Seismic Sequence Stratigraphy and Deepwater Turbidite Characteristics in The East Andaman Basin, Offshore Myanmar

Sudarat Charoensrisomboon

Petroleum Geoscience Program, Department of Geology Faculty of Science,
Chulalongkorn University, Bangkok 10330, Thailand

Abstract

Currently, turbidite reservoir is favorable for deepwater exploration. This paper presents a seismic sequence stratigraphy and deepwater turbidite distribution within the Miocene to Present-day succession in the East Andaman Basin, offshore Myanmar using 2D and 3D seismic data. Four sequences (A to D) were defined based on seismic facies characters in combination with seismic attribute analysis and global sea level change information. Major turbidite reservoir is predicted in sequence A (Early to Middle Miocene) particularly in by-pass channel which is characterized by steep-walled with U-shaped cross sections. This stacked turbidite channel is the primary exploration target in this region where slope canyon plays an important conduits for the transfer of sediment to the deepwater area.

Keywords: seismic sequence stratigraphy, deepwater turbidite, turbidite, East Andaman Basin.

Today, deepwater turbidite reservoir is an important target for oil and gas exploration and development around the world. The Andaman Sea is one of the frontiers for hydrocarbon exploration with a wide bathymetric range from very shallow water to over 3,500 m. A potential deepwater turbidite reservoir is expected to be found in the eastern part of the East Andaman Basin (Figure 1). In this part of the shelf-slop break setting, submarine canyons may act as conduits for transporting sand-sized sediments from the continental margin (brought in mainly by the Irrawaddy Delta) to deep sea since the Late Miocene (Racey & Ridd, 2015). Therefore, the deeper parts of the basins will be where sand deposition is most likely to have occurred. However, this area is classified as a green frontier exploration area and has no well explored yet. Current geological understanding has been made based on 2D and 3D seismic interpretations, unpublished well reports from adjacent exploration blocks and research papers (i.e. Curray, 2005; Wandrey, 2006; Morley, 2013; Srisuriyon & Morley, 2014; Racey & Ridd, 2015; Morley, 2017).

Geologically, the East Andaman Basin is an active back-arc basin. It is overprinted by block extrusion tectonics related to the Indian plate collision with the Eurasian plate during the Himalayan orogeny (Curray, 2005; Morley, 2013). Towards the north of the study area, the Andaman Sea formed as a complex pull-apart basin during the Cenozoic as a result of the motion of West Andaman and Sagaing Faults, both with right lateral movements. They have played important roles during the regional tectonic evolution in the study area in the East Andaman Basin. (Curray, 2005; Morley, 2013). The East Andaman Basin exhibit well developed sediment filled rift basins in the slope, shelf and continental areas (Morley, 2017).

The study area is located in the East Andaman Basin, offshore Myanmar. It is approximately 280 km west of Ranong and 260 km from Yetagun Gas Field (Figure 1). The study area covers 1,516 sq.km over continental shelf, continental slope and continental rise in water depth ranging from 700 m to 3,000 m. This study aims (1) to define and describe the sequence stratigraphic framework of the Miocene to Present-day succession by using 2D and 3D seismic data and (2) to emphasize the depositional history via seismic facies analysis and provide implication for potential turbidite reservoirs.

Data availability

There are no wells in the East Andaman Basin. Therefore, seismic sequence stratigraphy analysis in this study area was analyzed by using 2D seismic data in regional trend and using 3D seismic data in study area. The 2D seismic data

