Seismic geomorphology and high-resolution seismic stratigraphy of inner-shelf fluvial, estuarine, deltaic, and marine sequences, Gulf of Thailand

Hernán M. Reijenstein, Henry W. Posamentier, and Janok P. Bhattacharya

ABSTRACT

Pleistocene fluvial, estuarine, marine, and deltaic depositional systems were identified in the uppermost 80 m (262 ft) of the central Gulf of Thailand modern continental shelf, situated approximately 70 m (~230 ft) below sea level. Integration of offshore three-dimensional (3-D) seismic reflection data, high-resolution shallow-penetration two-dimensional (2-D) seismic reflection sparker and boomer profiles, and shallow geotechnical borehole measurements enabled the identification of seven depositional sequences.

The 3-D plan-view images at successive time slices exhibit single meandering channels (as much as 600 m [1969 ft] wide) and channel belts (as much as 10 km [6.2 mi] wide) deposited in the shelf during times of subaerial exposure. Additional geomorphic features imaged include incised valleys, interfluves, oxbow lakes, neck and chute cutoffs, and point-bar meander scrolls showing evidence of expansion and translation. The high-resolution 2-D profiles, with a tuning thickness of approximately 25 cm (~9.8 in.), enabled the discrimination of high-frequency stratigraphic discontinuities (sequence boundaries) and allowed a detailed bed-scale seismic facies characterization of fluvial (point bars), deltaic (clinoforms), estuarine, and marine deposits within a sequence-stratigraphic context. The complete succession shows that most fluvial systems lie

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within incised valleys in the lower parts of each depositional sequence, fluvial channels show a degradational stacking pattern, and no evidence of fluvial aggradation is observed; aggradation is limited to hemipelagic sedimentation during marine incursions.

A shallow (<35 m [<115 ft]) single-story incised valley was described in detail, placing particular emphasis on the recognition criteria and the controls on valley formation and preservation potential of different systems tracts in an inner-shelf location. The 3-D characterization of this system allowed differentiation of sand-prone point-bar deposits and mud-prone abandonment channel facies. The sinuous but continuous mud-filled channel may act as a lateral muddy barrier or baffle that can potentially subdivide a reservoir system into discrete compartments.

INTRODUCTION

Based on the advances in three-dimensional (3-D) seismic acquisition, processing, and data analysis for hydrocarbon exploration during the last decade, seismic geomorphology has become a key tool for the analysis of a wide spectrum of depositional settings from fluvial environments to deep-water settings, including shallow marine settings, shelf-edge deltas, slopes, and deep-water submarine fans (Feng, 2000; Posamentier, 2000, 2001; Miall, 2002; Carter, 2003; Posamentier and Kolla, 2003; Saller et al., 2004; Samorn, 2006; Davies et al., 2007; Posamentier et al., 2007; Wood, 2007). These studies illustrate that 3-D seismic data help in detecting detailed geomorphic elements; however, 3-D seismic data lack vertical resolution to detect bed-scale stratigraphic and sedimentary discontinuities in cross sections. Delineation of stratigraphic discontinuities and unconformities is required to organize a succession chronologically and to discriminate genetically different geomorphic units imaged in plan view (e.g., different fluvial channels and channel belts). Without those surfaces, it may be extremely difficult to chronologically separate closely spaced geomorphic features seen in conventional 3-D seismic data.

The primary limitation of conventional 3-D seismic data is that the cross sectional seismic expression of geomorphic depositional elements may be too crude to delineate stratigraphic discontinuities. Therefore, it is difficult to accurately and precisely correlate geomorphic elements in plan view with specific sequence-stratigraphic surfaces in cross section. It may be difficult to determine whether closely spaced channels and channel belts lie within different sequences or simply represent
autocyclic aggradational stacking of avulsing rivers. In this study, this difficulty was resolved by integrating high-resolution, shallow-penetration two-dimensional (2-D) seismic sparker and boomer lines with the 3-D seismic survey to allow much higher resolution of stratigraphic discontinuities. With a vertical resolution approximately 25 times greater than the 3-D seismic data, 2-D data afford resolution down to approximately 25 cm (∼9.8 in.) and permit identification of detailed stratigraphic architecture. Consequently, erosive high-amplitude stratigraphic discontinuities can be interpreted on 2-D data and then correlated with geomorphic features imaged in 3-D seismic data.

The study area lies within the Tertiary Pattani rift basin, located in the central Gulf of Thailand (Figure 1). The studied interval comprises the uppermost 80 m (262 ft) (70–150 m [230–492 ft] below sea level; Figures 2, 3) of the modern low-gradient Sunda Shelf. Within that interval, several fluvial systems were identified at different depths within the 3-D seismic volume and along 2-D sparker lines. Previous workers (Feng, 2000; Samorn, 2006) suggest that the uppermost section...
Figure 2. The (A) uninterpreted and (B) interpreted high-resolution two-dimensional sparker cross section (peak frequency $\sim 2000$ Hz; tuning thickness $\sim 25$ cm ($\sim 10$ in.)) showing six major stratigraphic discontinuities (marked in red) that define seven discontinuity-bounded stratigraphic (DS) units in the uppermost 80 m (262 ft) of the Gulf of Thailand Shelf. Note that valleys “hang” only from these discontinuities and do not show fluvial aggradation outside the valleys. Compare with Figure 3B for an alternative interpretation of the same cross section but derived from the three-dimensional volume. Refer to Figure 4 for the plan-view location of the cross section. Evolution and stratigraphic relationships are analyzed in detail in the sequence-stratigraphy section.
Figure 3. The same cross section as in Figure 2 but shown as a conventional three-dimensional (3-D) seismic cross section display (peak frequency \( \sim 70 \) Hz; tuning thickness \( \sim 5.7 \) m \([\sim 18.7 \) ft]). (A) Uninterpreted cross section and (B) interpreted cross section showing an alternative interpretation from that shown in Figure 2B; the interpreted cross section shows a single lowstand valley with a multistory low net-to-gross fill encased in older highstand deposits and capped by transgressive facies. Resolution of conventional (3-D) seismic data does not allow distinction of the discontinuities seen in Figure 2. This has a direct impact in the interpretation of stacking patterns of fluvial deposits. Refer to Figure 4 for the plan-view location of the cross section.
of the Gulf of Thailand Shelf is Pleistocene in age. Continental-scale fluvial systems imaged throughout the data set have the same order of magnitude as the modern Chao Phraya River, which flows through Bangkok and into the Gulf of Thailand and ranges from 150 to 220 m (492–722 ft) wide, approximately 50 km (~31 mi) inland from the shoreline. This report provides the first integrated study that combines detailed facies architecture of fluvial, estuarine, and deltaic systems, as determined from high-resolution 2-D seismic lines, with analysis of the plan-view geomorphic images derived from 3-D seismic data (time slices).

Although previous works have addressed the 3-D bed-scale facies architecture analysis of modern fluvial point-bar deposits (Bridge et al., 1995; Bridge, 2003) and ancient fluvial and deltaic systems (Corbeanu et al., 2004; Lee et al., 2007) using ground-penetrating radar (GPR), these studies are typically limited to small-scale surveys of a single bar, representing only small parts of the depositional system. The data presented in this report cover 1870 km² (722 mi²) and provide bed-scale seismic facies characterization of point bars and mouth bars and plan-view images of depositional systems, interpreted in a regional sequence-stratigraphic framework.

