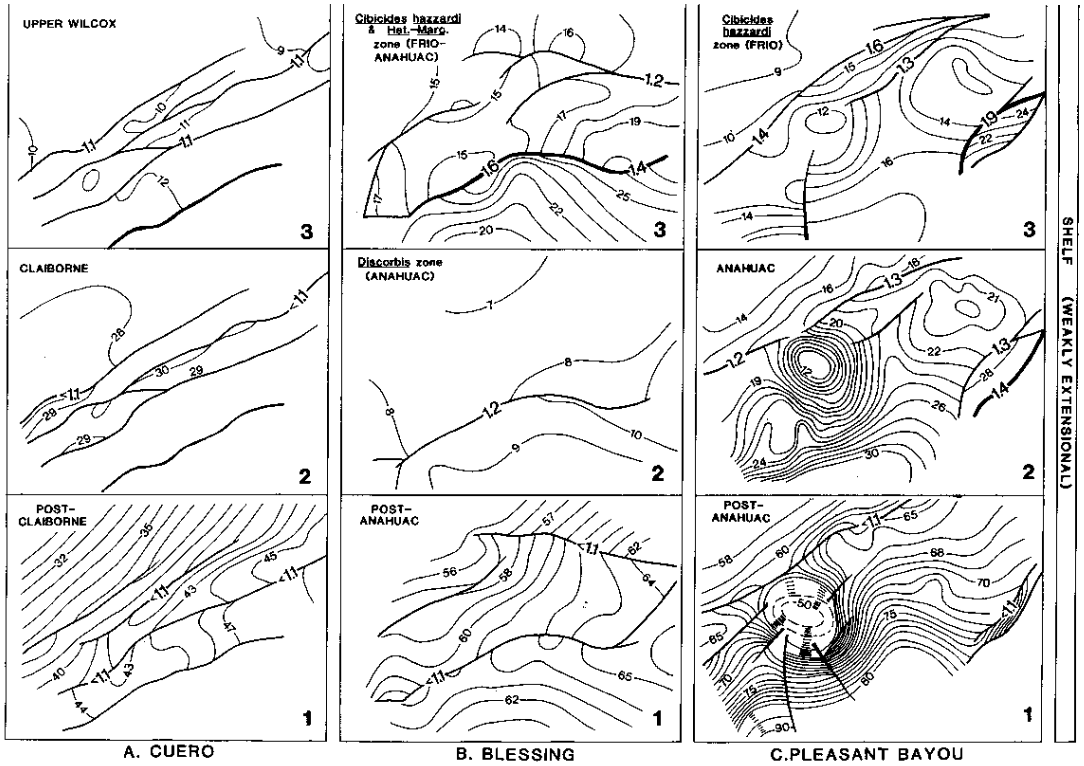
FIG. 7.—Structural evolution of three shelf margin deltaic sequences in Texas Gulf Coast Basin illustrated by successive isopach maps. Locations are shown in Fig. 2; dip sections of same areas are shown in Fig. 5; stratigraphic sections of Blessing area, unit 6, are shown in Fig. 8. Contour values × 100 ft. Shelf margin structures are characterized by maximum growth ratios and rollover; transition to shelf deposition is characterized by steady decline in growth ratios. Late stage is characterized by basinward tilting (A, B), or growth of salt domes and withdrawal basins (C). Note that in the case of salt tectonics, late contemporaneous structures may be entirely different from the early structures. Structural evolution is discussed in greater detail by Winker et al. (1981a, b).

ner, 1969; Berryhill, 1978, 1980; Sidner et al., 1978; Tatum, 1979; Berryhill and Trippet, 1980). Those studies have been based primarily on high-resolution seismic data, with sparse well and core control. As a result, they are useful for predicting the overall geometry of depositional cycles but less so for lithology and depositional environment.

