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Research article

Seismic Geomorphology in the Late Cenozoic Depositional Evolution of the Gulf of Thailand

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ABSTRACT

Recent development of three-dimensional (3D) seismic datasets enables geologists to visualize and analyze buried land- and sea-scapes revealed by subsurface geophysical data in a manner resembling surface geomorphology. The seismic geomorphology is useful to interpret seismic patterns for geomorphology of a formation, which is similar to using satellite and aerial photos of the Earth's surface. A successful study of seismic geomorphology at the Gulf of Thailand situated within the Sunda shelf reveals the detailed information of paleoenvironment of the Pleistocene to Holocene time. Three sequence boundaries have been observed from the 3D seismic data. These sequence boundaries are related to a change in relative sea level during Pleistocene to Holocene time. The study area is dominated by delta, estuarine and present-day marine environments. The stacked point bar zone has formed in the study area that is potential a reservoir for shallow gas and/or biogenic gas. These results are expected to be a useful tool for petroleum exploration and development in the Gulf of Thailand and adjacent areas.

Key words: Seismic geomorphology, Paleoenvironment, Gulf of Thailand, Sunda shelf

1. Introduction

The Gulf of Thailand belongs to an inner shelf continental margin of the Sunda shelf and consists of a number of petroliferous basins developed in the Cenozoic. The Sunda shelf was originally described as covered by marginal marine sediments that have been submerged and reworked during the last rise in sea level (Hanebuth *et al*., 2009). More recent studies, however, have shown that the Sunda shelf has experienced a more complex Late Ceonozic history than previous thought, particularly for the delta to the fluvial environment within inner shelf area (*e.g*. Hanebuth *et al*., 2009; Reijenstein *et al*., 2011). In addition, lithofacies analysis alone cannot provide sufficient evidences to evaluate the history of a relative sea level change known to control the complicated deposition of the latest Pleistocene–Holocene. Seismic geomorphology is useful to interpret seismic patterns for geomorphology of a formation, which is similar to using satellite and aerial photos of the Earth's surface. 3D seismic data from shallow depth have led to a new generation of fluvial studies that provide detailed information about the range of channel geometries and evolutionary histories. Recent development of 3D seismic data enables geologists to visualize and analyze buried land- and sea-scape revealed by subsurface geophysical data in a manner resembling surface geomorphology. Hence, numerous studies of seismic geomorphology have been investigated within the Gulf of Thailand in the last decade (*e.g.* Posamentier 2001; Miall, 2002; Reijenstein *et al*., 2011). In addition, recent publications and modern 3D seismic data show a great detail of seismic pattern of shallow succession, which can be used to constrain geomorphology study within this, study area (*e.g.* Reijenstein *et al*., 2011).

The objective of this paper is to investigate the recent depositional history of the Gulf of Thailand by performing seismic geomorphology observed from 3D seismic data. Results of this interpretation are then used to document sea-level fluctuations and the deposition environments within the Gulf of Thailand during the latest Pleistocene–Holocene. Furthermore, the variations with geomorphology changes of fluvial deposits of this study can be used in assessing fluvial architecture models and shallow marine geohazard in petroleum exploration.

2. Geological framework

The Gulf of Thailand is inherited from the opening of the Cenozoic rifting and clockwise rotation of the Himalayian orogeny during the Cenozoic. Major faults of this area are oriented mainly in a north-south direction (figure 1). As a result of this event, the fluival-lacastrine channels were then developed in the north-south grabens and half-graben basin. This basin is believed to be dominated by a rift system and has been subject to continued subsidence since the Late Oligocene time (Lockhart *et al*., 1997; Jardine, 1997; Morley and Westaway, 2006). The Gulf of Thailand is also located in Sunda shelf with an extremely low gradient (Hanebuth and Stattegger, 2004). This shelf was widely exposed during the Last Glacial Maximum giving sea level was approximately -123 m lower than today (Hanebuth *et al*., 2009). In addition, small relative sea level changes during the Pleistocene–Holocene may cause the variation of depositional environments and sedimentary facies.

The present day, the Gulf of Thailand has a mean water depth of about 45 m and maximum water depth of 80 m (Morley *et al*., 2011). During the Pleistocene lowstand, the area was subaerially exposed and fluvial river system extended to a coastline that lay several hundred kilometers to the south. The sea level fall led to erosion and reworking of the earlier highland deltaic sediments and redeposition further downstream together with material transported directly from the upper area of the river system (Morley and Westaway, 2006). Channels are recognized seismically in the Gulf of Thailand from their seismic termination pattern.