The presence of alternating fluvial and marine deposits in the uppermost 80 m (262 ft) of the Gulf of Thailand indicates exposure and submergence of the shelf numerous times during the Pleistocene. Changes in sea level, climate, and sediment discharge likely controlled the accommodation and resulting basin-fill geometry. In general, accommodation in upstream areas distal to the shoreline was controlled by local factors such as fluvial discharge and sediment supply fluctuations, whereas accommodation in downstream areas closer to the shoreline was controlled more by relative sea level fluctuations (Posamentier and Allen, 1999; Holbrook et al., 2006). The low-gradient Sunda Shelf probably allowed rapid and extensive transgressions and regressions, with only minor relative sea level changes. Subsidence and tectonics are considered to be less important controls because of the short time span (Pleistocene) of the studied interval.

The sequence-stratigraphic model (sensu Posamentier and Vail, 1988), originally based on marine seismic data, was later extended to continental strata (Shanley and McCabe, 1994) and applied in numerous studies, with particular emphasis on sea level, climate, sediment supply, subsidence, and tectonic controls (Schumm, 1993; Legarreta and Ulina, 1998; Blum and Törnqvist, 2000; Wellner and Bartek, 2003; Hanebuth and Stattegger, 2004; Murray and Dorobek, 2004; Darmadi et al., 2007). In this study, the model was used to better understand and explain the evolution of the sedimentary fill and specifically to evaluate the existence of inner-shelf, shallow incised valleys in a low-gradient shelf setting. In low-gradient settings, especially where relative sea level falls do not fully expose the shelf and deep knickpoints do not form, rivers may not incise very deeply, if at all, during lowstand time (Posamentier, 2001). Current models of incised valleys require multistory fluvial deposits as a fundamental criterion for recognition (Blum, 1994; Dalrymple et al., 1994; Shanley and McCabe, 1994, Zaitlin et al., 1994); in this study, we suggest that multistory valley fills may not be a requisite to define an incised valley. In other words, an incised valley can have an active meandering river sitting at its base during a lowstand of sea level, and if the proper physiographic and accommodation conditions are met during transgression, the valley can experience a rapid flood that results in an abrupt backstepping of the shoreline and a flooding of the valley and fluvial system. The resultant valley fill may not show an aggradational multistory valley fill, as predicted by Shanley and McCabe (1994), but instead be characterized by a single fluvial story sitting at the base of the valley, overlain by estuarine and/or open-marine mudstones. This situation is described in this study.

The objectives of this study were to (1) identify the principal depositional systems present in the continental shelf of the Gulf of Thailand and document the seismic facies manifestation of estuarine and deltaic deposits (previously seismically unidentified in the study area); (2) provide the first integrated seismic stratigraphic and seismic geomorphologic study based on 3-D seismic data and high-resolution 2-D seismic data, characterizing
the stratigraphic architecture and geomorphology of fluvial point bars, as well as deltaic deposits; (3) delineate bed-scale stratigraphic discontinuities in 2-D sparker lines to discriminate genetically distinct closely spaced fluvial features observed in 3-D time slices, thereby facilitating the correlation of geomorphic features with bed-scale stratigraphy; (4) interpret the sequence-stratigraphic evolution of the uppermost approximately 80 m (~262 ft), thus determining whether the vertical closely spaced channels and channel belts represent autocyclic aggrading fluvial systems or allocyclic degradational systems lying within separate sequences; (5) document the existence of an inner-shelf single-story incised valley; and (6) determine channel and channel-belt geometry and sand versus mud distribution within these fluvial systems.

DATA SET AND METHODS

The data set comprises a time-migrated 3-D seismic reflection marine survey (Figure 4) acquired by Chevron Thailand for hydrocarbon exploration purposes. A peak frequency signal of 70 Hz and an average seismic velocity of 1600 m/s for the shallow interval studied results in a vertical resolution of 5.7 m (18.7 ft). Sheriff (1991) defined resolution as the "minimum separation of two bodies before their individual identities are lost." Resolution of seismic data has two limits: limit of separability and limit of visibility (Brown, 2004). The limit of separability, commonly named vertical resolution or tuning thickness in the literature, is always $\lambda/4$ (one quarter of a wavelength) and it is the minimum thickness at which you can delineate and separate two distinct interfaces from each other. Below $\lambda/4$, destructive interference between the two corresponding wavelets progressively attenuates the amplitude signal, eventually ending up with no signal at thickness zero. The limit of visibility, also known as detectability, is a variable fraction less than $\lambda/4$ dependent on rock type/age and seismic phase and noise, and it is the minimum thickness at which you can still identify or detect the existence of two interfaces, without actually being able to pinpoint exactly their position or thickness (Kallweit and Wood, 1982; Brown, 2004). The horizontal expression of the limit of separability, known as the Fresnel zone, can theoretically reach a minimum diameter of $\lambda/4$ if perfect 3-D migration is performed, but realistically, $\lambda/2$ is more appropriate (Brown, 2004).

Despite the fact that both vertical and horizontal resolutions rely on the same data-dependent variables (frequency, wavelength, velocity, noise, reflection coefficient), below resolution but still detectable depositional elements (e.g., scroll bars in a point bar) are easier to visualize, detect, and interpret in plan view than in section view. This is not a matter of differences between vertical and horizontal resolution/detection, but a matter of visual perception. In general, it is easier to infer a geologic explanation from a plan view than from a section view image. Plan view–based interpretations (i.e., geomorphological analyses) yield more robust interpretations of lithology distribution and geologic process than section view–based interpretations (i.e., stratigraphic analyses). An example of this would be in the case of fluvial channels, where plan-view details such as meander scrolls, channel sinuosity, crevasse splays, and laterally incised tributaries are all potentially observable in plan-view images compared with much more limited information available in section views. Section views may characterize details such as channel asymmetry and reservoir architecture; however, the variety and richness of detail observable in section views are limited compared with what is available from plan views. In general, the ideal workflow should incorporate insights from both views, although plan-view images will ease and enhance the recognition of both resolvable and detectable geologic features.

In this 3-D data set, strata need to be at least 5.7 m (18.7 ft) thick for seismic data to be able to distinguish the base of a unit from the top (limit of separability). Similarly, two different reflecting points in horizontal space have to be approximately 10 m (~33 ft) away from each other to be recognized as two distinct features. However, in this excellent quality data set, which is near the sea floor and comprises young sediments, geologic features considerably thinner and horizontally closer can
nonetheless be detected (limit of visibility) both in plan view and cross section.

Seismic amplitude map displays at specific seismic times, that is, time slices, are characterized by dark-colored areas, where the negative parts of seismic wavelets are intersected by the time slice, and light colors where the positive parts of seismic wavelet are intersected by the time slice (Brown, 2004). The resulting patterns imaged on these seismic time slices extracted from the 3-D volume were analyzed to identify geomorphic features in plan view (i.e., seismic geomorphology; Posamentier, 2000). Coherence displays were used to assist in defining channel margins.

A 2-D high-resolution marine seismic reflection survey (sparker and boomer lines), acquired to identify possible shallow hazards that could constitute threats to the stability of the legs of offshore oil platform rigs, was used to obtain detailed cross sectional bed-scale stratigraphic relationships. Cross sections were analyzed on the basis of seismic reflection terminations (i.e., lapout). Lapout terminations defined a series of depositional sequences and component systems tracts (Vail et al., 1977).