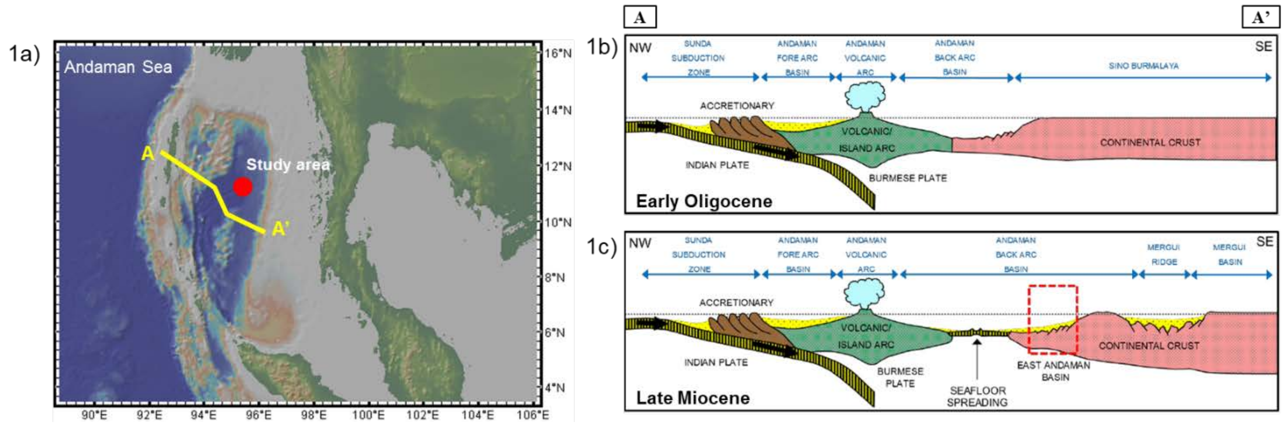

Figure 1: 1a) Map showing Andaman Sea location with direction of cross-section in yellow line, and Schematic cross-sections of study area (Jha, 2010). 1b) Schematic cross-section shows tectonic evolution in Early Oligocene. 1c) Schematic cross-section shows tectonic evolution in Late Miocene and location of East Andaman Basin in red dash box.

of 2,801 line-km is available in study area. The survey was acquired during December, 2013 to February, 2014. It was acquired using 8 km solid streamer with dual source array of 3,000 cu-in. There were 640 channels with the 12.5 meter of receiver group interval. The fold coverage is 160 fold. 49 sail lines of the survey area were oriented in a NNW-SSE in the dip direction and 7 sail lines were oriented in a NNE-SSWA in strike direction. The data quality is good in a shallow section and good to fair in complex structure and deeper section.

The 3D seismic data was acquired during March, 2016 to April, 2016. The water depth ranged from 1,800-2,500 m. The total survey program comprised 1,516 sq.km full fold. It was acquired using slant streamer 8,100 m of cable length with dual source array of 3,480 cu-in air. There were 648 channels with the 12.5 m of receiver group interval. The fold coverage is 160 fold. 46 sail lines of the survey area were oriented in a NNW-SSE in the dip direction. The data quality is good in a shallow section and good to fair in complex structure and deeper section.

In this study, the analysis of sequence stratigraphy is mainly based on the seismic data. Each sequence was defined by using seismic character, seismic termination combined with seismic attributes and was integrated of global sea level change information. However, the seismic data quality in deepwater area is always unclear and difficult to interpret. Therefore, seismic attributes analysis could help to improve seismic data results and accuracy.

Moreover, it could help to improve structural and stratigraphic identification and delineation.

In order to improve seismic quality before making interpretation, seven seismic attributes were calculated and tested which are Trace ACG, Structural Smoothing, Variance, Instantaneous frequency, Instantaneous phase, RMS Amplitude and Sweetness (Figure 2).

Seismic stratigraphy

A generalized Miocene to Present-day stratigraphy of the East Andaman Basin was constructed based on 2D regional lines. Moreover, this research used final Pre-STM 3D seismic data (WGS 1984, Zone 96E, Yangon) covering an area of 1,516 sq.km full fold. The data extends to a depth of 8.0 second TWT with good quality in a shallow section and good to fair in complex structure and deeper section.