The most distinctive feature common to deltas at unstable shelf margins is the rapid rate of subsidence, attributable to at least four effects: (1) flexural depression of the crust due to sedimentary loading on an elastic (or viscoelastic) lithosphere by the prograding depocenter (Walcott, 1972); maximum subsidence corresponds to the center of the applied load, which generally occurs at the upper slope or shelfbreak (Woodbury et al., 1973; Stuart and Caughey, 1977); (2) rapid extension at the shelf margin due to listric normal faulting, previously discussed, which causes a net regional thinning of the sedimentary section above the decollement zone; the resultant subsidence is concentrated on the downthrown side of faults; (3) salt withdrawal which may locally enhance subsidence; and (4) compaction of the thick section of recently deposited underlying sediments (an amplification mechanism).

Effects of rapid subsidence are most apparent in the geometry of progradational cycles. Along the modern shelf margin on the northwestern Gulf of Mexico, individual deltaic cycles tend to be thicker at the shelfbreak than at the inner shelf or mid-shelf (Fig. 3C). Clinoform stratification observed in high-resolution seismic lines is typically steeper for shelf margin progradation than for inner-shelf progradation (Winker, 1980).

In ancient sequences in the subsurface, clinoform stratification on this scale is not generally perceptible, either from log correction or on conventional CDP seismic sections. Progradation is, however, manifested as upward-coarsening cycles and funnel-shaped patterns on electric logs (Asquith, 1970); these cycles can be readily correlated within fault



blocks (Fig. 8). Such upward-coarsening shale-to-sandstone sequences, associated with growth faults and inferred to represent delta-front deposits (of shelf margin deltas by our interpretation) have been described from major stratigraphic units of the Gulf Coast Tertiary Basin: Paleocene Lower Wilcox Group (Fisher and McGowen, 1967), Eocene Upper Wilcox (Edwards, 1980, 1981), Oligocene Vicksburg Group (Han, 1981) and Frio Formation (Galloway and others, in press), Miocene (Curtis, 1970), and Pleistocene (Caughey, 1975a, b). In Tertiary sequences of the Gulf Coast Basin, substantial thickness variation of individual cycles is commonly observed, particularly in the downdip Frio trend (Fig. 8). Expansion of cycles across faults can be as great as 10:1, although more typically the growth ratio is less than 2:1.

Where a time-stratigraphic unit expands substantially across growth fault, its electric-log character typically changes markedly and may cause serious correlation problems. In the simplest style, the vertical sequence is essentially the same on both sides of the fault but is proportionally expanded on the downthrown side. In this case, the lateral continuity of individual sandstones is similar on both sides of the fault, but the thickest sandstones are on the downthrown side. A common complication of this pattern is the appearance of subcycles on the downthrown side and the breakup of individual thick sandstones into numerous thin sandstones at large amounts of expansion. In extreme cases, the electric-log character may be entirely different on the upthrown and downthrown sides (Fig. 8), with thin, laterally discontinuous sandstones on the upthrown side and thick, laterally continuous sandstones on the downthrown side. Our hypothesis for this last pattern is that at low subsidence rates, shifting channels (fluvial, distributary, and tidal) rework much of the section, reducing lateral continuity and even obscuring individual progradational cycles. At very high subsidence rates, channel reworking is much less important volumetrically.

Although the effects of subsidence rate on vertical sequence are readily apparent (Fig. 8), the extent to which contemporaneous structures directly control shallow water environments is less clear. Most Quaternary growth faults in the Gulf of Mexico do not have obvious bathymetric expression on the shelf (Figs. 3, 4) in contrast to the continental slope, which is characterized by bathymetric expression of contemporaneous structures (Martin and Bouma, 1978). As a general rule, sediment