Sparker and boomer lines are powered by an electromagnetic signal that can operate only in salt water to meet the conductivity requirements of the system. The advantage of offshore sparker and boomer profiles compared with GPR and other onshore sonar techniques is that no weathering or topographic corrections are to be made to the data, hence, the resulting images have less distortion.
The dominant frequency of these 2-D sparker and boomer lines is approximately 2000 Hz, which allows resolution of channel margins, channel-fill patterns, and internal bedding architecture, with a tuning thickness of 20 to 30 cm (Figure 2). An average seismic velocity of 1600 m/s was used to convert two-way traveltimes to depth in the shallow studied interval (uppermost 80 m [262 ft] of the shelf). This velocity is characteristic of young unconsolidated marine substrates rich in clay and sand (Orsi and Dunn, 1991; Brown, 2004).

Shallow geotechnical borehole descriptions and measurements of soil strength and water content at different depths, down to 150 m (492 ft) below the present sea bed, were used to obtain lithologic information of stratigraphic discontinuities seen in the 2-D sparker lines. No digital well logs, cores, or rock age dates were available for this study. Successful integration and manipulation of 3-D seismic volumes, together with 2-D high-resolution sparker lines, were accomplished using Paradigm’s geophysical 3-D canvas and VoxelGeo applications.

SEISMIC GEOMORPHOLOGY

A traditional approach in the analysis of 3-D seismic data consists of panning through the volume at successive seismic time slices to identify and characterize the evolution of geomorphic features and structural trends in plan view (Posamentier, 2000; Posamentier et al., 2007). Geomorphic analysis...
of seismic time slices works especially well where strata are nearly horizontal. In such instances, flattening on horizons (i.e., strata slices or horizon slices) and then slicing are not necessary, and simply slicing through the original volume yields a satisfactory result. Horizon slices (i.e., amplitude extractions parallel to tracked horizons) and flattened horizons are particularly useful when dealing with tilted or folded strata. Figure 4 shows a succession of time slices extracted from the seismic volume. Figures 5 and 6 show details of key fluvial systems observed at 120, 160, and 184 ms. Depositional elements shown in Figure 5 are also analyzed in high-resolution 2-D cross sections in the seismic stratigraphy section (see discussion below).

A cursory examination of the time slices reveals a complex landscape of clustered channels apparently superimposed on each other (Figures 4C–F, 6D–F). This is a direct result of the different channels and channel belts being closely spaced in vertical space, making it difficult to separate genetically different geomorphic features seen in the same 3-D time slice. In other words, the 3-D seismic slices cannot resolve closely spaced geomorphic features; hence, they appear to coexist on specific time slices, although they are not coeval. Ultimately, the 2-D seismic data were used to distinguish and differentiate the multiple channel systems. Correlation between channels and channel belts imaged in time slices with cross sectional channel-fill patterns (Figure 7) revealed that fluvial systems seen on time slices are systematically concentrated above the stratigraphic discontinuities that are imaged in 2-D lines (Figure 2). To image those
Geomorphic features, 3-D time slices were selected to coincide as close as possible with the level of the main stratigraphic discontinuities shown in Figure 2. Although seismic time slices represent horizontal planes that do not necessarily follow the irregular contour of the stratigraphic discontinuities apparent in the 2-D lines, this procedure proved to be a fair approximation for geomorphic imaging along these surfaces. Time slices at 88, 120, 160, and 184 ms (Figure 4) display a complete representation of the geomorphic features located just above the main stratigraphic discontinuities defined within the studied interval.

Starting at the sea floor, the first geomorphologically significant patterns visualized when panning down through the 3-D seismic volume are north-northwest–south-southeast–trending positive-relief elongate-shaped features with dimensions up to 3 km (1.8 mi) long, 300 m (984 ft) wide, and 5 m (16 ft) high, lying on the modern sea bed, at approximately 88 ms (~70 m [~230 ft] below sea level). Based on shallow geotechnical borehole studies done in conjunction with the placement of drilling platforms, it is known that these partially reworked deposits consist of soft clay sediments (mud mounds) that are aligned with modern north-northwest–south-southeast sea-bottom currents having speeds of 0.3 to 0.4 m/s (R. McAndrew, 2008, personal communication). Data outside the study area suggest that these elongate mounds comprise erosional remnants formed by scour of the sea floor. Refer to Figure 2 for vertical expression of mud mounds and Figure 4A for plan-view appearance. The first sea-floor reflection multiple is observed at approximately 170 ms subsea, obscuring the seismic imagery of geomorphic elements at that level.

Immediately below the sea bed, at 96 ms subsea, two fluvial systems were distinguished in the northeastern corner of the data set: an east-west–trending highly tortuous narrow channel and a wider north-northwest–south-southeast–trending channel belt showing downstream point-bar translation toward the south-southeast (Figure 4B). The east-west highly tortuous channel shows no evidence of channel migration and no apparent alluvial depositional elements within the channel.
Figure 6. The plan-view images of continental-scale channel and channel belts evident at 160 ms (A, B, C) and 184 ms (D, E, F). Panels A, B, and C represent the 160-ms time slice visualized as (A) conventional amplitude display, (B) coherence seismic attribute, and (C) mapped surface delineating the major geomorphic and depositional elements. Panels D, E, and F represent the 184-ms time slice visualized as (D) conventional amplitude display, (E) coherence seismic attribute, and (F) mapped surface delineating the major geomorphic and depositional elements. Refer to Figure 4E and F for location of time slices. Panel G is a modern analog with similar dimensions and comparable depositional elements, Ucayali River, Peru (data available from the U.S. Geological Survey).
The fluvial system imaged at 120 ms (Figures 4C, 5) also is characterized by paleoflow toward the south-southeast. This meandering system, which is similar in size and sinuosity to the modern Chao Phraya River, exhibits a highly sinuous upstream segment, followed by a central less-sinuous zone, and a highly sinuous downstream area, with point bars, scroll bars, and meander loops. The internal bed-scale point-bar architecture and channel-fill seismic facies will be discussed in the section titled Seismic Stratigraphy.

At 140 ms, we observe a single, narrow, north-south–trending tortuous incised channel across the center of the map, which merges with a wider south-southeast–trending meander belt toward the south (Figure 4D). Both the tortuous channel as well as the larger meander belt are characterized by incision into their respective floodplains.

Time slices at 160 and 184 ms exhibit the largest fluvial systems imaged within the seismic volume (Figures 4E, F; 6). These continental-scale rivers are slightly wider than the modern Chao Phraya River. As the resolution of the 2-D sparker lines decreases considerably with depth, fluvial architectural analysis was not able to be performed on these two systems.

Figures 4–6 illustrate how different amplitude and coherence map displays along time slices delineate geomorphic features such as channels, channel belts, and smaller incised tributary valleys that cut into the interfluves next to trunk fluvial systems. Within the channel belts, chute cutoffs and neck cutoffs are imaged, as well as point bars showing evidence of both meander loop expansion and downstream translation. Channel abandonment fills have a different amplitude response from bar deposits both in plan view as well as high-resolution cross sections (Figure 7; see also Seismic Facies discussion). This distinctive characteristic is interpreted to be the product of lateral variations in lithology, with inferred sand-prone facies associated with the bar deposits and muddy facies associated with the fill of the last position of the channel before abandonment, resulting in a mud plug. Moreover, greater
differential compaction directly over the abandoned channels supports the interpretation of mud-filled channel systems (discussed in the Seismic Facies section).

