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Differential subsidence and preservation potential of shallow-water Tertiary sequences, northern Gulf Coast Basin, USA

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ABSTRACT

Growth faulting, which accompanied shelf-edge progradation and filling of the northern Gulf Coast Basin, resulted in partitioning of the basin margin into fault blocks with contrasting subsidence rates. Study of correlative sections in juxtaposed fault blocks reveals that contrasting subsidence rates can result in strongly differing facies patterns in neighbouring areas. This complicates the task of predicting sandstone reservoir occurrence and properties. Shallow-water clastic sections from Eocene to Miocene in age were investigated using extensive well-log observations, supplemented with micropalaeontology and seismic profiles.

All depositional environments involve an ongoing, complex interplay between sedimentation and erosion at different time- and physical scales. In certain settings, a greater subsidence rate causes the preservation of certain facies that would otherwise have been eroded at lower subsidence rates by processes inherent to the environment. The critical subsidence rate that separates preservation from non-preservation is termed the preservation potential threshold for a particular depositional facies. Examples are provided for progradational mouth-bar facies in a deltaic setting (Wilcox), and storm-deposited shoreface–shelf muds in a prograding shoreline setting (Frio).

Where rates of subsidence are even greater, the growth fault may produce a topographical scarp at the surface, which will influence the disposition of depositional environments. Here, the concept of preservation thresholds is not adequate to account for the observed facies changes. Rather, the presence of the surficial scarp as the surface manifestation of the subsurface fault causes the preferential development and preservation of channel activity in the topographic lows, and progradational environments with channel bypass in the topographical highs. An example is provided for a series of prograding stacked deltas (Miocene).

These concepts may help to focus attention on the role of subsidence in constraining the appearance of the sedimentary record.

INTRODUCTION

In growth-faulted regions, such as the northern Gulf Coast Basin of Texas and Louisiana, contemporaneous faulting structurally offset stratigraphical surfaces shortly after their formation. Through time, the sediment on the upthrown block (footwall) subsided at a lower rate than sediment on the downthrown block (hangingwall). This setting provides the opportunity to study the relationship between the preserved stratigraphical record and changing subsidence rates, while other important variables, such as eustatic sea-level, sediment supply and depositional environment, remain comparatively unchanged.

Exploring in such regions, it is common to drill into fault blocks in which strata of a particular age have not been penetrated previously. Typically, little is known about how the downthrown section will differ from the comparatively well-known equivalent section on the upthrown block. This paper describes several examples of characteristic changes that take place across growth faults, and attempts to explain the observed changes.

The most obvious manifestation of the effect of growth faulting on sedimentation is an increase in thickness of a genetic unit from the upthrown to the downthrown blocks. Expansion ratios (downthrown thickness divided by upthrown thickness; Thorsen, 1963) as great as 10 have been documented. In addition to thickness, other properties that vary across the faults include net sandstone, percentage sandstone and log facies development. The way in which these properties change across growth faults will be described in the examples below.

The interpretation of three stratigraphical units, the Palaeocene–Eocene Wilcox Group, the Oligocene Frio Formation, and the Lower Miocene (no formal nomenclature) of the Texas–Louisiana Gulf Coast all illustrate contrasting relationships between growth-faulting and sedimentation patterns. One important relationship concerns the relative rates of subsidence and sediment supply in shallow-water clastic depositional systems, in which sea-level is the major constraint on base level (Wheeler, 1964). If sediment supply is much greater than subsidence, then significant relief is unable to develop where the fault trace emerges at the depositional surface. However, where differential subsidence rates are sufficiently high, significant topographical relief can be created, which can then influence sedimentation patterns.

Sedimentologists and stratigraphers commonly invoke mechanisms such as changes in sea-level, subsidence rate and sediment supply to explain the distribution of sedimentary facies and the characteristics of vertical profiles. In ancient sediments it is generally impossible to validate these interpretations independently or to isolate their respective effects. However, growth faults that rise to the depositional surface cause contrasting subsidence rates in juxtaposed areas, while other conditions are relatively unchanged. Hence it is possible to identify those changes that most likely relate to subsidence rate.

Sequence stratigraphy has heightened interest in the temporal significance of certain types of stratigraphical surfaces. Peculiarly, emphasis has been given to surfaces that are admittedly not isochronous (e.g. sequence boundaries; see Posamentier & Weimer, 1993) as opposed to surfaces that are (e.g. flooding surfaces; see Galloway, 1989). The requirement that sequence boundaries everywhere separate older from younger sediments adds to the demands placed on the stratigrapher to resolve the age of a stratigraphical section. Thus, the lessons learned while studying the effects of growth faulting can be applied to the problems of attempting to distinguish surfaces formed by normal environmental processes, such as channel migration (termed 'source diastems'; Swift *et al.*, 1991), from those formed by imposition of external relative sea-level controls, such as 'incised valleys' (which are components of sequence boundaries).

STUDY AREA AND SCOPE

Examples from diverse geographical locations and geological ages (Fig. 1) have been chosen to illustrate the principles set forth in this paper: the Palaeocene–Eocene Upper Wilcox Group of South Texas, the Oligocene Frio Formation of South Texas, and the Lower Miocene of southwest Louisiana. The data set consists primarily of well logs at a scale of 1 in. = 100 ft, supplemented by seismic and micropalaeontological data. With cali-

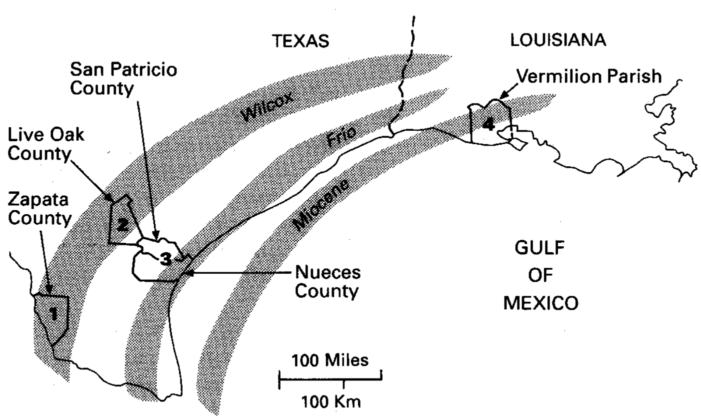

Fig. 1. Index map to the location of the four examples presented in this paper: 1, Upper Wilcox in Zapata County; 2, Upper Wilcox in Live Oak County, 3, Frio in Nueces and San Patricio Counties; 4, Lower Miocene in Vermilion Parish. General location of regional sandy shelf-edges are indicated in stippled patterns for Wilcox, Middle Frio and Lower Miocene trends. (From fig. 2, Winker & Edwards, 1983.)

bration from whole cores, it is possible to make fairly reliable inferences about lithology from the electric logs (Fig. 2). In this paper, diagrams show only the spontaneous potential (SP) curves, but all logs were examined and interpreted by integrating the SP with the induction logs.

The Upper Wilcox of South Texas (areas 1 and 2, Fig. 1) was deposited in a series of shelf-edge delta lobes as part of the Rosita delta system (Edwards, 1980, 1981). A variety of sand geometries reflecting a varied depositional environment were identified. Strike continuous, upward-coarsening sand bodies, appear to represent wave-dominated shorelines, such as strandplains, whereas sections with scattered, blocky and fining upward sandstones suggest deposition along wave-influenced deltas with pronounced mouth-bar development.

The Frio of South Texas includes an interdeltaic embayment dominated by stacked and prograding barrier bar and strandplain sandstones that have pronounced strike continuity (Boyd & Dyer, 1964; Galloway *et al.*, 1982a, b). Sandstones pinch out into lagoonal and continental mudstones and siltstones up-dip, and grade down-dip into storm-deposited interbedded siltstones and mudstones of the shelf.