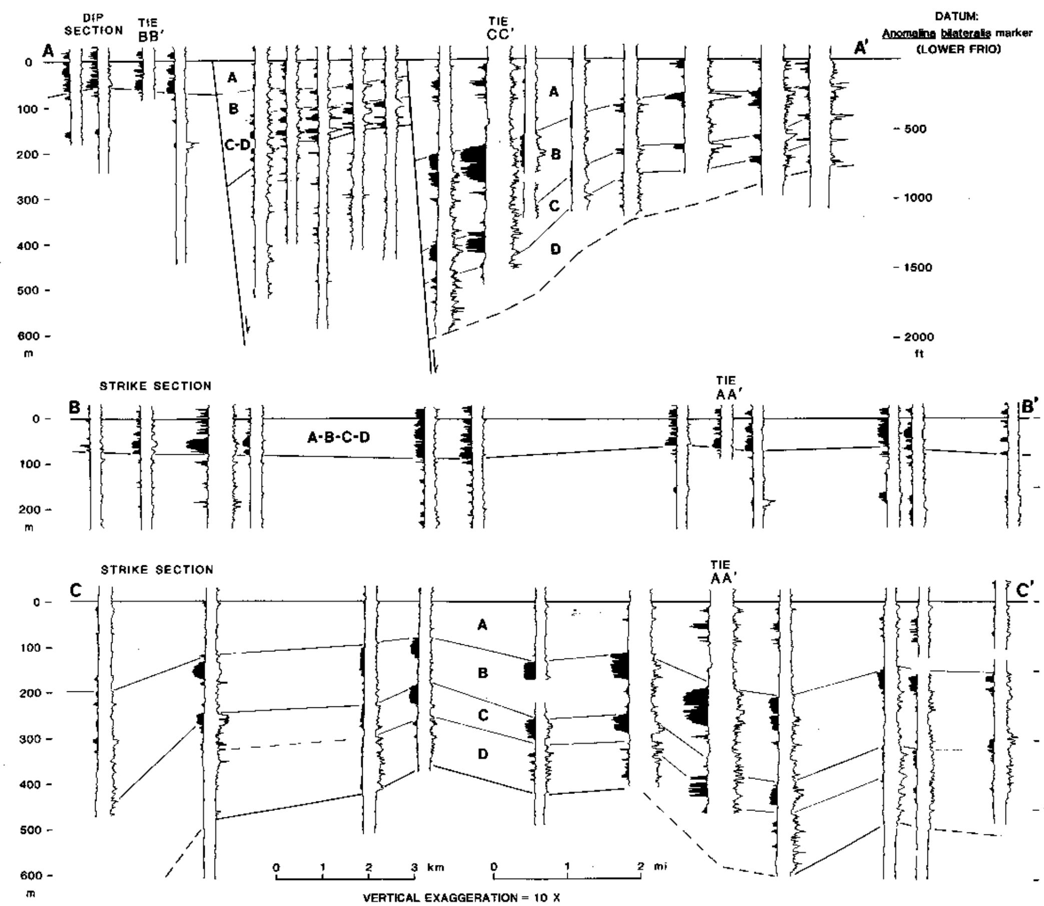
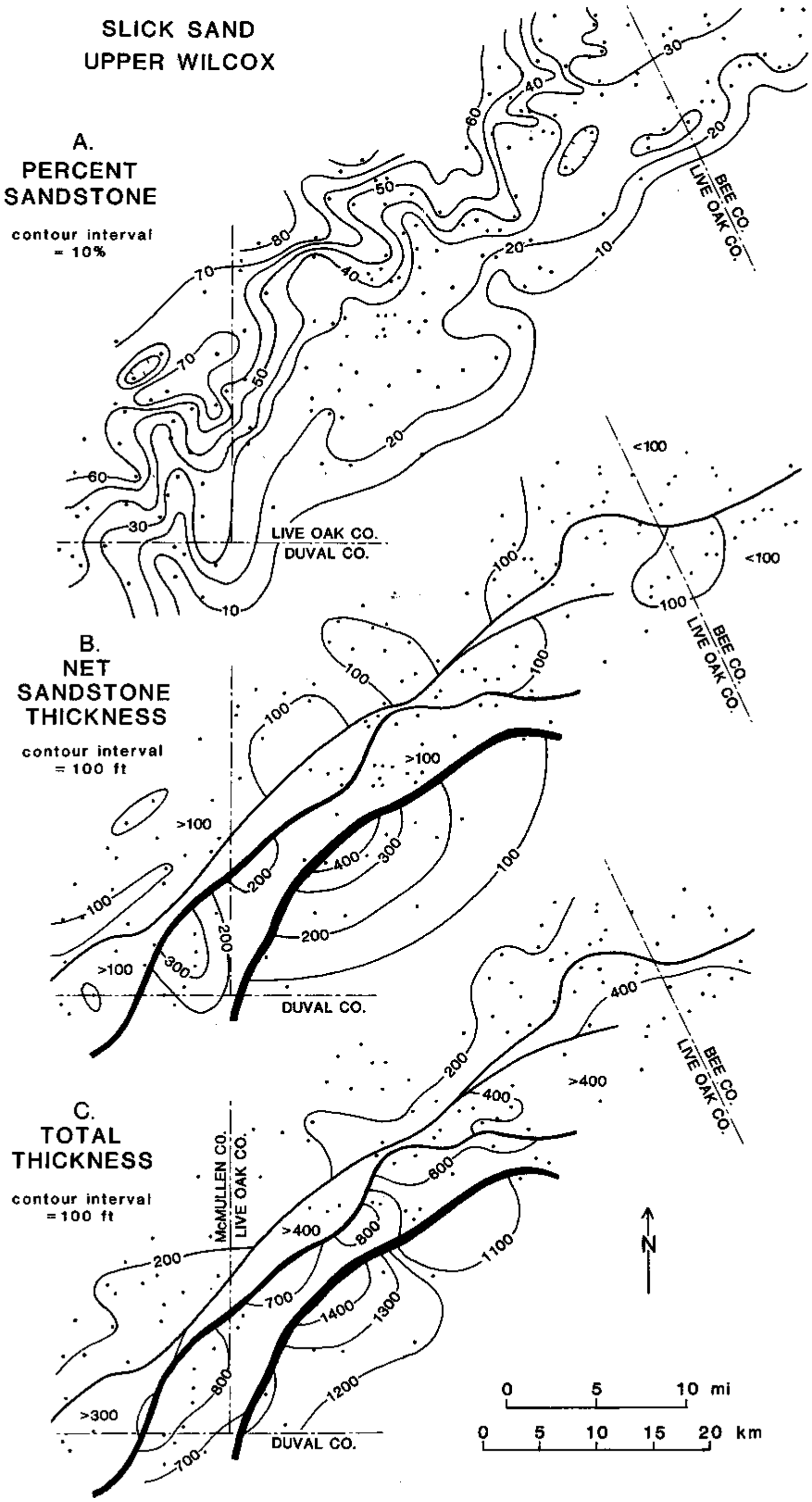