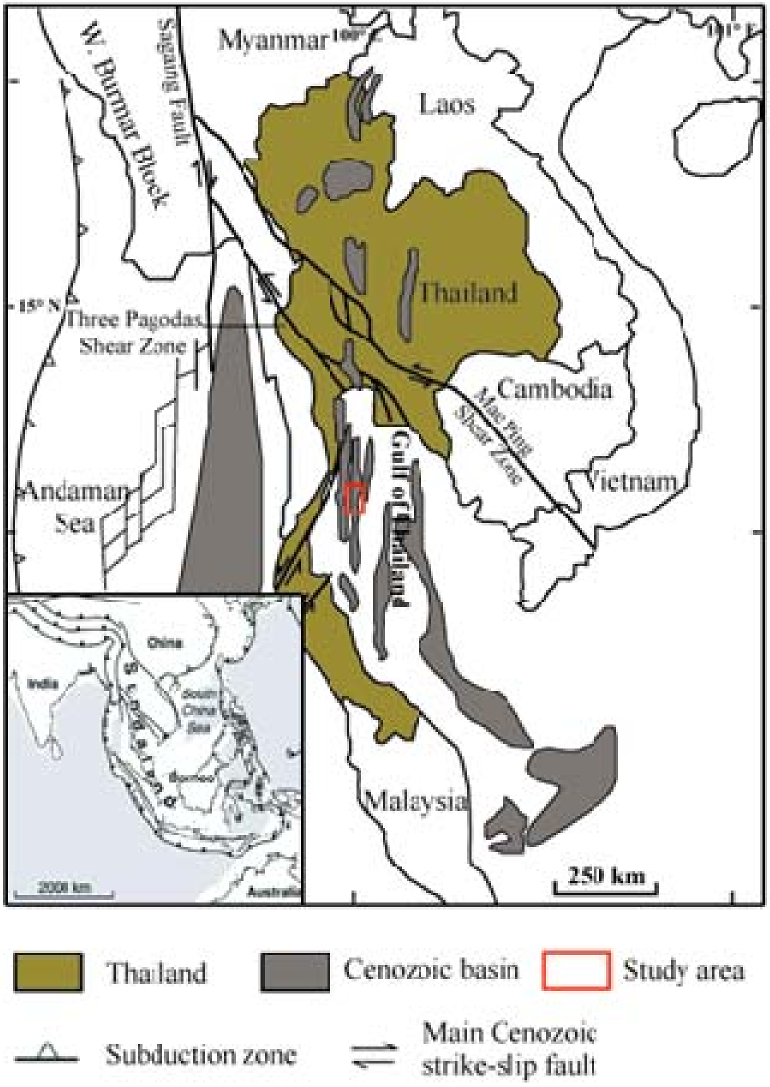

Figure 1. Location of major Cenozoic basins in Thailand and a simplified structural outline of the region. Basin and fault outlines shown are modified from Fyhn *et al.* (2010).

3. Methods and data

The data presented here are 3D seismic data images from shallow subsurface depths. The focus of this study has been the overburden succession (Pleistocene to Holocene) and data down to approximately 400 ms two-way travel-time (TWTT) were analyzed in detail. The highest frequency present in the seismic data is about 70 peak frequencies. The seismic volume is the full stack volume, where acoustic impedance increases ("hard" reflections) are indicated by positive amplitudes illustrated as white troughs. Bin spacing is 12.5m in both directions. The typical resolution in the seismic data set is about 5 to 10 m vertical (l/4) and 10 to 20 m horizontal (l/2) when assuming an average seismic interval velocity of 1680 m/s for the entire Pliocene to Holocene overburden.

Visualization techniques included time amplitude slices and vertical amplitude displays were chosen, representing changes in channels geometry across the study area. Five time slices were generated for observing details of key channels. These are the slices at TWTTs of 390, 280, 230, 170 and 140 ms. The time slices illustrate a complex landscape of clustered channels apparently superimposed on each other. Hence, a superimposition of underlying and overlying time slices was drawn to increase the confidence for geomorphic feature interpretation (figure 2).

One unavoidable but serious limitation of our study is the lack of lithological data for discussing, although we provide, where available, well logs and summaries of lithological information from published studies. This study is mostly based on the interpretation of 3D seismic geomorphology and the interpretation of recently published seismic data to constrain the accurate interpretation (*e.g.* Riegentian *et al*., 2011).