The Lower Miocene of southwest Louisiana was deposited as a series of stacked delta lobes at the initiation of the major sediment influx during the Miocene (Curtis, 1970). Intense contemporaneous structural activity focused sediment into a series of

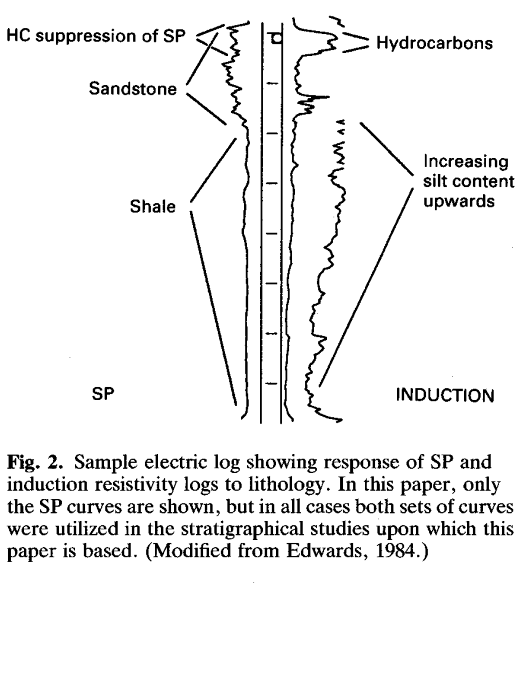

Fig. 2. Sample electric log showing response of SP and induction resistivity logs to lithology. In this paper, only the SP curves are shown, but in all cases both sets of curves were utilized in the stratigraphical studies upon which this paper is based. (Modified from Edwards, 1984.)

structural basins (Sloane, 1971), probably largely controlled by subsurface salt movement. Detailed mapping indicates that deltas were supplied by large distributary channels and incised valleys.

Numerous subsurface studies in this region have shown that the major sand-bearing stratigraphical units on the contemporaneous shelf and upper slope can be divided into regressive packages, or cycles, that can be correlated from tens to hundreds of miles along strike (e.g. Curtis & Picou, 1978). These packages are bounded by transgressive shales that are associated with marine flooding surfaces or maximum flooding surfaces. Recent studies tying planktic foraminiferal assemblages to a chronostratigraphical framework suggest that the cycles have durations of about 100–200 ka (Edwards, 1990; Mitchum & van Wagoner, 1991). A recent attempt to relate Lower Miocene oxygen-isotope cycles to well-log cycles suggested a dominant periodicity of 100 ka (Ye *et al.*, 1993). In the examples that follow, most of the correlation markers shown are thought to bound cycles of this order (see Figs 5, 9, 10, 11 & 14).

EFFECTS OF GROWTH FAULTING ON SEDIMENTATION

A considerable literature covers many aspects of the setting and effects of growth faulting on sedimentation. Curtis & Picou (1978) placed the major growth-faulted trends of the Gulf Coast Basin into an offlapping delta model. Winker & Edwards (1983) examined the delta model in a shelf margin setting and pointed out some of the ways in which this setting differs from a platform setting. We can envision growth faults as part of the extensional head region of a large gravity driven slope failure that also includes a contractional toe region with folds and thrusts in deep water. Study of salt tectonics in the past few years has focused on the role of salt in terms of both lateral and vertical flowage. Growth faults in salt-dominated areas can form in response to: the evacuation of deep salt into extruding diapirs, the evacuation of salt sheets, or combinations of salt-driven and slope-driven gravity systems (Vendeville & Jackson, 1992).

The most obvious effect of growth faulting on sedimentation is the change in thickness (Thorsen, 1963). Aside from such thickness changes, the character of a stratigraphical unit can appear unchanged, or can show significant changes across a growth fault. In either case, it is important to attempt to predict sandstone properties for the purpose of hydrocarbon exploration and production. The following sections present examples of various depositional responses across growth faults.

Expansion only

Stratigraphical sections with large expansion ratios usually display significant stratigraphical changes across a growth fault. A noteworthy exception occurs in the Upper Wilcox in Zapata Country. A fault with an expansion ratio of greater than three, shows no obvious changes in percentage sandstone or log facies (Fig. 3). These sandstones were illustrated in stratigraphical and structural sections (see Edwards, 1981, Figs 10 & 11).

Comparison between the upthrown and downthrown blocks is facilitated by changing the vertical scale of one of the logs, in order to make correlation markers subparallel (Fig. 3). This procedure of 'double datuming' attempts to reconstruct the stratigraphy as if all of the locations had been subject to the same subsidence rate. In this and the following examples, no attempt has been made to decompact the sections in order to compensate for greater compaction of shale relative to sandstone. Contrasting amounts of compaction could influence present-day thickness where lithology changes significantly across the fault. However, these sections are overpressured, which has resulted in comparatively small amounts of shale compaction.

Inspection of the two logs (Fig. 3) indicates that percentage sandstone and log facies are largely unaffected by the fault, except for the presence of a high-frequency signal in the middle part of the down-dip well. In this example, the proportion of net sand in the two wells is the same as the expansion ratio.

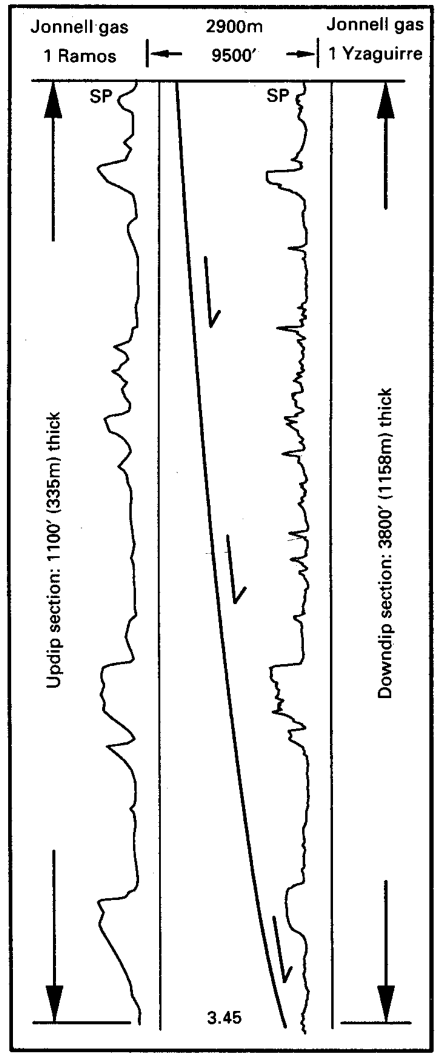

Fig. 3. Stratigraphical dip section across a large growth fault in Zapata County, South Texas. The vertical scales of stratigraphically equivalent section both upthrown and downthrown to the fault have been adjusted to compensate for differential subsidence. Note the similarity of the SP logs, despite the expansion ratio of 3.45. Similar 'double-datumed' sections are also shown in Figs 5, 11 & 13. (Modified from Edwards, 1984.)

Facies changes and channel erosion

Extensive mapping in the South Texas Upper Wilcox (Fig. 1) reveals the presence of stacked delta lobes with mappable distributary channels (Edwards, 1980, 1981; Winker & Edwards, 1983). A set of eight wells arranged in a dip section (Fig. 4) has been selected to show thickness and log facies changes (Fig. 5).