Most fluvial systems in the studied section consist of single-channel meandering rivers that range from less than 50 m (<164 ft) to as much as 600 m (1970 ft) wide. Although some fluvial systems are narrow and do not show channel-belt and bar deposition, the meandering systems seen at 120, 160, and 184 ms show clear channel-belt development with widths as much as 10 km (6.2 mi) (Samorn, 2006; Reijenstein, 2008). These dimensions are slightly larger than the modern Chao Phraya River but are comparable to other continental-scale analogs such as the Ucayali River in Peru (Figure 6G).

Of all the observed fluvial systems in the volume, the meandering channel seen at 120 ms (Figures 4C, 5, 7) illustrates the best example of preserved channel-belt and valley-fill deposits, in both 2-D sparker sections and 3-D time slices. The northern part of the trunk valley exhibits well-imaged incised tributary valleys that are seen at successive time slices and are observed to incise into the interfluves.

The central part of the system shows narrower channel-belt widths, which coincide with a decrease in sinuosity, and an increase in downstream scroll bar translation (Figure 5). This suggests that valley width may exert control on bar expansion and translation and therefore the sinuosity of the channel.

A widening of the valley is visible in the southern region of the channel belt, where sinuosity increases and meander loop abandonment and oxbow lake formation can be observed. An unusual small-scale, asymmetric, subparallel drainage pattern was observed on top of the inner bends of point-bar deposits exclusively in the southernmost downstream limit of this system. The point bars and associated drainage pattern seem to be restricted within the confines of the valley (Figure 8A). All these characteristics were recognized by Jones et al. (2003) in the modern shallow-marine epicontinental Gulf of Carpentaria’s East Coast (Australia), where a diurnal mesotidal regime exists and intertidal deltaic point-bar deposits are constantly being reworked by tidal currents (Figure 8B). These entrenched drainage patterns (i.e., small channels that extend into the adjacent supratidal mud flat) are tributaries to the main meandering tide-dominated channel and carve into underlying point-bar deposits. The similarities between the modern and ancient examples suggest that the fluvial point-bar deposits seen in the 3-D volume (Figure 8A) were later partially reworked by tidal currents. The south-southeast regional paleoflow direction, coupled with the presence of increasing tidal influence and meander loop abandonment toward the southern parts of the fluvial system, indicates that this part of the system was close to a shoreline affected by a tidal regime at that time. Tide-dominated channels can extend as far as 15 km (9.3 mi) from the coast, where they become river dominated but still tidally influenced (Jones et al., 2003).

This incised fluvial system has an average channel-to-channel belt width ratio of 1:10 and a channel-to-valley depth ratio of 1:2. The basal 15-m-thick point-bar deposits comprise about half of the valley fill, with the remaining (i.e., upper) section of the valley fill characterized by inferred estuarine and marine mudstones (Figure 9). The interpretation of estuarine and marine deposits of alternating silt and mud is based on the continuous moderate-to-high-amplitude nature of these reflections from one side of the valley to the other (see discussion below). The topographically higher adjacent interfluve shows a regional slope of 0.091° toward the valley (Figure 2). Although no multistory fluvial deposits are observed within the main valley, three main genetic units can be distinguished: an initial fluvial stage, followed by a transgressive estuarine phase, and a final open-marine interval that capped the entire valley and onlapped the regional gently sloping interfluve (refer to the Discussion section for interpretation). Point-bar architectural analysis and seismic facies descriptions were conducted on this fluvial system (at 120 ms or ∼95 m [∼312 ft] below sea level). Deltaic clinoforms at approximately 170 ms were characterized based on observations from two 2-D lines. No plan-view deltaic geomorphic features were observed at this interval probably because of interference with the sea-floor reflection multiple.
SEISMIC STRATIGRAPHY

Seismic Facies

Examination of high-resolution 2-D sparker lines allowed differentiation of seven seismic facies based on reflection strength, continuity, and geometry: (1) convex-up moderate- to high-amplitude reflections (commonly associated with lateral accretion surfaces as seen in dip view), (2) convex-up bidirectionally downlapping moderate to high-amplitude reflections (commonly associated with strike-view transects across the core of point bars), (3) chaotic low-amplitude reflections (commonly associated with high-energy point-bar tops), (4) high-amplitude discontinuous reflections (commonly associated with lateral accretion surfaces as seen in dip view), (2) convex-up bidirectionally downlapping moderate to high-amplitude reflections (commonly associated with strike-view transects across the core of point bars), (3) chaotic low-amplitude reflections (commonly associated with high-energy point-bar tops), (4) high-amplitude discontinuous reflections (commonly associated with lateral accretion surfaces as seen in dip view).
associated with channel-lag deposits), (5) concave-up low-amplitude continuous seismic reflections (commonly associated with deltaic clinoforms), (6) high-amplitude laterally continuous reflections (commonly confined within valleys and associated with estuarine fill), and (7) low-amplitude to transparent laterally continuous reflections (commonly associated with widespread marine sediments) (Figure 10).

Seismic facies were used to describe the internal architecture of fluvial point-bar deposits and deltaic clinoforms (Figure 11) and evaluate the differences between fluvial, marine, deltaic, and estuarine seismic character. Seismic facies also were critical for explaining the distribution of different environments of deposition in time and space within a sequence-stratigraphic context.

Deltaic clinoforms exhibit concave-up geometry with a seaward decrease in slope, ranging from 1.76 to 2.04° in clinoform tops to 0.37 to 0.91° toward the base. In contrast, point-bar lateral accretion surfaces display sigmoidal to convex-up geometries with high angles in middle positions of the point bar and low angles at the top and base. Observed slope angles range from 0.49 to 0.62° in point-bar tops and bottoms and up to 3.74° toward the middle of the bar. However, because most seismic traverses are not oriented along true dip, the actual slope angles likely are somewhat higher.

In addition to the geometric differences previously described, two of the most important distinctions between clinoforms and point-bar lateral accretion surfaces are scale and areal extent. Individual clinoform reflections in the deltaic systems extend approximately 1.5 km (~0.9 mi) horizontally from the point of toplap where they are truncated by erosion to the point where they terminate as downlap and merge into a condensed section at the base, whereas single fluvial point-bar lateral accretion surfaces rarely exceed 300 m (984 ft) in length from top to bottom. Furthermore, the top-truncated clinoforms on Figure 11 represent the preserved fraction of what had been thicker mouth-bar deposits, suggesting that the original clinoform dimensions were of greater areal extent. The minimum estimated area (based on multiple 2-D sections) of the mouth bar is at least 11 km², whereas the area of the point bar is only 6.2 km². The preserved thickness of the clinoform package reaches 20 m (66 ft), whereas point bars do not exceed 15 m (50 ft).