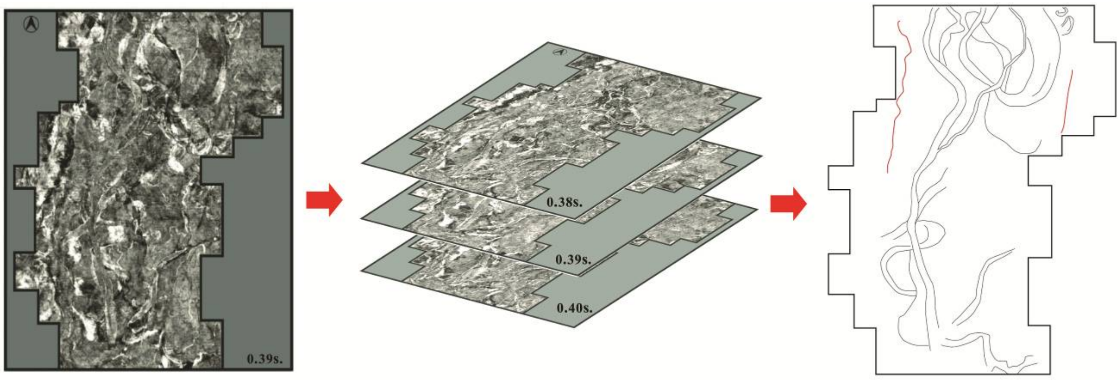

Figure 2. A superimposition of the time slices drawn to emphasize the vertical succession of features along within the study area.

4. Results

4.1) Vertical seismic

The vertical seismic facies established 4 sub-zones within the Pleistocene to Holocene interval. This interval is interpreted as a highstand to lowstand system tract, which is eroded by a major incision surface (sequence boundary) that were identified by high amplitude refection and base erosive character. The major variations in the vertical seismic profiles and seismic facies lead to the key sequence boundaries. These are located approximately 350, 210 and 160 ms TWTT presented as erosional surfaces (figure 3). These erosional surfaces suggest the lowstand system trace or sea water-level dropping

(Wood, 1996). In depositional sequence, the sequence boundaries are overlain by transgressive surface follow by mud-porn sediments corresponding to transgressive system tract (TST). The maximum flooding surface (MFS) commonly caps the underlying TST and is in turn overlain by highstand. In uppermost of the depositional sequence has been observed low amplitude and lateral continuous seismic characters suggested open marine deposits (Reijenstein *et al*., 2011).

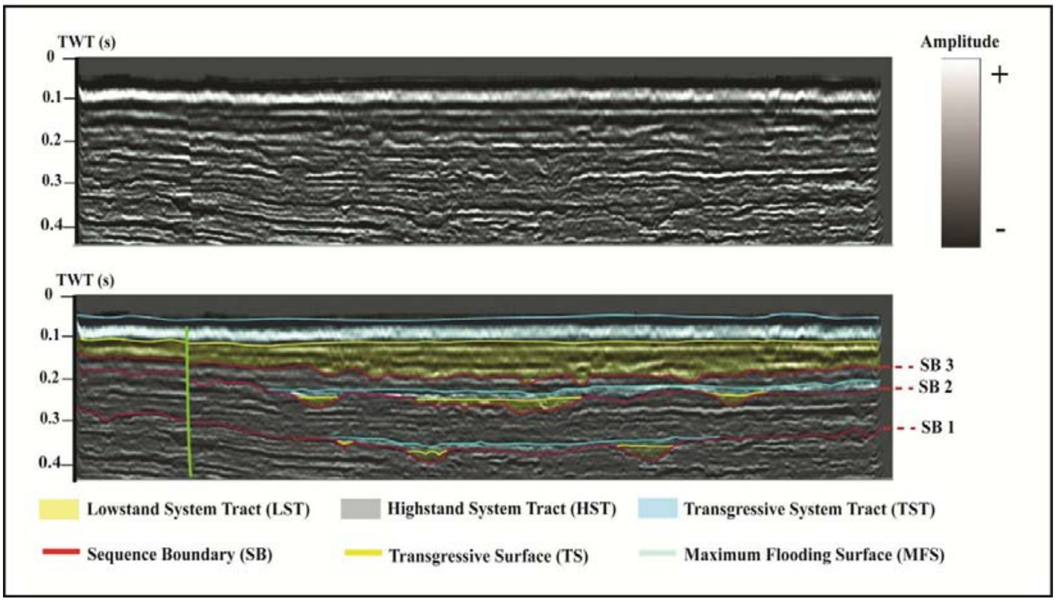

Figure 3. The uninterpreted (top) and interpreted (bottom) vertical section showing three erosion surfaces (marked in red) define that three depositional sequence unit.