In an unfaulted area, with a uniformly increasing subsidence rate down-dip (flexure), a gradual change in log facies would be expected, with a change from distributary channels up-dip, through mouth bar to distal mouth bar down-dip. However, in this example (Fig. 5), a striking change in log facies occurs at the up-dip growth fault (between wells 2 and 3), with more subtle changes at the other faults. The effects of growth faults on stratigraphical preservation can be observed by comparing and contrasting adjacent

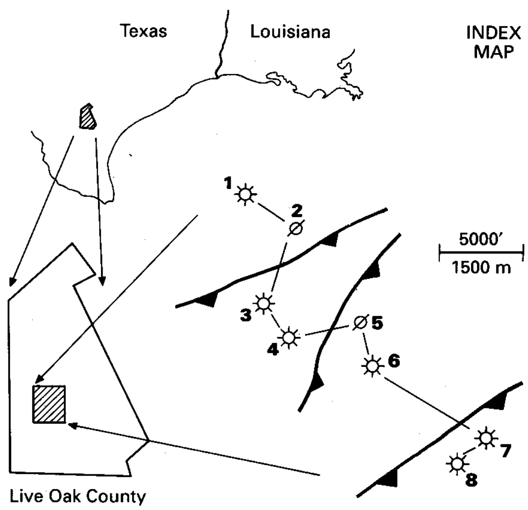

Fig. 4. Index map showing the location of wells depicted in Fig. 5, Live Oak County, Texas (see Fig. 1 for context).

subsidence-normalized wells that are in the same versus different fault blocks. For example, in the Luling regressive cycle (Fig. 5B), wells 1 and 2 are very similar, as are wells 3 and 4. However, wells 2 and 3 are clearly different.

The preserved components of each progradational deltaic cycle (Fig. 5) include mouth bar and distal mouth bar deposits, typically arranged in upward-coarsening successions; distributary channel deposits represented by blocky sandstones and upward-fining successions; and coastal plain and interdistributary bay deposits, which consist of mixed sandstones and shales in a variety of patterns, usually thinner than the overall regressive succession.

Subsidence creates space for the preservation of facies beneath erosion surfaces. In this example, major fluvial erosion is represented by the base of the blocky and upward-fining sandstones. Subsidence allows the deposition and burial of progradational facies beneath the depth of erosion attained by channels. This relationship becomes critical in up-dip areas, where the decreasing thickness of the space available for preservation of progradational facies approaches the depth of distributary channels. Up-dip of this point, the Slick and Luling genetic regressive successions are characterized by amalgamated sandy channel-fill deposits.

Subsidence rate also affects regional facies trends. High subsidence rates favour stacking of delta lobes with 'foreshortening' of dipwise facies gradients (the distance along dip from proximal to progressively distal facies) rather than down-dip translation of facies belts by continued progradation into the basin.

A schematic facies preservation diagram (Fig. 6) enables prediction of the depositional sequences that can be juxtaposed across a growth fault in a prograding delta. At the top (Fig. 6A) is a subsidence rate graph. The duration of the progradational phase is suggested to have lasted about 1000 yr, although it could have been much shorter or longer. The growth-fault curve (solid line) shows subsidence rates that reflect the thickness changes observed due to growth faulting and roll-over (up-dip thickening on the downthrown block toward the fault). The vertical steps show the locations of individual growth faults. Shown for reference is the flexure curve (dashed line), which assumes a linear increase in subsidence rate down-dip. Arrows labelled U and D are explained below.

Figure 6B illustrates some of the facies relationships and inferred environments of deposition. After transgression and abandonment of the previous delta lobe, the cycle begins by progradation of the delta front, with superimposed higher frequency transgressive–regressive cycles. The progressive basinward shift of environments down-dip has been shown by the down-dip termination of channel erosion surfaces and mouth bars. Coastal-plain facies are depicted as blocky sandstones, although they are in reality complex intercalations of various channel and bay deposits. There is a total of 50–200 ft (15–60 m) of subsidence at the up-dip end, whereas at the down-dip end there is 250–2000 ft (75–600 m) of subsidence. It is assumed that distributary channels are 50–200 ft deep regardless of location, although it is likely that they would decrease in depth down-dip due to channel bifurcation and discharge through crevasses.

The subsidence curves can be used to estimate preservation of vertical sections on either side of a growth fault. At a growth fault, the regionally averaged subsidence rate does not occur. Instead, much higher subsidence rates occur on the downthrown block, and much lower rates occur on the upthrown block. On the upthrown block (see Fig. 6A), the lower subsidence rates resulted in a vertical section that resembles that developed up-dip. This is shown by the arrow U, which is projected to the left until it intersects the flexure curve, where the appropriate lower subsidence rate would have occurred in a non-growth-faulted setting (depicted by flexure curve in

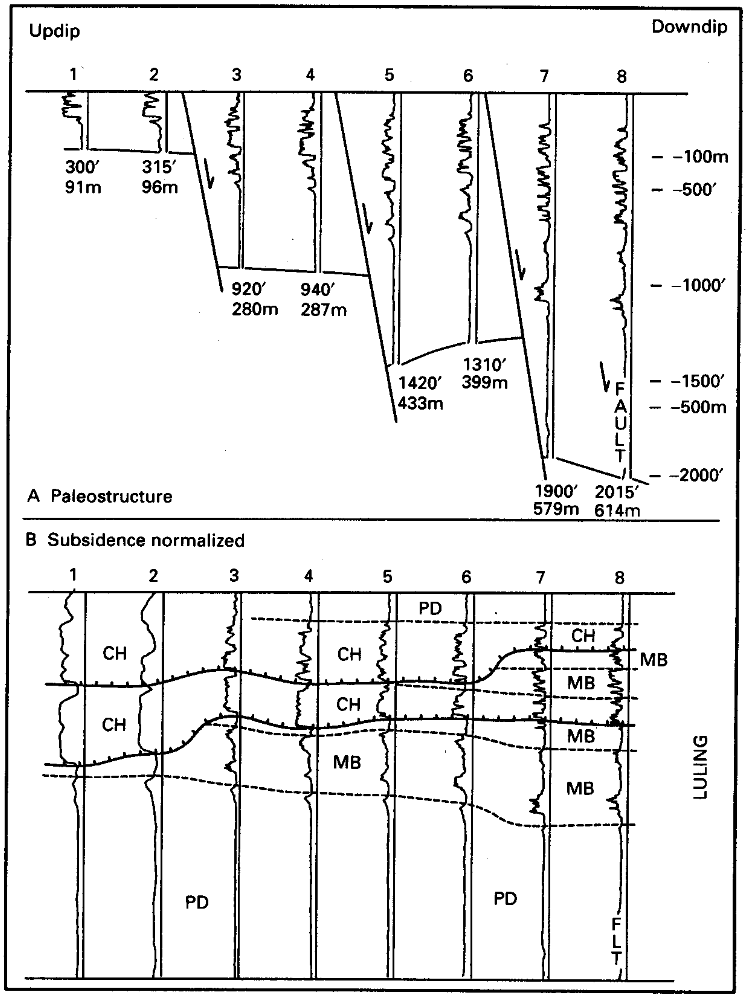

Fig. 5. Thickness and facies changes in two stacked delta complexes, the older Luling (A and B) and the younger Slick (C and D) units in the Upper Wilcox of South Texas (see Figs 1 & 4 for locations). For both deltas the upper panels (A and C) show a palaeostructural cross-section with the top to the delta complex as the upper datum, and growth faults that were active during delta formation. The lower panels (B and D) are 'double-datumed' sections in which vertical scales were adjusted to normalize for differential subsidence. Generalized deltaic facies are identified using electric log characteristics. CH, channel; MB, mouth bar; PD, prodelta. No horizontal scale.

Fig. 6A and facies distribution in Fig. 6B). At the intersection point, the arrow is then extended down into the facies diagram, in order to determine the vertical section that corresponds to that subsidence rate.