FIG. 8.—Stratigraphic sections of an Oligocene shelf margin delta, Blessing area, Matagorda County, Texas. Locations of sections are shown in Fig. 7B diagram 6; regional setting in Fig. 2. Differentiation of progradational cycles increases with subsidence rate, resulting in extreme changes of log character across growth faults. Where subsidence is slow, the sequence if probably dominated by channel reworking, resulting in lateral discontinuity of individual sandstones. Where subsidence is rapid, the sequence is dominated by alternating progradation and transgression, resulting in stacking of upward-coarsening cycles with better differentiation and greater continuity of individual sandstones. Compare with sand geometry in Fig. 3A, and progradational cycles in Fig. 3C.

supply to the shelf is sufficient to fill bathymetric irregularities as quickly as they are formed by structural growth. In ancient growth-faulted shelf-margin deltas, variations in subsidence rate appear to have influenced thickening of the progradational cycle and therefore caused lithologic variation related to preservation potential and reworking, but may not have been a major control on depositional environment.

On a regional scale the rapidly subsiding shelf margin acts as a major sediment trap permitting the accumulation of thousands of feet of shallow water deposits during a major regressive episode. With rapid slumping of the continental slope, translation of fault blocks is an important mechanism of mass transport into the deep basin, which could be expected to reduce relative importance of downslope sediment transport by other mechanisms such as

FIG. 9.—Sand distribution in plan view of an Eocene shelf margin delta, Texas coastal plain (after Edwards, 1980). Sandstone percentage (A) highlights deltaic lobes and provides prediction of down-dip pinch out. Net sandstone thickness (B) is strongly influenced by expansion of section across growth faults (C), resulting in patterns that would be difficult to interpret if faults were not recognized. Regional net-sandstone map shows an elongate strike-oriented high. Compare with Figs. 1C, 3A, and 8.