The incised valleys were interpreted to form only when the magnitude of sea-level fall was great enough to expose the entire shelf (Posamentier, 2001). Maynaerd *et al.* (2010) simply defined an incised valley to be any channelized element that is bounded at its base by a sequence boundary. Hence, incised valleys can be used to infer a change in sea level within the area. The channel fills typically begin to accumulate during the next base-level rise, and may contain deposits of the following highstand and subsequent sea-level cycles. Likely, due to limitations in seismic resolution, no internal architecture is imaged within these fills.

4.2) Horizontal time slice

According to vertical section results, sea level has strongly related to the depositional environment of the area. Five horizontal time slices show different channel patterns and geomorphic features for each time slice. The depositional elements are based on a best estimation of vertical location of each illustrated river system. Horizontal time slice in lowstand (390, 230, 140 ms TWTT) is characterized by straighter channels and incised channels. While, horizontal time slice in highstand (280 and 170 ms TWTT) is characterized by meander channels, point-bar, meandered scar and flooding surface. The selected horizontal time slices from each section are presented in figures 4 to 8.

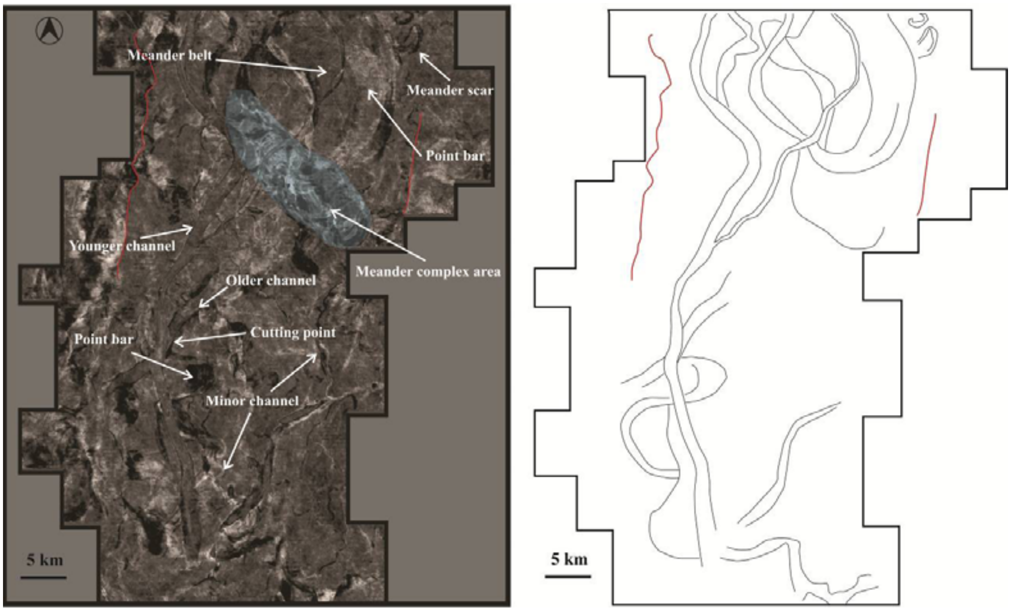

Figure 4. Interpreted fluvial systems in the 390 ms seismic time slice. The absence of parts of the older channel at cutting point in this time slice indicated that the younger channel cuts the older channel. Meander complex area is marked in blue area. Faults are highlighted in red lines.