A similar procedure can be carried out for the downthrown block by projecting the downthrown subsidence rate to the right (arrow D, Fig. 6A) until it intersects the flexure curve, and then extending it down into the facies diagram below. This procedure predicts that the vertical sections on either side of the growth fault would show considerable differences in facies profiles that could not be explained solely as a function of changing palaeogeographical location. The thickness of the upthrown and downthrown profiles could then be expanded or contracted to restore their present-day relative thicknesses. However, this method may predict excessive lateral

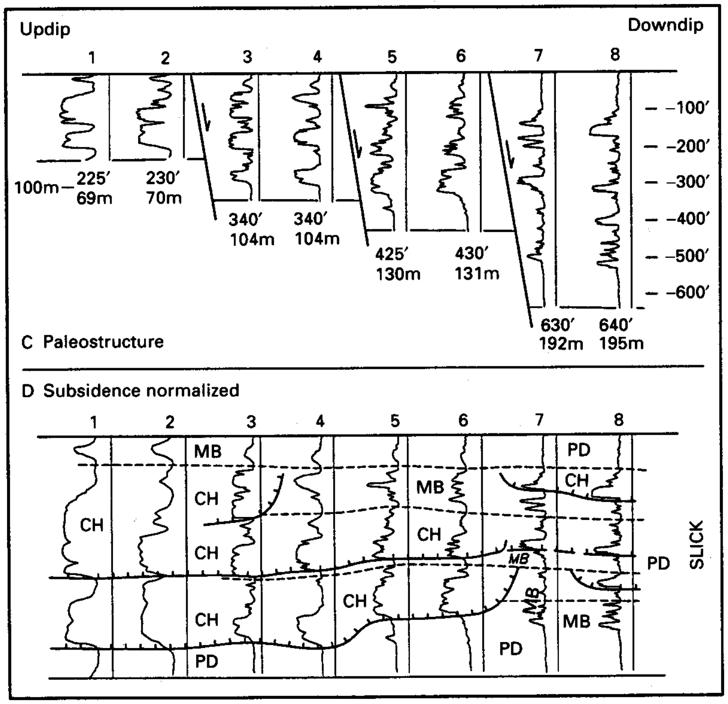

Fig. 5. (*Continued.*)

facies changes because the distance between the two schematic wells (below arrows U and D, Fig. 6) will be greater than the actual distance between two wells on either side of a growth fault.

Facies changes and storm/wave erosion

The South Texas Frio Formation (Fig. 7) illustrates shorelines that prograde as a line source (i.e. wave-dominated deltas, barrier islands and strandplains), rather than point sources (such as river-dominated deltas). It is based on complex stratigraphical and structural relationships determined from approximately 600 well-logs (Weise *et al.*, 1981; Bebout *et al.*, 1982; Edwards, 1986), coupled with micropalaeontological studies that indicate neritic to coastal environments throughout the section, with overall shallowing upwards (Martin, 1969, 1970).

The sandy, wave-dominated Frio shoreline was bordered by muddy coastal plains up-dip, muddy slope deposits down-dip, and by major deltaic depocentres along strike (Galloway *et al.*, 1982a, b). These palaeogeographical relationships strongly suggest that sand was supplied to the Frio shoreface by wave-driven alongshore transport in the foreshore/upper shoreface, rather than by prograding deltas (Martin, 1969).

A typical well-log in the Frio shows an upward transition from shelf mudstone to strandplain sandstone over a depth range of about 5000 ft. Subdivision of the section into component cycles reveals that the thickness of the cycles increases markedly with greater depth, from less than 50 ft to almost 500 ft (Fig. 8). This suggests that structurally deeper sediments were deposited at much greater subsidence rates than shallower Frio sediments. Rigorous correlation of hundreds of well-logs in the area allows the tracing of these varied cycles across growth faults. Palaeostructural cross-sections (Figs 9 & 10) show the position of growth faults and their effect on thickness and log facies.

The analysis of log facies changes is presented in a set of four well-logs, each in different fault blocks (Fig. 11). The log correlations look questionable at their original depth-scales, but when normalized for differential subsidence, the correlation of the indi-

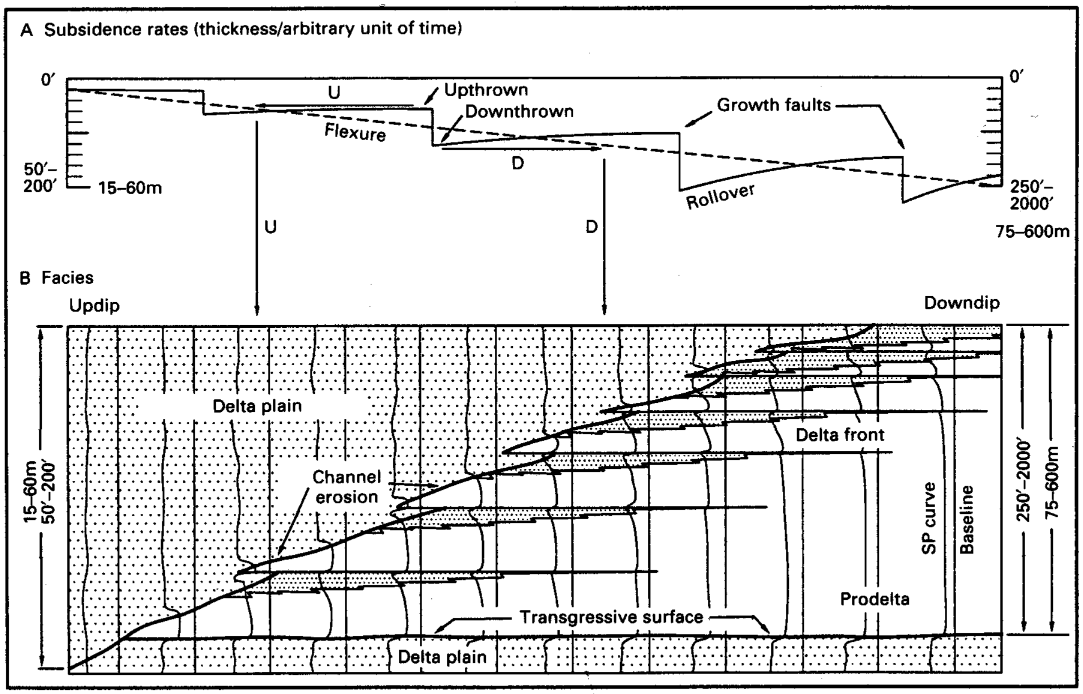

Fig. 6. Schematic diagram of facies preservation relationships in a deltaic environment characterized by significant channel erosion. (A) Two subsidence rate relationships are shown, a straight dashed line indicating uniformly increasing subsidence rate with distance as in a flexure, and a complex solid line indicating abrupt increases in subsidence rate down-dip across growth faults and decreasing subsidence rate up-dip within some fault blocks due to roll-over. (B) Facies preservation trends and characteristic SP logs. Proximal to distal facies trends have been exaggerated. The figure can be used as a kind of nomograph to estimate facies changes across growth faults in this setting. See text for additional explanation. (Modified from Edwards, 1984.)

vidual cycles is much more obvious. Figure 11 illustrates the change in log facies from thick sand bodies up-dip, to thin interbedded sandstones (siltstones) and mudstones down-dip. The palaeostructural sections emphasize that the facies changes take place abruptly across the growth fault. However, the correlatability of the individual cycles across the fault suggests that significant sea-floor relief was not maintained at the location of the fault.