Fluvial Architecture

The internal architecture of modern sandy point bars shows erosive basal surfaces and lateral accretion surfaces that exhibit abrupt lateral changes in inclinations. These changes in inclination were interpreted by Bridge et al. (1995) to represent discrete episodes of bar accretion and erosion associated with flood recurrence intervals of decades to centuries. Corbeau et al. (2004) used 2-D and 3-D GPR data, outcrop descriptions, and drill-hole information to study the internal architecture of ancient marine-influenced point-bar deposits. The lateral accretion surfaces they describe form concave-up inclined bedsets. Lee et al. (2007)
<table>
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<th>2-D Seismic Facies</th>
<th>Reflection Character / Sedimentologic Interpretation</th>
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| ![Image](image1.png) | **Convex-up lateral accretion surfaces.**  
High-amplitude inclined seismic facies |
| ![Image](image2.png) | Point-bar lateral accretion surfaces as seen in a dip-view cross section; Convex-up geometry with downdip increase in slope: 0.48° to 0.62° (point-bar tops) and 0.48° to 3.74° (basal point bar). |
| ![Image](image3.png) | **Convex-up bidirectional downlap;**  
High-amplitude inclined seismic facies |
| ![Image](image4.png) | Point-bar lateral accretion surfaces as seen in a strike-view cross section |
| ![Image](image5.png) | **Low-amplitude chaotic seismic facies**  
Reworked point-bar top deposits |
| ![Image](image6.png) | **High-amplitude channel lag seismic facies**  
Basal coarse-grained channel lag |
| ![Image](image7.png) | **Concave-up clinoforms;**  
Low-amplitude inclined seismic facies |
| ![Image](image8.png) | Clinoform deltaic mouth bar deposits; Concave-up geometry with downdip decrease in slope: 1.76° to 2.04° (clinoform tops) and 0.37° to 0.91° (basal section) |
| ![Image](image9.png) | **High-amplitude, confined, laterally continuous reflections;**  
Seismic terminations onlap against valley walls |
| ![Image](image10.png) | Early transgressive estuarine muddy facies |
| ![Image](image11.png) | **Low-amplitude (transparent), laterally continuous seismic facies**  
Open marine muddy facies |

**Figure 10.** The classification of high-resolution two-dimensional seismic facies based on reflection strength, continuity, and geometry. From the seven defined seismic facies, the first four correspond to fluvial channel bar deposits (within the channel belt). The following three seismic facies represent deltaic facies, estuarine deposits (abandoned channel and upper valley fill), and open-marine mudstones.

identified three GPR seismic architectural elements within an ancient top-truncated mixed fluvial-and tide-influenced delta, distinguishing between fluvial-dominated mouth bars, shallow delta-slope channels, and subhorizontal tidally influenced bars. Although these studies have addressed the 3-D bed-scale facies architecture analysis of different deposits, they are limited by the lower penetration depth of GPR (<15 m [<49 ft]) when compared with the sparker data presented in this study (~120 m (~394 ft)).

The 2-D sparker dip-view cross sections along point bars (Figures 11, 12) show abrupt lateral changes in inclination of lateral accretion surfaces similar to those described by Bridge et al. (1995) and Bridge (2003). However, nearly strike-view
cross sections along the outer bends of single-channel meandering point bars (Figures 9, 11, 13) show bidirectional downlap that resembles braid-bar internal architecture as proposed by Bristow (1993), Bristow and Best (1993), and Bridge (2003). These bidirectionally downlapping surfaces represent lateral accretion surfaces of meandering channels as seen in oblique view. Therefore, bidirectional downlap alone is not diagnostic of a braided fluvial system.

The irregular shape of point-bar tops (Figures 11, 12) reflects the undulating depositional nature of accreting point bars and subsequent minor chute-channel reworking on top. This rugosity of the point-bar top as seen in section view corresponds to the apparent scroll bars observed in plan view.

The transverse cross section along the outer bend of the point bar shown in Figure 13A exhibits the preservation of estuarine (Figure 13B) and

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**Figure 11.** The two orthogonal interpreted and uninterpreted two-dimensional sparker cross sections and a time slice showing the internal architecture and plan-view depositional elements of fluvial point-bar deposits (yellow), estuarine deposits (green), and deltaic clinoforms (orange). Seismic facies characterization allowed the seismic distinction between these deposits in cross section and proper correlation to plan-view depositional elements in time slices. Black arrows indicate paleoflow direction. For a regional plan-view location of the two cross sections, refer to Figure 5.
point-bar deposits (Figure 13C) corresponding to the last pulse of bar accretion under low-flow conditions before channel abandonment (Figure 13D). Changes in inclination of the point-bar deposits (lateral accretion surfaces) in dip view result in discontinuity-bounded strata sets (Figure 13C) that relate to changing discharge conditions. Point-bar accretion is interpreted to be constructed during both low- and high-flood conditions, therefore, the preservation of fluvial sandy point-bar deposits provides insight to paleoflow conditions. Low-flow bar components (i.e., discontinuity bounded strata sets lying in stratigraphically lower parts of the point bar) scale to a lower water depth and lower discharge conditions, whereas high-flow bar deposits scale to higher discharge conditions. The high-amplitude, discontinuous, and “bursty” reflections observed at the base of the point bar probably correspond to coarse channel-lag material (coarse sand to gravel). The moderate-amplitude seismic reflections that characterize the middle part of the point-bar deposit likely corresponds to the presence of homogeneous sand, whereas the upper part of the point bar is characterized by discontinuous low- to mid-amplitude reflections that likely correspond to low-energy and reworked sand and mud that caps the point bar.

The fill of abandoned channels comprises an integral part of the fluvial deposits observed here. Abandoned channel deposits, such as those that fill the oxbow lake observed in Figures 9 and 13, are characterized by continuous and sagging seismic reflections. The sagging aspect of these reflections, as well as the continuous nature of these reflections, suggests a differential compaction effect associated with a silt- or mud-prone fill. These deposits are more compactable than associated sand-prone point-bar deposits, hence, the sagging reflection character.

**Estuarine Architecture**

Continuous moderate- to high-amplitude reflections are commonly observed within the upper parts of the incised valleys. These reflections onlap both valley margins and are inferred to correspond to predominantly fine-grained sediments. Evidence for marine influence is observed within the downstream reaches of some of the incised valleys observed. This evidence is in the form of short, tightly spaced drainage lines originating at the tops of point bars and directed orthogonally toward associated channels (Figure 8). The degree to which abandoned channel plugs are filled with estuarine sediments is not clear. Where meander loop cutoffs can be observed, the mud plugs associated with oxbow lakes likely comprise a combination of lacustrine (toward the base) and estuarine (toward the top)
deposits. However, where mud plugs are observed in association with entire fluvial system abandonment, then an estuarine origin for these deposits is possible. These observations suggest that the estuarine facies represented here comprise late-stage fills of incised valleys.
Sequence Stratigraphy

Geotechnical borehole measurements of soil strength and water content at different depths revealed the existence of several overconsolidated horizons, which correlate to high-amplitude stratigraphic discontinuities seen in high-resolution 2-D lines (Figure 14). Consolidation of the substrate may be the product of soil development and compaction during subaerial exposure, which results in an increase of soil strength and bulk density at these horizons. Seismically, an increase in bulk density results in an increase in the reflection coefficient and acoustic impedance contrast between discrete layers, giving rise to the high-amplitude reflections previously described. Similar surfaces described as buried soils that formed during subaerial exposure also have been documented in the Texas Gulf Coast Pleistocene alluvial plain deposits of the Beaumont Formation (Blum, 1993; 1994) and in the central Sunda Shelf (Hanebuth et al., 2002).

Based on seismic reflection termination geometries observed on 2-D lines, the interpretation of seismic facies can be integrated with 3-D–derived plan-view interpretations of depositional systems. This analysis resulted in identification of seven depositional sequences (DS.1 through DS.7) with associated systems tracts (sensu Mitchum et al., 1977; Vail et al., 1977; Posamentier and Vail, 1988; Van Wagoner et al., 1990). These depositional sequences are bounded by sequence boundaries (SBs) that were identified based on the following criteria: (1) high-amplitude reflections and basal erosive character (i.e., stratigraphic discontinuities) as observed on 2-D sparker lines, (2) existence of plan-view trunk fluvial systems being fed by numerous incised tributary valleys located on associated interfluves (Posamentier, 2001) and display dendritic gullies in time slice view, and (3) presence of overconsolidated horizons thought to result from soil development during subaerial exposure, as measured by geotechnical borehole soil properties.