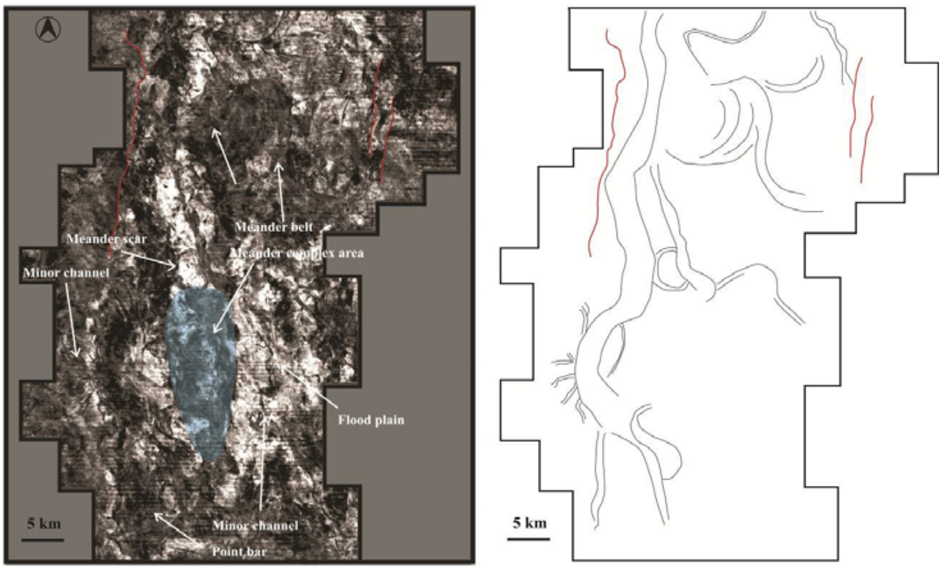

Figure 5. Interpreted fluvial systems in the 280 ms seismic time slice. The minor channels at western part are interpreted to flow toward the main channel. Meander complex area is marked in blue area. Faults are highlighted in red lines.

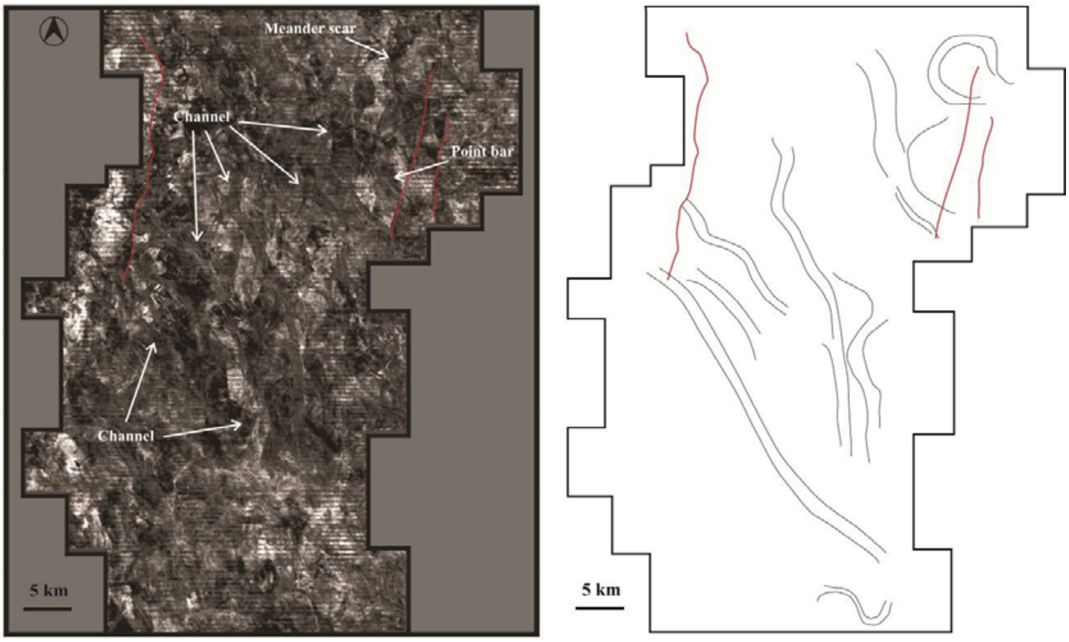

Figure 6. Interpreted fluvial systems in the 230 ms seismic time slice. Faults are highlighted in red lines**.**