Core study of the down-dip interbedded facies (Berg & Powell, 1976) suggested that the sandstones were deposited by turbidity currents. Studies of the modern Texas shelf, however, suggested that shelf sands are deposited from storm-generated geostrophic flows that produce turbidite-like beds (Morton, 1981). Transport is oblique to the shoreline, but the resulting thin beds have enormous strike continuity (Snedden & Nummedal, 1991). The continuity is consistent with the excellent gas production that can be achieved despite the thin, ratty character of the sands. The large amount of interbedded mudstone was presumably derived from the adjacent deltaic depocentres.

A schematic diagram (Fig. 12) suggests how abrupt facies changes can develop across growth faults, without the necessity of an abrupt change in depositional environment. The model proposed in Fig. 12 relies upon differential subsidence to produce a contrast in the sediments preserved, even though the depositional processes on both sides of the fault are virtually identical. Unfortunately, the available data do not allow many aspects of the model to be resolved until additional core data are obtained.

The dynamics of shoreface–shelf systems have been discussed by many authors (e.g. Swift & Thorne, 1991), however, a considerable number of issues remain contentious. For the present discussion, it suffices to emphasize the key points. The

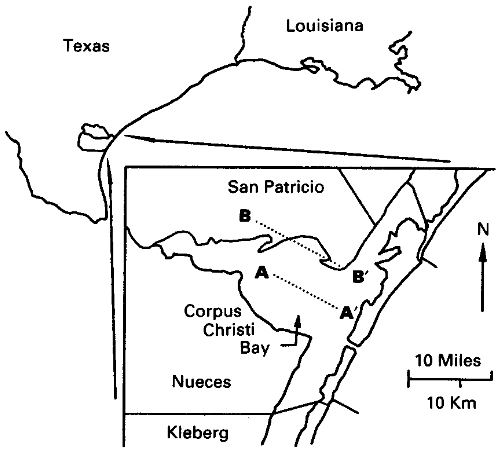

Fig. 7. Index map showing location of cross-sections A–A′ and B–B′ in Figs 9 & 10, and general location of Frio investigation around Corpus Christi Bay.

precise roles of fair-weather versus storm conditions in transporting sediment on the upper shoreface is often unclear and may vary from one shoreline to another. The Frio shoreline prograded steadily through time due to the high sediment supply, and significant wave transport along shore and storm transport to the inner shelf.

Logs and whole cores indicate a progression from relatively coarse-grained homogeneous sandstones up-dip, through interbedded thick sandstones and shales, to thinly interbedded 'ratty' siltstones and shales down-dip. It seems likely that the coarse-grained shelly sandstones up-dip were deposited in a foreshore and upper shoreface setting and are composed of wave-reworked and amalgamated storm beds. The ratty interbedded section down-dip was deposited on the lowermost shoreface to shelf and consists of interbedded storm-deposited sands and muds. The abrupt facies change at the fault remains to be explained. The important distinction is that mud layers are preferentially preserved on the more rapidly subsiding down-dip block. The mud could have been deposited from suspension either by turbid nearshore, semi-permanent currents, or by waning flow following a storm event. In either case, it is important that the mud was not eroded subsequently, either by storms or fair-weather wave activity.

The Frio shelf system can be regarded in terms of profiles of equilibrium and changing base levels. Areas of greater subsidence rate permitted less sediment to be reincorporated by storm currents and bypassed on to the shelf, and hence more sediment was allowed to accumulate. If eustasy and sediment supply are held constant, then the high subsidence rates on the downthrown block effectively raise the local base level (increase accommodation), increasing the probability that storm-deposited muds would be preserved. At some critical subsidence rate, sand beds stop being amalgamated, and instead are separated by thin mud layers. At this point, the reservoir characteristics of the sand body change drastically.

The most rapidly subsiding areas immediately down-dip of the growth fault would probably have

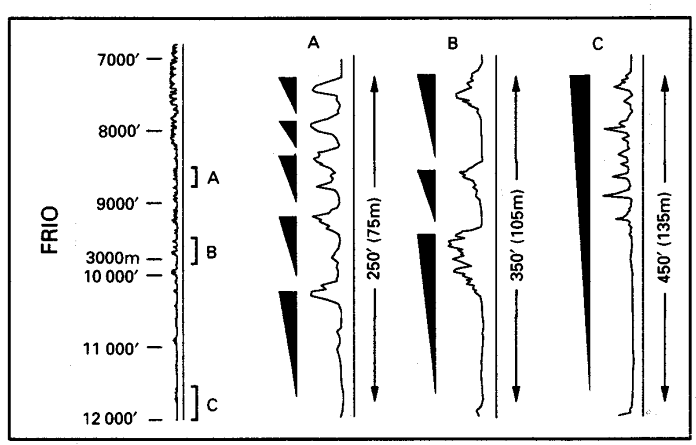

Fig. 8. Example of Frio log from Corpus Christi Bay showing vertical changes in cycle thickness, suggesting increasing subsidence rate with depth. Small portions of the log have been enlarged to illustrate cycle styles and thickness. The numbers next to logs A, B and C refer to the thickness of the log segments illustrated.

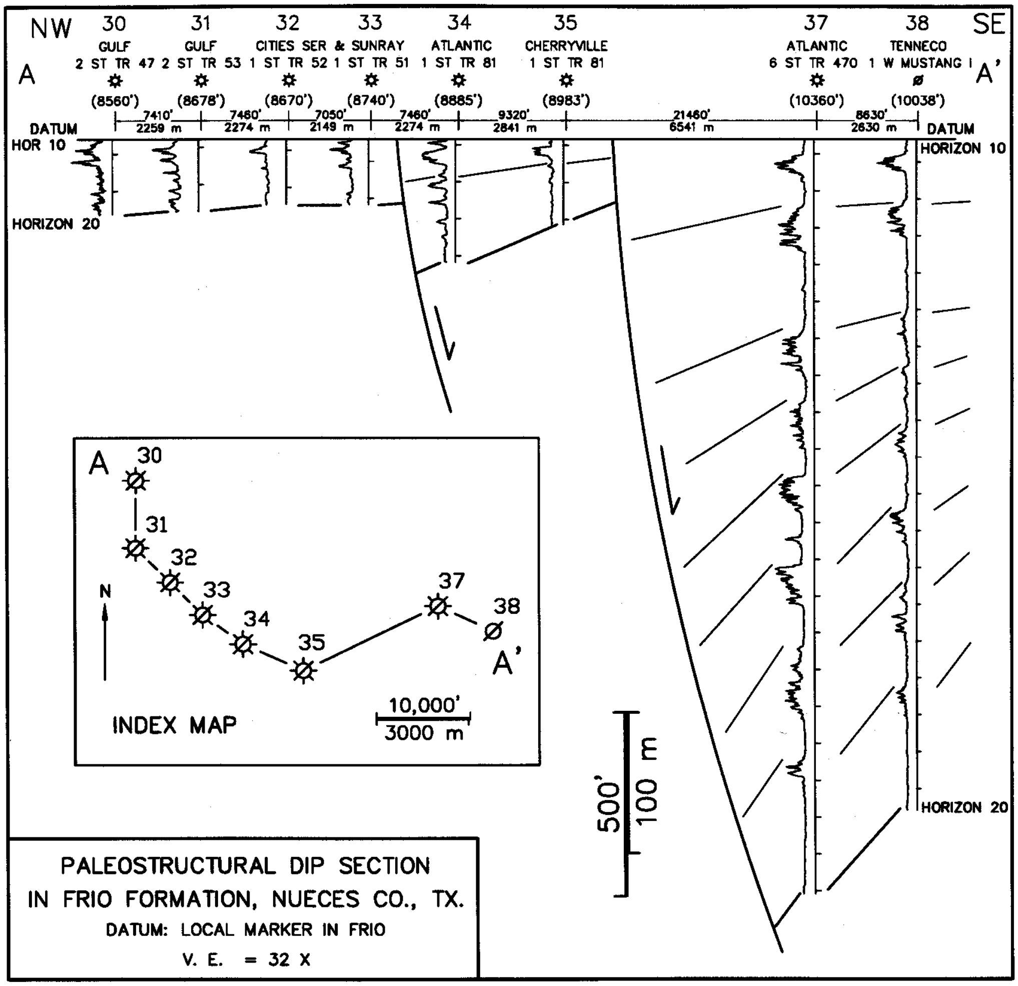

Fig. 9. Frio palaeostructural section A–A′ (see Fig. 6 for location and Fig. 1 for setting) showing an overall regressive stratigraphical interval bounded by marine flooding surfaces expanding dramatically across two growth faults, with concomitant facies changes. (Modified from Edwards, 1986.)

served as an effective sediment trap, especially as the local onshore-directed subsidence gradient was opposed to the obliquely offshore-directed sediment-transport gradient. Storm-deposited sands typically pinch out down-dip, leading to the development of combination traps in off-structure positions.