SLICK SAND
UPPER WILCOX
A.
PERCENT
SANDSTONE
contour interval
= 10%
B.
NET
SANDSTONE
THICKNESS
contour interval
= 100 ft
C.
TOTAL
THICKNESS
contour interval
=100 ft
BEE CO.
LIVE OAK CO.
LIVE OAK CO.
DUVAL CO.
McMULLEN CO.
N
0 5 10 mi
0 5 10 15 20 km

turbidity currents, mudflows, and shallow-seated slumps. Diapiric structures tend to create many small basins on the slope which trap sediment moving down the slope. As a result, the greatest sedimentation rates are generally found along the shelf margin, and regional isopach maps (Fig. 9C) for a particular time interval should depict the shelf margin as a strike-oriented depocenter or trough (Woodbury et al., 1973).

Maps of net sandstone thickness (Fig. 9B) for a particular time interval will show a similar pattern of regional strike-oriented maxima of sandstone thickness. To interpret depositional environments and to locate axes of fluvial sand input, maps of sand percentage (Fig. 9A) are more meaningful as they remove the element of differential subsidence and emphasize depositional control on lithofacies distribution.

GEOPRESSURE AND FLUID MIGRATION

In typical geopressured reservoirs in the Gulf Coast Basin (Fig. 5), sandstones are isolated on the landward side by large fault displacements (generated near the shelf margin) against older slope shales and on the basinward side by sandstone pinch-outs. The "cap" is typically a transgressive shale wedge or an interbedded sequence of sandstone and shale, and the "top" of geopressure is usually transitional over hundreds of feet (Harkins and Baugher, 1969; Fowler, 1970). This relationship with structural and stratigraphic geometry appears to hold true for a large number of Cenozoic fields regardless of age. Apparently, given the right stratigraphic and structural setting (characteristic of the shelf margin), geopressure can develop soon after deposition (Stuart, 1970), i.e., within a million years or so, and be maintained for at least 50 m.y.

Although generation of excess fluid pressure is a complex physical and chemical phenomenon, maintenance of excess pressure over extended periods of time is essentially a hydraulic problem and can be explained in terms of either a static model (perfect sealing) or a dynamic steady-state model (slow leakage with continuous replenishment of fluids). Recent studies on diagenesis of geopres-