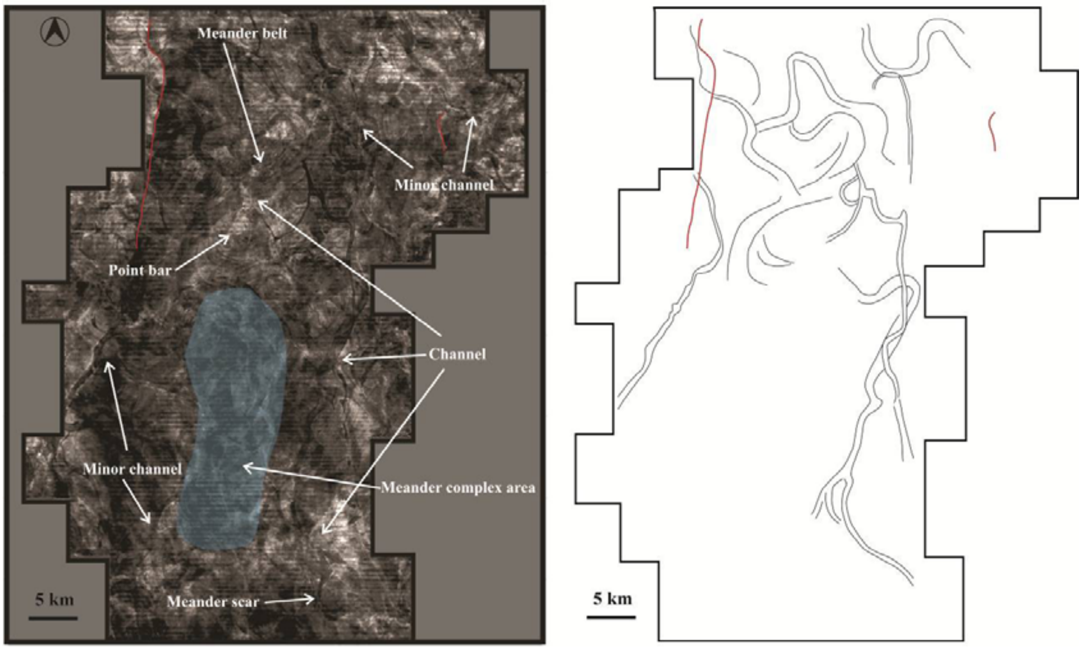

Figure 7. Interpreted fluvial systems in the 170 ms seismic time slice. The small channels as "bird nest" pattern are dominated in this time slice. Meander complex area is marked in blue area. Faults are highlighted in red lines.

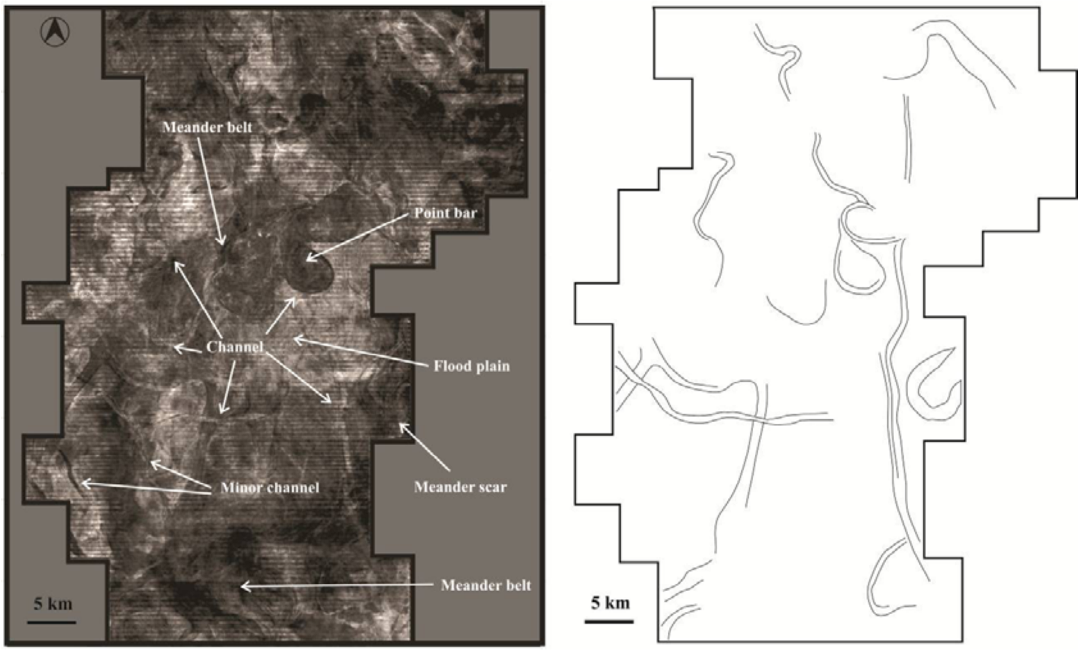

Figure 8. Interpreted fluvial systems in the 140 ms seismic time slice. The channels in this time slice are relatively small compared to underlying time slice.

4.3) 390 time slice

A prominent channel is presented in the central part of the analyzed 390 ms time slice (figure 4). This channel is the main incised channel and it is therefore concluded that at this level presented the base level of lowstand system trace. The flanks of the channel system are cut by gully-like features and are characterized by continue parallel reflections. Incised channel is single and oriented mostly in the north-south direction. Upper part of this channel is tortuous and elongate in center and lower part. Oder channels are a single channel with higher meander than incised channel. Faults in this study area lie in north-south direction.

4.4) 280 time slice

The meandering channels are clearly visible in the 280 time slice (figure 5) and they are somewhat narrower than in the underlying time slice (typical up to 500 m, vs the 700 m width in the 390 ms time slice). Numerous minor channels are visible, mostly of low sinuosity. In the northern part of the area is a prominent meander belt with a meander radius of approximately 3 km. Meander scrolls are clearly visible. Channels are oriented in north-south and northwest-southeast direction. Geomorphic features exhibit point bar development in the upper part of the area. Younger channels are also developed in north-south direction and their meander ratios are less than older channels.