Facies changes at faults that develop topographical relief

The balance between sediment supply and subsidence occasionally results in a significant topographical scarp being developed where the fault intersects the sea-floor. This is illustrated by the Lower Miocene of southwestern Louisiana (Fig. 1), where a large depositional basin formed as a result of the sudden and rapid removal of subsurface salt, and then stabilized when the salt body was fully evacuated (Edwards, unpublished).

Thin stratigraphical units in this area were mapped using almost 2000 well-logs, micropalaeontological data, and seismic data. The maps show the devel-

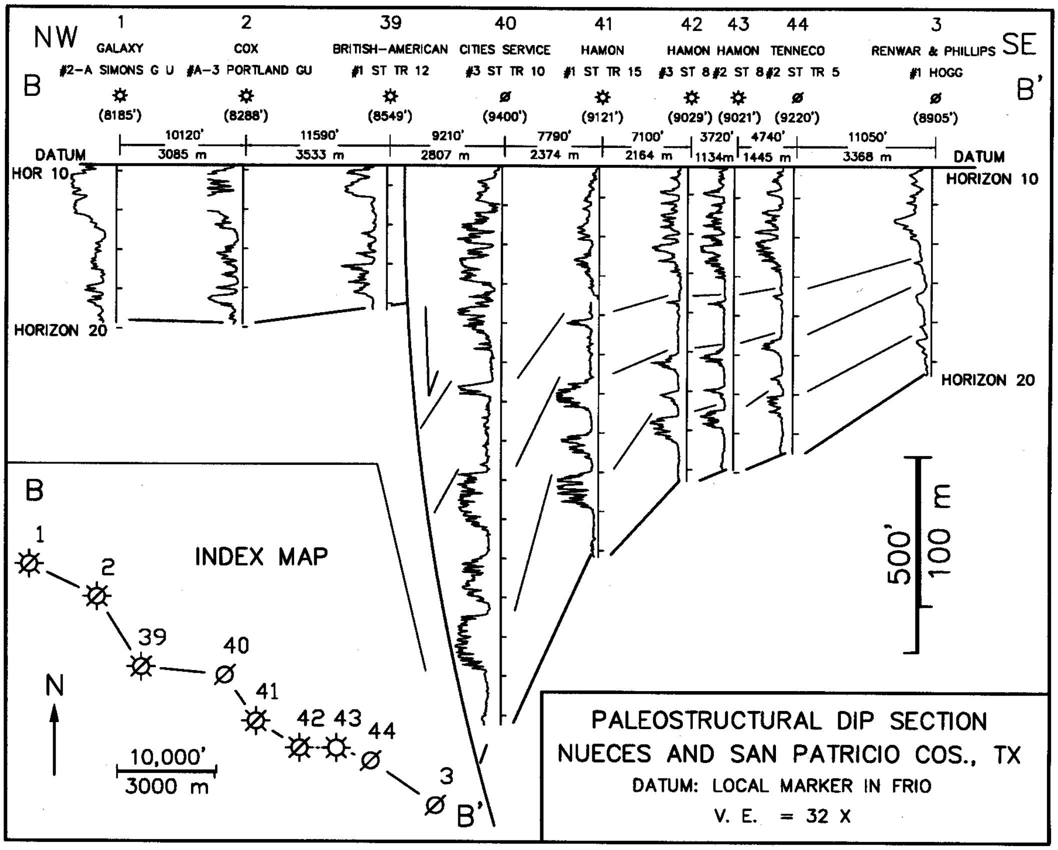

Fig. 10. Frio palaeostructural section B–B′ (see Fig. 6 for location and Fig. 1 for setting) showing dramatic expansion of two sandy regressive cycles, each bounded by marine flooding surfaces, across a growth fault, with concomitant facies changes. Note excellent roll-over structure with expansion and improved development of sandstones up-dip to the northwest into the growth fault. (Modified from Edwards, 1986.)

opment of channel sandstone bodies that traverse the up-dip stable shelf and trend toward the down-dip basin, where large quantities of sand were deposited on the downthrown side of the fault (Fig. 13). The pattern is repeated in several successive units (Fig. 14).

The coincidence of the structural boundary and the facies boundary indicates that the basin was a topographical as well as a structural low, which not only collected sediment but also attracted distributary channels and incised valleys from the adjacent highs (Fig. 13B). Similar relationships between structures, relief and facies have been recognized in other settings (e.g. Hopkins, 1987; Leeder & Alexander, 1987).

The up-dip areas (Fig. 13B) appear to be comprised largely of shallow-water mudstones and localized mouth-bar sandstones, which were deposited while sea-level was relatively high. The development of narrow incised valleys allowed the preservation of these fine-grained deposits, and contrasts with the Wilcox example, described above, in which there was extensive scouring at the bases of distributary channels. The apparently stable channels suggests a relative fall in base level, due either to eustasy or to local structural uplift beneath the upthrown block

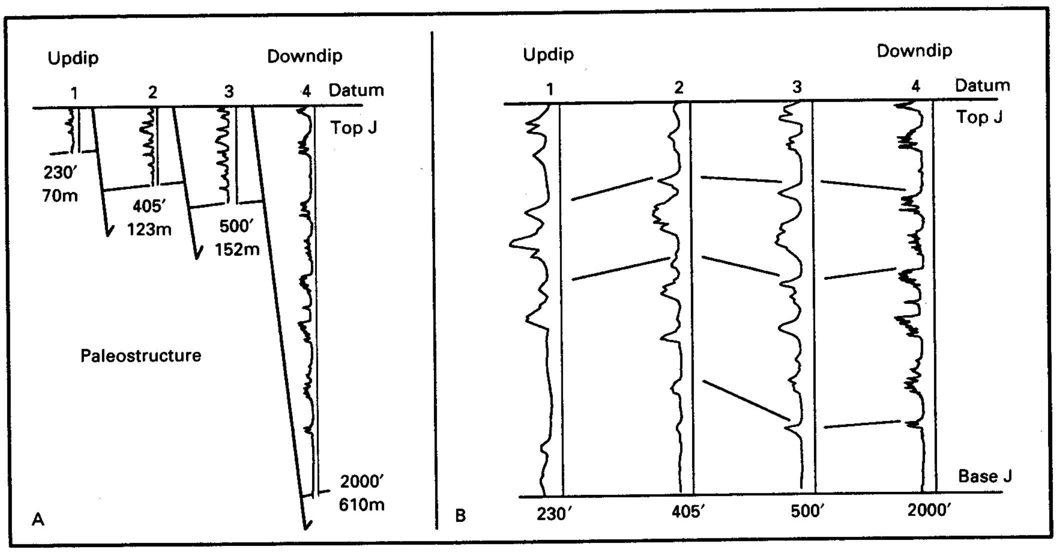

Fig. 11. (A) Frio schematic palaeostructural section of one stratigraphical unit ('J') with well-log segments selected from four wells. (B) Frio stratigraphical section with vertical scales adjusted to normalize for differential subsidence across growth faults. The correlations suggest that thin digitated SP facies up-dip have closely time-equivalent ratty/serrated SP facies down-dip. Figures 9 & 10 demonstrate that the facies changes occur at growth faults.

due to movement of deep salt. The down-dip basin-fill attests to the huge sediment volumes that were bypassed through the relatively small valleys.