In term of tectono-stratigraphy, three main tectonic events could be identified by seismic data which are, from bottom to top, pre-rifting, syn-rifting and post-rifting events (Figures 3, 4 and 5). These events are separated by angular unconformities related to the tectonic activity increased due to plate collision and rotation. The pre-rifting section was not well defined due to the seismic quality and the target interval is too

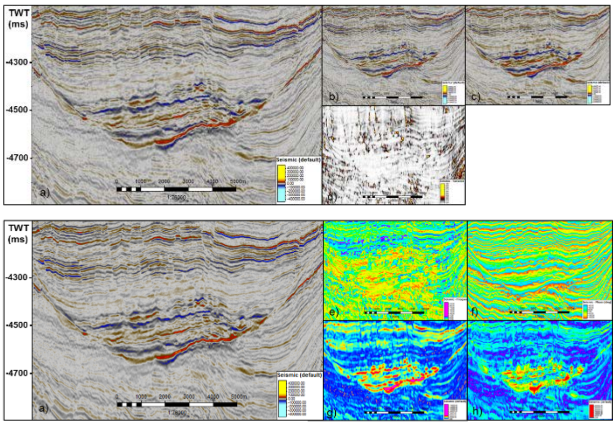

Figure 2: Seismic image improvement using volume attribute on the Final PSTM 3D seismic data (crossline 6100). a) Original data, b) Trace AGC, c) Structural smoothing, d) Variance, e) Instantaneous frequency, f) Instantaneous phase, g) RMS and h) Sweetness.

deep (deeper than 7.0 second TWT). However, it was identified from relatively low amplitude, discontinuous reflector zone. The syn-rifting section was characterized by east-dipping extensional growth fault and can be defined from thickened section of syn-rift sediments where the depositional environment is shallow marine condition. The strong reflectors was expected to be shallow marine mix terrestrial source rocks.

The post-rift succession formed during the Miocene to Present-day. It is underlaid by the near Early Miocene regional unconformity, which is well defined by strong and continuous reflectors. The seismic terminations (i.e. onlap and truncation) can be observed at erosional surfaces. This unit illustrates relatively flat to gentle west-dipping reflectors with local unconformities. Active normal faults indicate that the post-rift unit is now interrupted by recent rifting to the west of the 2D seismic survey (Figure 4).

Five horizons have been interpreted, which consist of Seabed, Top Pliocene, Near Late Miocene, Near Middle Miocene, and Near Early Miocene horizons (Figures 4 and 5). Approximate ages of these horizons are inferred from published reports of Mergui Basin, Andaman Sea, which is located around 150 km toward the southeast from the study area (Srisuriyon and Morley, 2013). Therefore, the seismic sequence stratigraphic unit of this research in post-rift event can be divided into four sequences as shown in the Figure 3.

The sequence boundaries of Near Early Miocene were identified and considered as the base of main reservoir target intervals. The reservoir potentials are stacked channel (Turbidite LST) which were deposited in Near Early Miocene to Near Middle Miocene. The transgressive shale in Late Miocene period was interpreted as a regional vertical and lateral seal. The Top Pliocene horizon was identified at the top of strong reflectors of Pliocene fan package.

Seismic interpretation

Seabed (Figure 6) is represented by peak correspond from low to high impedance contrast between water and sediment. Seabed represent similar structural to Top Pliocene and water depth is deeper in the northwest corner. Moreover, the seabed surface displays the Present-day canyon in northeast-southwest trend.

Top Pliocene surface (Figure 6) is represented by strong contrast between soft and harder sediments. This surface shows configuration almost parallel to seabed surface. It has erosion due to incision and canyon as well. Moreover, very high amplitude events were observed, which possibly correspond to shallow gas (gas chimney). Isolated basins have been observed along the base of slope canyons, which may form as a result of differential compaction under sediment load.

Near Late Miocene surface (Figure 6) is represented by top of low amplitude feature which was interpreted as a main vertical seal in this area. It shows similar structural configuration as the Middle Miocene surface. Surface termination occurs where it onlaps on the near Early Miocene unconformity in slope canyons to the east of the study area.