This time slice was believed to be influenced by marine from sea level rising.

4.5) 230 time slice

The major channels are clearly visible in the 230 time slice (figure 6). The observed channels in this time slice and their width are slightly altered from underlying time slice. This time slice is dominated with straight channels and less meander belts. Older channels are oriented in northwest-southeast direction. These channels are meandered and developed point bars. While, younger channel is oriented in northwest-southeast and it is appeared as straight channel. The straight channels cross the area from the north to the south of the area. It has a similar geometry to low energy channels of the common type in fluvial-dominated area far from sea level. This may indicates the sea level drop during short period of time. Minor channels at the flank of channels are seen in this time slice.

4.6) 170 time slice

The channel width in this time slice decreases from the underlying time slice. Channels are oriented in northwest-southeast direction (figure 7). In this time slice, older channels are well developed in highstand and given channel elements and geomorphic features similar to the horizontal time slice 280 ms TWTT. The prominent meander belt is clearly seen in the 170 ms TWTT with radius of approximately 4.5 km. It should be noted that the meander belt appeared only northern part of the area, then the channel seems to be likely straighter in the southern part of the area. This may indicate of the change in current energy along the channel. This time slice is also characterized by "bird nest pattern" of the minor channels probably indicated the low energy channels in the area close to sea level.

4.7) 140 time slice

Channels in this time slice (figure 8) are oriented in various directions and are mainly narrow. The channels are narrower than underlying time slice. The most sharply defined channels are moderate to high sinuosity. In addition, a "bird nest" pattern is dominated on this time slice. The orientation of the minor channels is an E-W direction. Point bar and oxbow lake were clearly observed in this time slice. The uppermost part of the shallow time slice (above 140 ms TWTT) is quite smooth landscape and is difficult to observe geomorphic features suggested that the formations are probably mud dominated due to the influence of marine environment at the present. Hence, above 140 ms TWTT interval is interpreted as a marine origin.

5. Discussions

5.1 Channel system

Interested interval, Pleistocene to Present succession, has been observed three erosional surfaces suggested the lowstand system trace alternating with highstand system. Channels are well developed in the area and they appear within every depositional system. Channel width decreases upward from the lower to upper section. Most channels have low sinuosity ratio (1-1.5) and exhibit straight geometry (sinuosity ratio convergence to 1). The channels in lowstand period are characterized by low meandering, while meandering is medium to high in highstand period. Main geomorphic features in both highstand and lowstand systems are point bar, flooding surface and meander scar. Incised channel is typically found in lowstand system. These geomorphic features and incised channel can be used to compare to the previous published study nearby area (*e.g.* Reijenstein *et al*., 2011).

In addition, the changes of the channel direction from north-south to approximately east-west in the uppermost part may indicate the change in the paleography, which controls the constriction forcing the channel to reroute in an orientation. This is still uncertainty and need to be verified in this area.

5.2 Paleoenvironment

Regarding to previous publication and well data (internal report), the geomorphic features and seismic facies of this study are very comparative to previous publication by Dalrymple and Choi (2007) and Reijenstien *et al*. (2011) indicated that this area is probably an estuarine and a deltaic environment origin deposits associated with incised valley. This study area can be interpreted to be deltaic environment and estuarine environment from lower to upper section, respectively. The geometry of the incised valley system of the area is narrow divergence at the downstream which is similar to model of Dalrymple and Choi (2007). Continuous moderate- to high amplitude reflections within the upper part of the incised valleys have been observed above erosional surface at 170 ms TWTT which is interpreted to be marine origin. The change of the local paleoenvironment has been observed and was believed to relate to the changing of sea-level within the Gulf of Thailand. To better understand the evolution of the environment of the area, a schematic cartoon is shown in figure 9. The detail of each period is summarized as follows.

1. Lowstand period is represented by horizontal time slice 390, 230, 140 ms TWTTs. These horizontal time slices have been controlled by large scale incised valley trending north-south. Environment for 390 and 230 ms TWTTs are interpreted to be an upper delta plain and are dominated by fluvial influence. The environment of 140 ms TWTT is interpreted to be an upper estuarine. The uppermost section is interpreted to be recent marine system with marine-sediment filled channels.