PRESERVATION POTENTIAL THRESHOLDS

The above examples raise the question as to why some of those faults that are not associated with depositional topography show dramatic facies changes, whereas others do not. It is customary to express the significance of a growth fault in terms of its growth ratio, as this can be measured directly in the subsurface data. However, this ratio gives no information about the *absolute* rates of subsidence on either side of the fault. It seems likely that a major factor controlling facies development is the absolute subsidence rate.

Along a continuum of subsidence rates, will be rates that separate domains that are associated with the preservation or non-preservation of a particular facies component, or sedimentary feature (Fig. 15). These specific subsidence rates can be referred to as preservation potential thresholds for a particular sedimentary feature in a particular depositional environment. As noted above, absolute subsidence rate has to be evaluated in the context of the other variables that affect base level: eustatic fluctuations, and the amount and calibre of sediment supply (e.g. Swift & Thorne, 1991). For example, in the deltaic setting discussed above, distributary channels are a significant source of erosion. With sufficiently low subsidence rates, migrating channels will remove all or most of the progradational facies, resulting in amalgamated multistory channel sand bodies. When the threshold subsidence rate is exceeded, progradational facies will be preserved. Another example is the balance of erosion and deposition on the shoreface. A threshold value of subsidence, in the context of the other controlling variables, separates regimes in which mud layers will be eroded from those in which they are preserved. Analogous thresholds could be postulated for other environments and sedimentary features.

CONCLUSIONS

1 The interplay between erosional and depositional processes in sedimentary environments is controlled to a large extent by subsidence rates. The latter

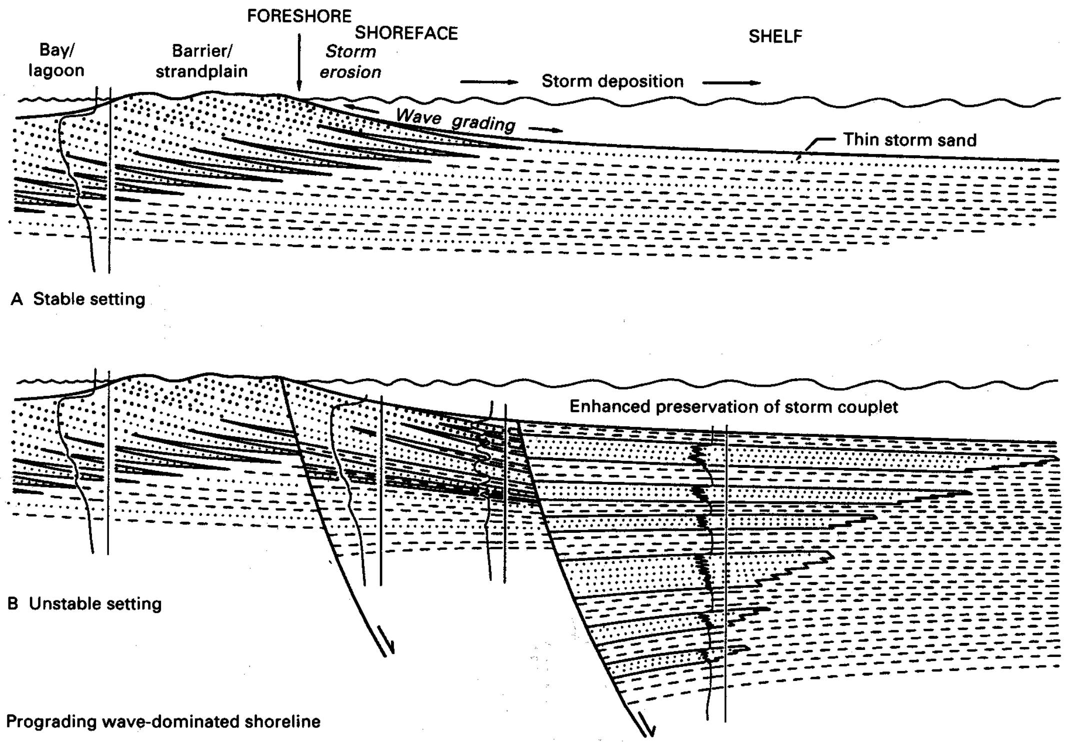

Fig. 12. Schematic cross-sections showing wave-dominated shoreline progradation in (A) stable and (B) unstable settings. Characteristic well-logs (SP only) are shown. (A) This section indicates the presence of wave grading shaping the foreshore and upper shoreface, and storm events resulting in erosion of the upper shoreface and deposition of a storm couplet on the shelf. (B) The enhanced subsidence rates in the unstable setting allows for the preservation of the muddy portion of the storm couplet from erosion, whether by wave grading or a subsequent storm event. The enhanced preservation seems to have resulted from greater subsidence rates, which modified local base levels. (Modified from Edwards, 1984.)

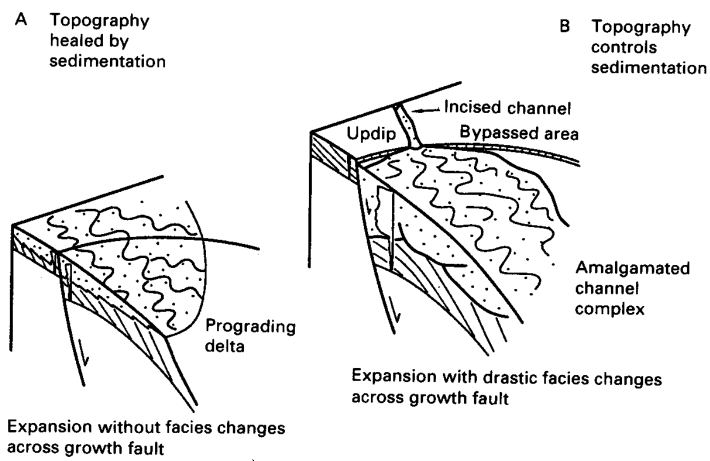

Fig. 13. Schematic block diagram contrasting: (A) normal sedimentation across growth fault without development of topographical relief, versus (B) growth fault with associated topographical scarp and bypassing of coarse sediment across up-dip block to rapidly subsiding down-dip block. Based on a study of the Lower Miocene. (Modified from Edwards & Tuttle, 1993.)