Depositional sequences average approximately 20 m (~66 ft) and rarely up to 40 m (131 ft) thick. Typical sequences comprise a simple sedimentary fill showing basal valley-confined fluvial strata, overlain by estuarine and subsequently marine seismic facies and/or occasional concave-up clinoform seismic facies. Fluvial lowstand deposits (convex-up lateral accretion surfaces or bidirectional downlap seismic facies) commonly overlie SBs and are overlain by a transgressive surface followed by mud-prone estuarine deposits corresponding to the transgressive systems tract (TST) (confined laterally continuous seismic facies). The maximum flooding surface (MFS) commonly caps the underlying TST and is in turn overlain by highstand open-marine muddy sediments. Seismic character toward the top of the highstand transparent seismic facies shows an increase in acoustic impedance contrast, probably representing the late stages of the highstand systems tract (HST) (see top of DS.3 in Figure 2B). The late HST is rarely preserved and in some cases, complete depositional sequences were removed by erosion associated with the subsequent SBs (e.g., DS.3 in Figure 2B). Maximum relief of these erosive surfaces reaches 35 m (115 ft) (i.e., the depth of incised valleys). The sequence-stratigraphic evolution of the studied section is summarized below and in Figure 2B. Limited resolution

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**Figure 13.** (A) The strike-view cross section across a point bar (yellow); lower point-bar deposits show well-preserved lateral accretion surfaces along the curved edges of the point bar and bidirectional downlap in the middle parts. Black arrows show paleoflow direction. (B) The point-bar deposits are draped by valley-confined laterally continuous estuarine seismic reflections (green); notice the differential compaction above the channels, suggesting they are filled with mud. (C) The fluvial architecture showing discontinuity bounded stratases that separate units with different seismic reflection character and inclinations, probably associated with changing discharge conditions. (D) Details showing one of the curved edges of the point bar with preserved low-flow bar deposits; the vertical stratigraphic section is probably characterized by basal interbedded sand and coarse sand, followed by homogeneous sandstones, and interbedded sand and mud, conforming a fining-upward succession capped by estuarine mudstones. (E) The plan-view location of cross section (A) showing the transect orientation relative to the point bar and evidence of a southward paleoflow direction. Refer to Figure 11 for the vertical location and to Figure 5 for the regional plan-view location.
Figure 14. The high-resolution two-dimensional (2-D) sparker line and shallow geotechnical borehole log illustrating water content (%) as a function of depth. Note that low water content values (overconsolidated horizons) correlate to high-amplitude reflections seen in the 2-D line. The water content can be used as a proxy for bulk density and, therefore, used to identify key reflectors or stratigraphic discontinuities, possibly associated with sequence boundaries. The location is not shown in map view because of the proprietary nature of these data.
below DP.6 restricted the interpretation to the uppermost six depositional sequences:

1. Early fluvial sedimentation in DS.6 was interpreted to have been followed by a relative sea level rise and subsequent northeast deltaic progradation during the HST.

2. A regional erosive surface-truncated clinoform tops and created SB.5 (possible forced regression). Transgression followed and highly continuous marine transparent seismic facies onlapped SB.5. No lowstand fluvial deposits were seen on DS.5.

3. Sequence boundary SB.4 truncated older marine deposits of DS.5 and was locally truncated by the overlying SB.3, resulting in little preservation of DS.4 (Figure 2B). However, in other areas within the data set where subsequent erosion was less severe, lowstand fluvial systems of DS.4 were better preserved (Figure 6A–C).

4. Sequence boundary SB.3 is one of the most widespread erosion surfaces in the study area and DS.3 shows diverse seismic facies. Confined lowstand valley-fill fluvial deposits characterize the early fill. Toward the top of the valley, changes in seismic character define the transgressive surface first and the MFS second, with open marine deposits on top. An upward increase in acoustic impedance contrast likely corresponds to the early stage of the late HST.

5. Sequence boundary SB.2 locally truncated the entire DS.3 (Figure 2B) and shows a well-developed lowstand fluvial incised-valley fill with the overlying early transgressive seismic facies (estuarine muds) indicated by both 2-D lines and 3-D time slices. The lowstand systems tract (LST) and early TST are capped by highly continuous open-marine seismic facies (transparent seismic facies) of the HST.

6. Sequence boundary SB.1 is probably related to the last glacial maximum and does not exhibit deep incision or well-imaged fluvial systems. However, neighboring areas show good preservation of lowstand deposits (L. Meagher, 2008, personal communication). These deposits were rapidly overlain by a thin layer of transgressive deposits, which were later reworked into the north-northwest–south-southeast positive-relief elongate-shaped mud mounds that sit on the modern sea floor.

**DISCUSSION**

**Recognition of Incised Valleys**

Extremely wide incised valleys of tens and even hundreds of kilometers have been described in the literature (Dalrymple et al., 1994; Van Wagoner 1995; Anderson et al., 1996; Wellner and Bartek, 2003), some of them exceeding depths of hundreds of meters (Van Wagoner et al., 1990; Dalrymple et al. 1994). Other described valleys are barely tens of meters deep (Willis, 1997; Reynaud et al., 1999; Lobo et al., 2003; Wellner and Bartek, 2003). Although most incised valleys show multistory fluvial deposits (Blum, 1993; 1994; Shanley and McCabe, 1994) the shallow incised valley (<35 m [<115 ft]) described in this study exhibits a simple valley fill with single-story fluvial deposits on the bottom, overlain by valley-constrained estuarine facies, and capped by open-marine mudstones (Figure 15).

The criteria used in this study to interpret the fluvial system seen at 120 ms (Figure 5) and contained within DS.2 (Figure 2B) as a shallow incised valley are enumerated below. Both cross sections (2-D data) and time slices (3-D data) exhibit evidence of valley incision.

Cross section evidence (high-resolution 2-D data):

1. Presence of incised tributary valleys cutting into their own floodplain (Figure 11), leaving the once active floodplain abandoned and serving as interfluves (Posamentier, 2001).

2. The regional slope toward the valley (Figure 2B) and the absence of topographically higher levees and associated overbank deposits reinforces the interpretation of an abandoned floodplain.

3. The tops of the point-bar deposits lie at half the height of the interfluve level (Figures 9, 15), a paleobathymetric attribute that suggests that even when the river was at flood stage, the flow...
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was unable to overtop the adjacent antecedent floodplain (i.e., interfluves).

4. The existence of transgressive valley-confined seismic facies draping channel point-bar deposits and onlapping the valley walls, suggesting confinement, probably related to an estuarine setting (also see plan-view evidence below).

Plan-view evidence (3-D data):

1. Presence of subordinate incised tributary valleys that extend as far as 5 km (3.1 mi) away from the principal trunk valley (Figure 5); these erosive features imply that the floodplain was inactive and characterized by permanent drainage systems.

2. The existence of tidal drainage reworking patterns sitting on top of point bars (Figure 8), coupled with the cross sectional evidence of transgressive valley-confined seismic facies sitting on top of the fluvial deposits, suggests a paleoenvironmental interpretation associated with the upstream part of a tide-dominated estuarine embayment, consistent with the model of Dalrymple et al. (1992) and characteristic of the initial flooding stage of the valley.