Near Middle Miocene surface (Figure 7) is represented by top strong reflection which was interpreted as a top reservoir that deposited in slope canyon. This zone is proposed as potential exploration target. Similar to the Near Late Miocene surface, termination of the Near Middle Miocene surface occurs where it onlaps

Seismic Facies Identification	Sequences
Topmost seismic facies with very low amplitude,	D
Prograding clinoform,, bright reflections with moderate to high amplitude and moderate to low continuity. *Near Late Miocene*	C
Backstepping, onlapping with low amplitude *Near Middle Miocene*	B
Prograding wedge shaped with parallel internal reflection, low amplitude, higher values at channel infillings and fan lobes. *Near Early Miocene* *(unconformity)*	A
Truncation erosion surface, complex structure	Pre-Miocene

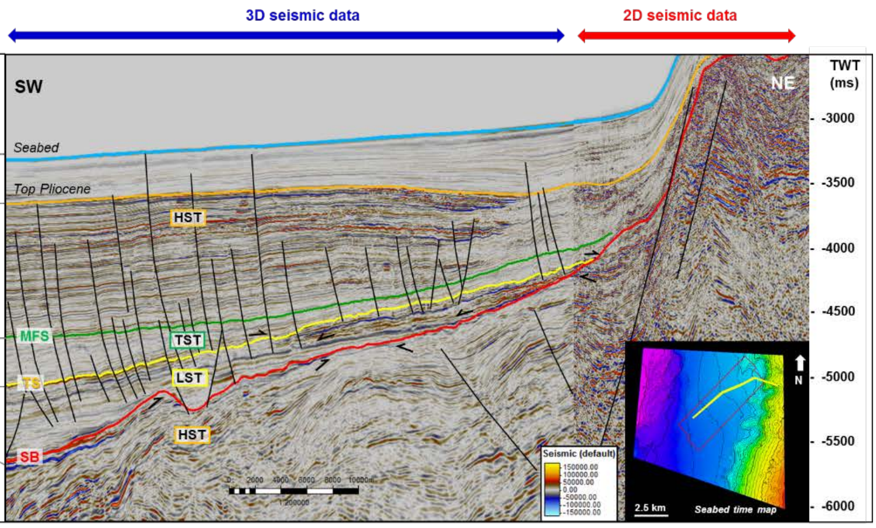

Figure 3: Seismic characteristics of research area in the East Andaman Basin showing the nature of sequences with horizons interpretation from 2D and 3D seismic survey.

on the near Early Miocene unconformity in slope canyons to the east of the study area.

Early Miocene unconformity (Figure 7) is represented by the strong amplitude and continuity which was interpreted as an unconformity and base of reservoir. This erosional unconformity was characterized by many incisions and canyons that have been filled with younger sediments i.e. Middle Miocene slope channels, fans and canyon fills around the shelf break.

Sequence stratigraphic framework

In this part, 3D seismic data is the main dataset for constructing the sequence stratigraphic framework. Four seismic sequences (A to D) in the post-rift succession are described. The seismic data in adjacent areas with previous studies in this region were used to assign ages to seismic horizons. Moreover, the global relative change of sea level was taken into account (Polachan and Racey, 1994). The model of depositional environment was created based on the current dataset. The lithostratigraphic column is shown in Figure 8.

The designation of the petroleum system which are source rocks, reservoir rocks, seal and migration time are also presented.

Sequence A (Near Early to Middle Miocene)

The sequence A was defined from Near Early Miocene (SB) surface to Near Middle Miocene (TS) surface (Figure 9). This sequence is the beginning of post-rift sediment which bounds by the unconformity below and transgressive system tract above. Seismic characters in this sequence show the prograding wedge shaped with parallel internal reflection with higher amplitude values at channel infillings. Therefore, this sequence was interpreted as a lowstand system tract (LST).

After the rifting, the syn-rift sediments were exposed due to marine regression and erosion which is demarcated by the angular unconformity. This unconformity is the basal sequence boundary in Near Early Miocene. It shows the downlap terminations (Figure 9) of seismic reflection above and truncated feature below. Moreover, it also shows the slope canyon feature and LST fill deposited which was deposited during an interval of relative sea level fall and slow relative sea level rise. The shelf commonly becomes exposed as the shoreline facies migrates basinward.

Sequence B (Near Middle to Late Miocene)

The sequence B was defined from Near Middle Miocene (TS) surface to Near Late Miocene MFS surface (Figure 10). Seismic character in this sequence shows onlapping feature with low amplitude value. This sequence was interpreted as transgressive system tract (TST) based on the onlap feature towards the shelf and polygonal fault was observed by variance seismic attribute. It bounds by the transgressive surface (TS) below and maximum flooding surface (MFS) above.