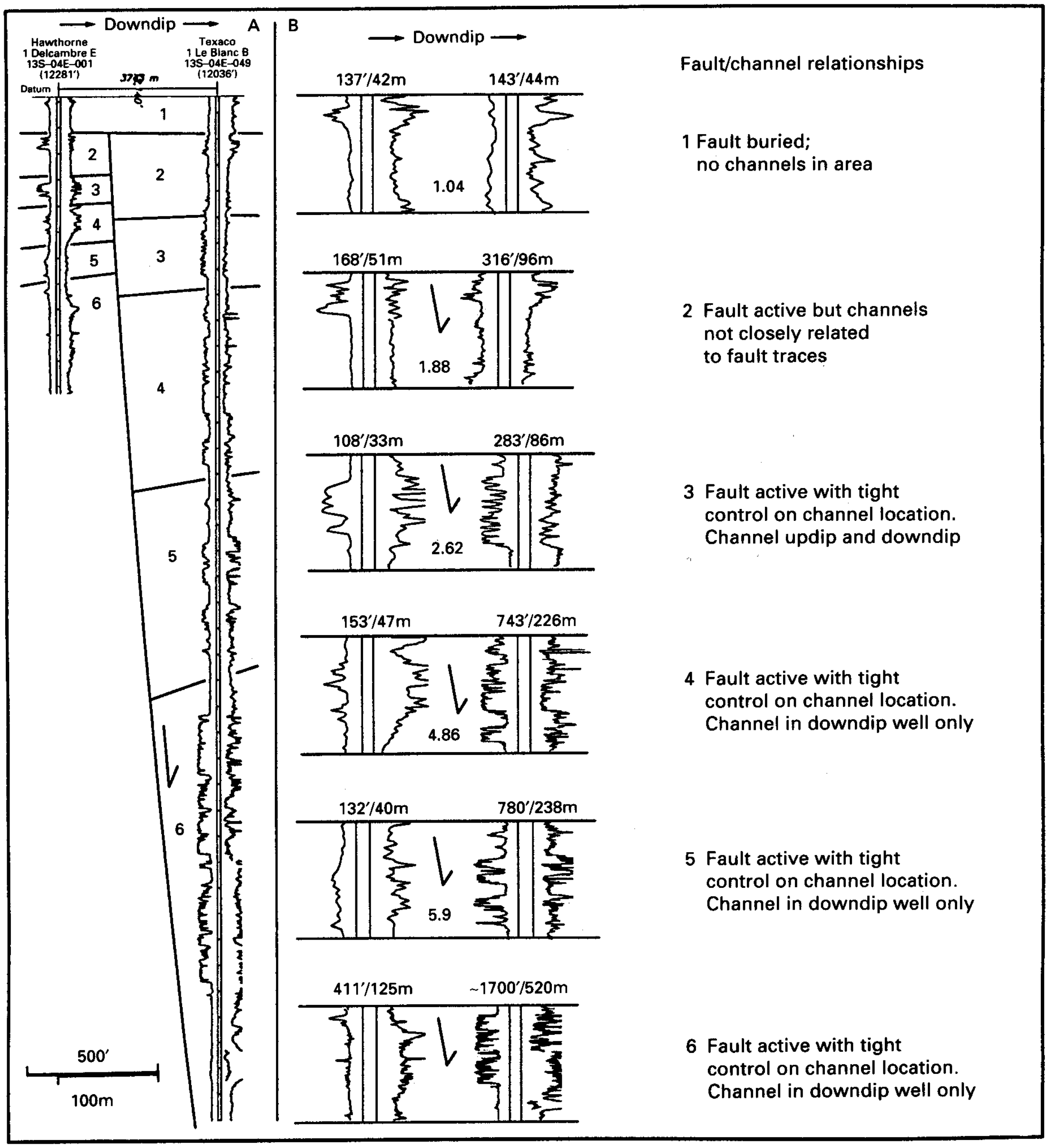

Fig. 14. (A) Palaeostructural cross-section showing change of Lower Miocene section across a prominent growth fault that had topographical relief developed during part of its history. The section was subdivided into six units for mapping and correlation, of which the deepest unit has no clear lower boundary in this well. (B) The six units are shown with vertical scales adjusted to normalize for differential subsidence across the fault. For each layer, the original thicknesses are shown, and the expansion ratio is shown between the logs.

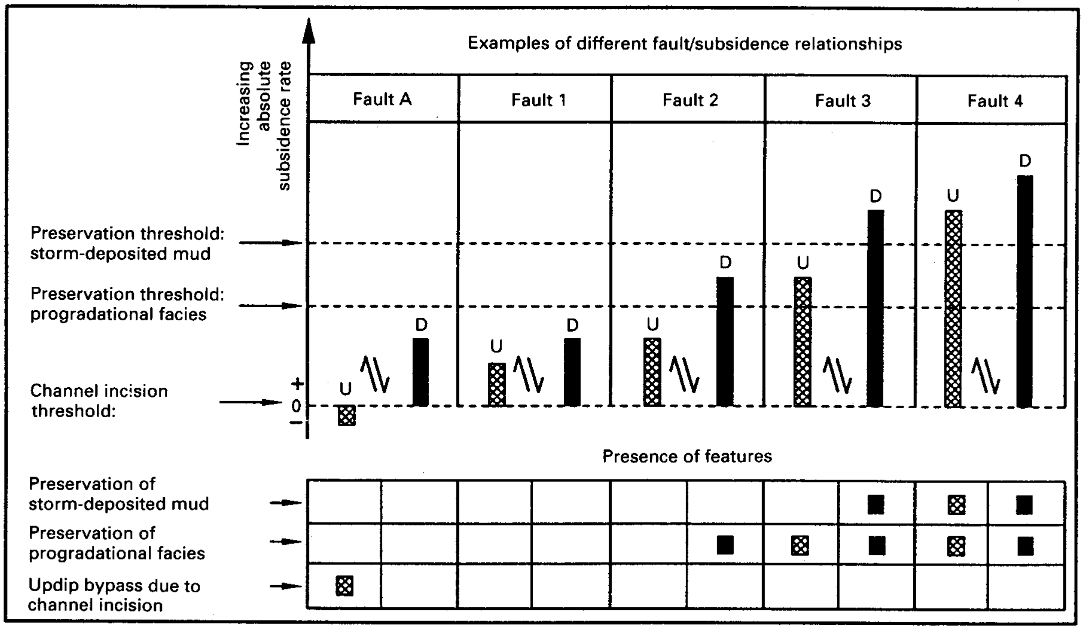

Fig. 15. Representation of preservation potential thresholds in growth-fault settings. The vertical axis shows increasing absolute subsidence rate, but is schematic with no scale. Most of the stratigraphical units depicted in this study are considered to be 'fourth order', and hence have a duration of the order of approximately 100 ka. Preservation thresholds are depicted for progradational facies at a lower rate than that for storm-deposited mud in the transitional lower shoreface to shelf environment. Five different fault situations indicate how various combinations of depositional environment and subsidence rates determine whether particular facies will or will not be preserved across specific growth faults. Note that expansion ratio is related to relative rather than absolute subsidence rate. If blocks on either side of a growth fault are on the same side of the preservation threshold, then facies patterns will be similar with regard to the particular process threshold, although thickness will be different. Settings that represent examples described in this paper are fault A, Lower Miocene of southwestern Louisiana; fault 1, amalgamated sandstones on both sides of fault common in up-dip areas; fault 2, Wilcox in Live Oak County, Texas; fault 3, Frio in South Texas; fault 4, thick sections with similar facies on both sides of the growth fault, common in down-dip areas.

affects preservation potential via thresholds that separate domains of facies preservation versus erosion.

2 Subsidence rates, through their effect on preservation potential, influence facies composition, including geometry, bedding characteristics, fabric, palaeontology and seismic response. The effect of subsidence rates is readily demonstrated in the Gulf Coast Basin due to the presence of growth faulting. In tectonically stable basins, the effect of subsidence rate on facies composition may not be determined readily.

3 Where subsidence rates were sufficient to create topographical scarps at the depositional surface, the effect of faulting on sedimentary facies is greater, as there is then a feedback effect on the location of major facies, and not just the preservation potential of sensitive component facies.

4 The documented effects of preservation thresholds on reservoir architecture indicate that it would be useful to be able to predict preservation patterns on unexplored fault blocks in growth-faulted basins. However, the present study indicates that expansion ratios are generally inadequate to make such predictions: absolute subsidence rates are required, but are often difficult to obtain or predict.

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