An implicit but fundamental characteristic, not only of this fluvial system, but of the entire succession, is the degradational nature. Channels and channel belts are vertically restricted to the lower positions of each sequence and are systematically positioned inside valleys, without any evidence of fluvial floodplain aggradation outside those “containers.” Figure 2B illustrates this distinctive degradational stacking pattern that shows that the LST and TST are only preserved within the valleys, whereas the overall aggradation is strictly limited to the inferred marine mudstones of the HST. The controls that affect these stacking patterns will be discussed in the following section.

Controls on Valley Formation, Accommodation, and Preservation Potential

The main controls in producing large-scale stratigraphic discontinuities and valley incision in tectonically stable shelf settings are subsidence, eustasy, and climate change (fluvial discharge and sediment supply). Fluvial discharge, in most instances associated with climate change, controls the depth of fluvial incision, valley size, and scale of depositional elements. Subsidence regulates the overall section thickness, and eustasy controls the high-frequency stratigraphic events that punctuate the succession. The combination of these factors determines the overall accommodation on the shelf and controls the preservation potential of different environments of deposition and systems tracts. However, the role of eustasy rapidly diminishes upstream, as local factors such as tectonics and climate become dominant (Posamentier and Allen, 1999) (Figure 16).

Recent studies focused on Southeast Asia emphasize the importance of climatic and fluvial discharge controls on the formation of incised valleys, instead of eustatic sea level falls (Wellner and Bartek, 2003; Clift, 2006). An interpretation of discharge-driven control suggests that incision and gully formation occurs during periods of maximum fluvial discharge regardless of sea level position. In glaciated terrains, ice melt is a key driver of discharge fluctuations; in nonglaciated terrains, climate variations can have a similar effect. Climate change can occur at any time during a sea level cycle and is not necessarily tied to periods of glaciations or deglaciation, although it is suggested that more significant climate changes likely occurred during the transition from the Pleistocene to the Holocene than within a particular sea level lowstand or highstand period. Nevertheless, it is difficult to sort out the specific effects of sea level change versus climate change in the genesis of fluvial valley incision.

Figure 15. The time slice and cross section across the valley showing three discrete valley-fill stages: (A) point-bar accretion during active fluvial deposition (lowstand), (B) transgressive deposits passively onlapping the valley walls, and (C) open-marine highstand sediments capping the entire incised-valley complex. Refer to Figure 8 for the location of time slice and cross section. Schematic block diagrams reproduced with permission of AAPG (Posamentier, 2001); landscape photos reproduced with permission of SEPM (Posamentier and Allen, 1999).
Posamentier and Allen (1999) suggested that in downstream sections, sea level change is the primary cause of fluvial incision, whereas in upstream sections, climate change and tectonics are the dominant drivers.

If eustatically driven, the relatively shallow incision depths (<35 m) of the rivers observed here may be explained by the absence of a nearby knickpoint in the low-gradient (~0.007°) Gulf of Thailand shelf. This could result from the significant distance of the study area from the shelf edge (>1000 km [>621 mi]). Under this low-gradient condition, the shoreline can shift enormous distances with only minor relative sea level changes, exposing or flooding large areas in short periods (Pelejero et al., 1999; Hanebuth et al., 2011). Under this low-gradient condition, the shoreline can shift enormous distances with only minor relative sea level changes, exposing or flooding large areas in short periods (Pelejero et al., 1999; Hanebuth et al., 2011). Indeed, the relatively small area covered by incised tributary valleys compared with the area of trunk fluvial systems would suggest short-lived sea level lowstands. Alternatively, the limited extent of incised tributary valleys may suggest that short-lived climatic change and its role in fluvial discharge variation, instead of eustasy, was the cause of fluvial incision. However, this is not to say that eustasy played no role at all. The role of sea level change was to cause huge shifts of the shoreline through time. Consequently, coastal deposits tended to accumulate either near the shelf edge (during sea level lowstands), hundreds of kilometers downstream from this study area, or near the innermost margin of the shelf (during sea level highstands), hundreds of kilometers upstream from this study area.

Once incised valleys form, they tend to fill exclusively with fluvial and estuarine sediments (Allen and Posamentier, 1993). Clear imaging of alluvial depositional elements within incised valleys (Figure 5) suggests a high preservation potential of fluvial deposits (Posamentier, 2001) but limited
only to incised “containers.” Conversely, the absence of distributive channel patterns or delta lobes between marine highstand deposits and the succeeding lowstand fluvial deposits suggests low preservation potential of regressive deltaic successions in this area. In the inner-shelf to midshelf positions, which characterize the study area, the shoreline likely did not become stationary, but rather was in rapid “transit,” heading either seaward during sea level fall, or landward during sea level rise. As explained before, this is especially common in low-gradient shelf settings where even minor fluctuations of sea level would result in significant shifts of the shoreline. Nonetheless, it cannot be ruled out that the shoreline could have paused in this area although for such a short time that no significant record of this period was preserved. Only one clearly recognizable marginal marine depositional element was recognized here, a top-truncated deltaic mouth bar identified on two 2-D sparker lines. It can be said, therefore, that the landward parts of LSTs (i.e., fluvial incised-valley fill) and the seaward parts of HSTs characterize the stratigraphic section in this study area.

The stratigraphic architecture in this area of the Gulf of Thailand is characterized by aggradation that is entirely restricted to marine deposition, which occurs during sea level highstands (Figure 2B). During lowstands, fluvial systems tended to act as bypass systems with minor deposition, delivering sediments to the paleoshoreline via shallow incised valleys. Preserved fluvial deposits likely correspond to the late stages of sea level lowstands when the rate of creation of accommodation began to increase. Consequently, SBs extend from the base of incised valleys laterally across interfluves where they merge with transgressive surfaces. The TST is represented here only as estuarine caps of incised valleys (Figure 9), with little or no deposition on associated interfluves.

The delineation of sequence-stratigraphic surfaces such as incised valleys, SBs, and maximum flooding surfaces depends on the resolution and scales of the data used. Samorn (2006) described seven sequences within the last 26 m.y. (Oligocene to present) in the Gulf of Thailand, equivalent to an average of approximately 5 m.y./sequence. This study demonstrated the existence of higher frequency sequences clear on the 2-D data but more difficult to resolve in the 3-D data. High-resolution 2-D lines permitted the identification of seven high-frequency sequences in just approximately 80 m (~262 ft) of strata, which likely represents 600 to 700 k.y., assuming 100-k.y. Milankovitch cycles. Previous studies revealed that major sea level lowstands during the Pleistocene had a predominantly approximate 100-k.y. recurrence interval based on δ18O records (Pillans et al., 1998; Caputo, 2007) and uranium-series dating methods (Gallup et al., 1994; Scholz, 2005). Only sea level lowstands of those magnitudes were great enough to fully expose the modern 70- to 130-m submerged shelf in the study area (Posamentier, 2001), hence, the interpretation of the time span representing the studied section.

As a result, within each sequence described by Samorn (2006), several smaller scale sequences (10–30 m thick) of marine transgression and regression are likely linked to low-accommodation, low-gradient, and low-subsidence rates. The 3-D seismic data probably scale to third-order sequences (1–10 m.y.; Vail et al., 1977) or sequence sets, whereas the 2-D data have sufficient resolution to define fourth-order (0.1–1 m.y.) to fifth-order (0.01–0.1 m.y.) sequences, which would likely correspond to Milankovitch frequencies.