2. Highstand period is represented by horizontal time slice 280 and 170 ms TWTTs. These horizontal time slice are dominated by narrow- to medium-width channels with larger point bar compared to lowstand system trending in northwest-southeast and north-south. Geomorphic features are characterized by point-bar, meander scar and flooding surface. Environment is interpreted to be a lower delta plain and is dominated by marine influence.

5.3 The importance of recognizing stacked point bar zone

Stacked point bar deposits, as recognized through the uppermost interval, are characterized by broad negative zone. They usually consist of silt to sand size, which is preliminary container for shallow gas storage. Therefore, recognizing and avoiding stacked point bars in shallow sections would have the potential to improve efficiency and reduce shallow marine geohazard for development program. The morphological character of the stacked point bar is concave scroll pattern, which is identifiable in time slice of 3D seismic data. In this case, basic geomorphological principles are essentially useful in the interpretation of 3D seismic data. In addition, high resolution 3D seismic and various kinds of seismic attribute may be able to use for investigating fluid phenomena within stacked point bar zone.

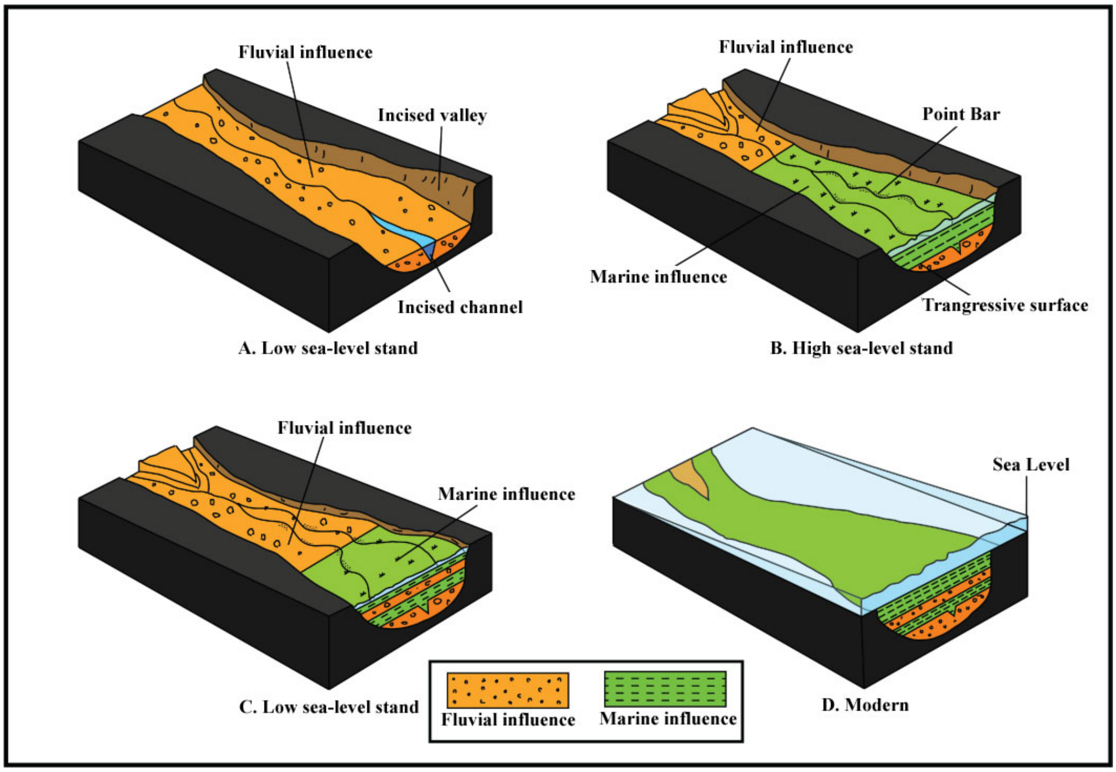

Figure 9. Schematic cartoon of the development of the paleoenvironment in the study area (modified after Allen and Posamentier, 1993) a. The incise valley was formed during low stand; b. The sea-level rise, a transgressive environment facies was formed; c. the local sea-level dropped and underwent to lowstand; d. Sea-level has been slightly increasing since the last low stand

6. Conclusion

Small relative sea-level changes during Pleistocene to Holocene cause the change in the paleogeography of the shelf in the Gulf of Thailand. Hence, the local sequence boundaries are similar to those sea level curves described on the previous works of the Sunda shelf. The inner shelf of the Gulf of Thailand is dominated by delta, estuarine and present-day marine environments. The stacked point bar zone has formed in the study area, which is potential, a reservoir for shallow gas and/or biogenic gas.

7. Acknowledgements

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