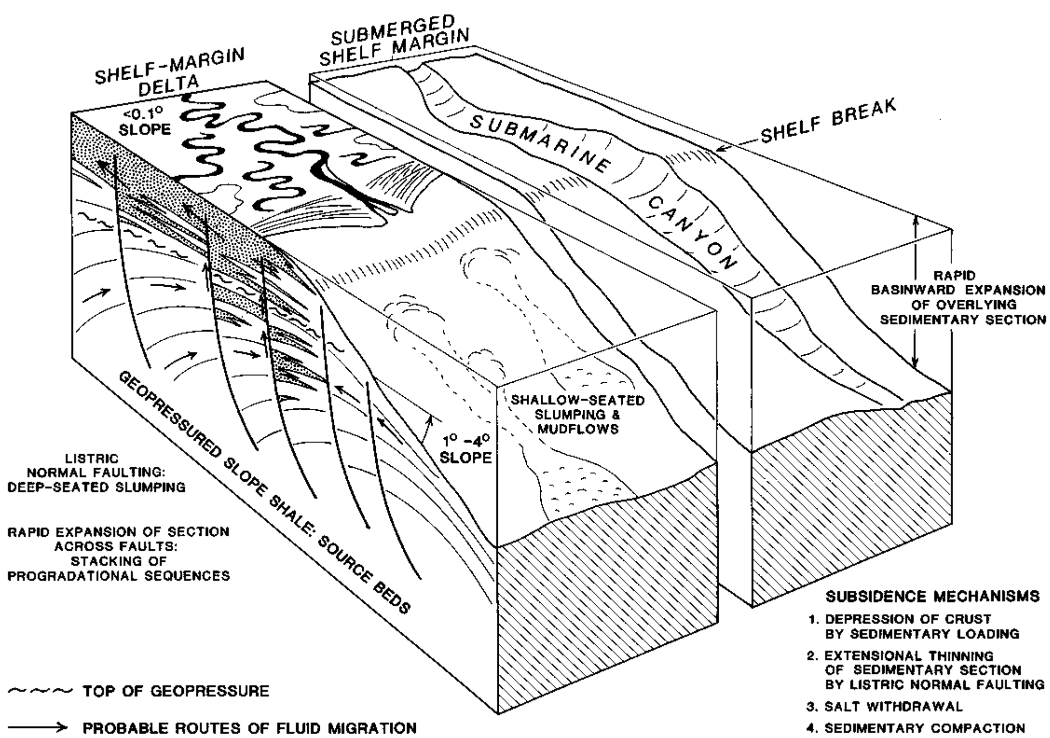


FIG. 10.—Generalized model of contemporaneous deposition, structural growth, and fluid movement in an unstable shelf margin system. Structural styles, depositional environments, and delta types are highly variable. Postulated fluid movement is based on a dynamic model of geopressure maintenance, with slow leakage up faults or across bedding planes; this model may be more useful than a static model for explaining hydrocarbon accumulation and diagenesis in deep geopressured sandstones.

sured shelf-margin sandstones in Texas (Loucks and others, 1977; Bebout et al., 1978; Milliken et al., 1981; Land and Milliken, 1981) suggest that large volumes of water must be flushed through these formations to account for the observed dissolution, replacement, and cementation (Boles, 1982; K. L. Milliken, personal commun., 1982). If we accept the hypothesis of early development of geopressure, the observed diagenesis would require a dynamic rather than a static model of geopressure maintenance. Distribution of hydrocarbons in the abnormally pressured Chocolate Bayou Field also appears to require a dynamic model (Fowler, 1970).

The most likely source for the required amount of water is the large volume of slope shale that underlies the shelf margin sandstones and is juxtaposed against them by faulting, but which is rarely penetrated by the drill and is therefore poorly described or understood. The probable role of slope shales in generating fluids is particularly significant in light of their high potential as source beds (Dow, 1978), in contrast to the generally poor potential of shallow water shale (Brown, 1979). In addition, slope shales should reach thermal maturity much sooner than would the younger shallow-water deposits in hydraulic continuity with them (Dow, 1978). From these considerations, we can expect that shelf margin systems are important not only as geopressured reservoirs, but also as part of the "plumbing" for hydrocarbons and diagenetic fluids (Fig. 10).

SUMMARY

1. Ancient shelf margins can be recognized and mapped on the basis of criteria such as timing of growth faulting, maximum rate of deposition, and top of geopressure, where data on sedimentary structures and microfaunal assemblages are not available, albeit with less precision.

2. Progradation of shelf margins can be used to explain the evolution of growth faults, diapirs, and related structures. As a general rule, the shelf margin represents a strongly extensional regime, and the lower slope a strongly compressional regime. The shelf margin structural style tends to increase in complexity as the shelf margin progrades into the basin, partly due to overriding of diapirs previously formed along the lower slope.

3. Unstable shelf margin deltas differ substantially in cross-sectional geometry from stable inner-shelf deltas, due primarily to differences in subsidence rate. Environments and facies tracts probably do not differ greatly between the two types of deltaic systems. Their stratigraphic expression, however, can be much different because high subsidence rates increase the differentiation of progradational cycles and reduce the relative importance of reworking by channels.

4. Rapid growth faulting along unstable shelf margins tends to hydraulically isolate shallow-water sandstones against dewatering slope shales, thus leading to the development of geopressured reservoirs.

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