**IMPLICATIONS FOR HYDROCARBON EXPLORATION**

Understanding fluvial dynamics helps to predict sandstone distribution and reservoir compartmentalization. Accurate 3-D characterization of point-bar sandstone bodies and their internal configuration allows a better understanding of reservoir connectivity. Bed-scale discontinuities can be caused by mud-drape deposition during low-flow hydrodynamic conditions (Willis, 2007) affecting reservoir connectivity, whereas large-scale discontinuities, such as channel abandonment mud plugs and/or incised-valley walls, can act as lateral stratigraphic seals to the adjacent sandy channel-belt bar deposits, resulting in a compartmentalized reservoir system.
A common pitfall in hydrocarbon exploration and field development is to assume that channels, which may be imaged in 3-D seismic time slices, are homogeneous reservoir-filled elements. A tendency to overlook the inherent complexity within channel-fill deposits exists; the observations presented here highlight this complexity and can prove invaluable for the construction of more precise and accurate static reservoir models. Integration of high-resolution 2-D lines with 3-D time slices in this area clearly shows that the reservoir-prone elements commonly are the point-bar deposits, whereas the channels themselves tend to be mud filled, corresponding to filling with mud that occurs subsequent to channel abandonment. These mud-filled channels repeatedly cut across the sand-prone point-bar deposits, potentially isolating one point bar from another, creating reservoir compartments. The degree to which the mud plugs will serve as baffles or barriers depends on the nature of the abandonment fill. Commonly, channel-lag deposits at the base of the abandoned channel can serve as connections, albeit tenuous, between point-bar compartments (Donselaar and Overeem, 2008). Where such channel lags are continuous, the abandoned channel plugs may serve only as baffles to hydrocarbon flow, and barriers, where lags are discontinuous to absent (Figure 17).

This study also suggests that in inner-shelf to midshelf settings, incomplete systems tracts are observed. That is, HST deposits are predominantly characterized by distal marine nonreservoir facies, whereas LST deposits are characterized by fluvial incised-valley-fill deposits. Transgressive systems tract deposits appear restricted to nonreservoir estuarine incised-valley sediments commonly observed to overlie lowstand fluvial deposits.

Figure 17. The combined three-dimensional and two-dimensional block diagram showing the control of complex fluvial architecture in sandstone compartmentalization. Yellow overlay indicates channel-bar sand-prone facies, whereas the channel and interfluves are mud prone. (A) The mud-filled meandering channel compartmentalizes the sandy channel belt in four separate reservoirs. (B) The interpreted block diagram shows a close-up view of a point bar. Detailed strike and dip view cross sections along the point bar display bidirectional downlap and lateral accretion seismic reflections, respectively. Chute channels sit on top of the point bar. Note that the mud-filled channel may act as a lateral barrier for hydrocarbon migration in reservoir-prone point-bar deposits if the mud plug sits right on top of the channel-belt floor and no channel-lag deposits are present. Refer to Figure 5 for the regional location of panel A.
CONCLUSIONS

This article integrates plan-view geomorphic images of shelf depositional systems derived from 3-D seismic data (time slices), with detailed facies architecture and bed-scale seismic facies characterization of fluvial point bars, estuarine valley-fill deposits, and deltaic mouth bars (clinoforms), as determined from high-resolution 2-D seismic lines. This integrated approach permitted precise description of the complex stratigraphic architecture of different geomorphic features seen on time slices, thanks to the very high resolution 2-D data, with a tuning thickness of approximately 25 cm (∼9.8 in.).

Successful delineation of high-frequency stratigraphic discontinuities in 2-D sparker lines allowed a chronological organization of the approximately 80-m (262-ft)-thick succession that led to accurate correlation of geomorphic elements in plan view with specific sequence-stratigraphic surfaces in cross section. In addition, recognition of these surfaces in section view clarified the temporal relationship between channels and channel belts observed in the same 3-D time slices (channel clusters). Thus, it could be determined that these channel belts lie within different sequences and do not represent mere stacks of autocyclic avulsing fluvial systems.

The dominant style of deposition in this area comprises highstand distal marine shelf and minor marginal marine deltaic sedimentation and lowstand incised-valley fluvial sedimentation. Minor amounts of estuarine deposition are observed capping incised-valley fills. The creation of new shelf accommodation occurs primarily during transgressions and subsequent highstands, with minimal accommodation, mostly restricted to incised valleys, during lowstands.

Depositional elements observed here include fluvial and tide-influenced point bars, estuarine valley fills, abandonment mud plugs (including oxbow lake fill as well as entire abandoned channel fill), and marginal marine deltaic mouth bars. Dipping reflections that are characteristic of both point bars and mouth-bar clinoforms can be differentiated based on whether they have concave-up geometries, indicative of point bars, versus convex-up geometries, indicative of point bars. Furthermore, point-bar lateral accretion surfaces tend to discretely downlap, whereas mouth-bar clinoforms tend to have long runouts before they eventually end. Bidirectional downlap of fluvial-bar deposits, which was previously proposed as diagnostic of braided systems (Bristow, 1993; Bristow and Best, 1993; Bridge, 2003), was shown to occur in association with a single-channel side-attached point bar in this study, suggesting that transect orientation can be critical to a correct interpretation.

Incised valleys are a common feature in this part of the shelf. A detailed analysis of the channel belt seen at 120 ms (Figure 5) revealed that it is a single-story system emplaced within a shallow (<35 m [<115 ft]) incised valley. The criteria used for recognition of this system as an incised valley included the presence of incised tributary valleys, absence of levees and associated overbank deposits, observation that the top of the point-bar deposits lie at half the height of the interfluve level, existence of a valley fill that includes a fluvial and an estuarine stage, and the regional slope of the interfluvies toward the valley. The most likely controls for valley formation are inferred to be an increase in fluvial discharge associated with climate change. These variations are superimposed on the deposition of sequences involving a series of marine to nonmarine successions that are inferred to be associated with high-frequency, high-amplitude sea level changes.

Different amounts of erosion along SBs and the varying styles of accommodation created at different times determined the degree to which LSTs, TSTs, and HSTs of each depositional sequence were preserved. In contrast, with clear evidence for fluvial and distal shelf deposition in this area, little or no evidence for highstand nearshore marine deposits is found here. This is likely because in this midshelf to inner-shelf location, the shoreline rarely remained long enough to produce any significant deposits; instead, it was in rapid transit across this area. Likewise, because accommodation creation during times of transgression was mostly confined to flooded valleys, TST deposits are only minimally represented here, in the form of the tops of incised-valley fills.
Single-channel fluvial systems associated with side-attached point bars are the dominant fluvial style in this area. In association with this style of fluvial system, abandoned channels are a common feature. The recognition that these abandoned channels are mostly mud filled has important consequences for hydrocarbon exploration and development. Such mud-filled channels can serve as mud plugs that can serve as barriers or baffles to hydrocarbon migration.

REFERENCES CITED


Blum, M. D., 1994, Pleistocene Beaumont alluvial plain construction in response to interacting glacio-eustatic and climatic controls, Texas Gulf Coast plain (abs.): Gulf Coast Association of Geological Societies and Gulf Coast Section of SEPM Meeting (AAPG Gulf Coast Section), Austin, Texas, v. 78, no. 9, p. 1450–1450.


Hanebuth, T. J. J., H. K. Voris, Y. Yokoyama, Y. Saito, and


Shanley, K. W., and P. J. McCabe, 1994, Perspectives on the...