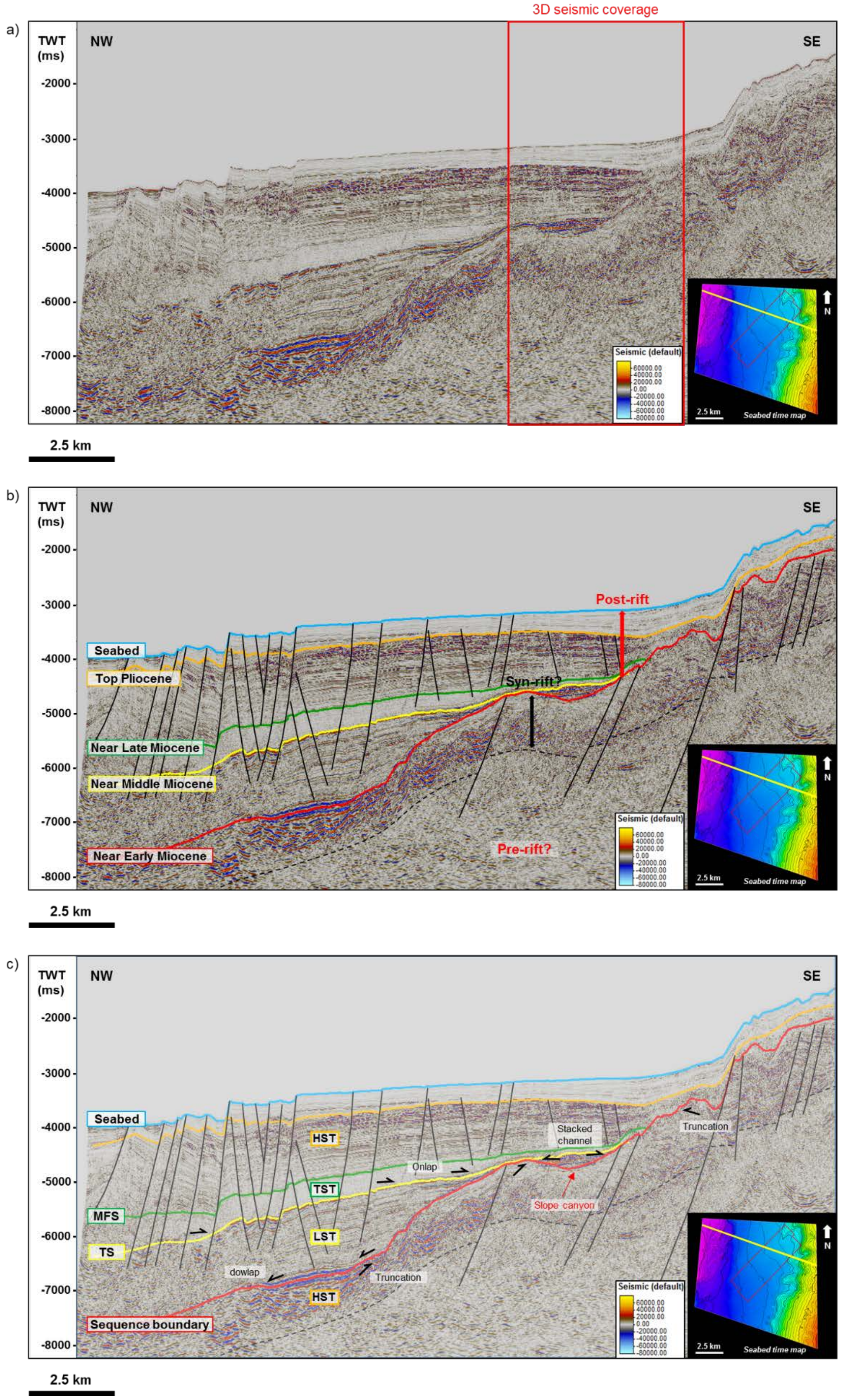

Figure 4: 2D seismic cross section a) without interpretation b) with interpretation and three main tectonic events in study area C) with interpreted seismic sequence stratigraphy related to the global sea level changes.

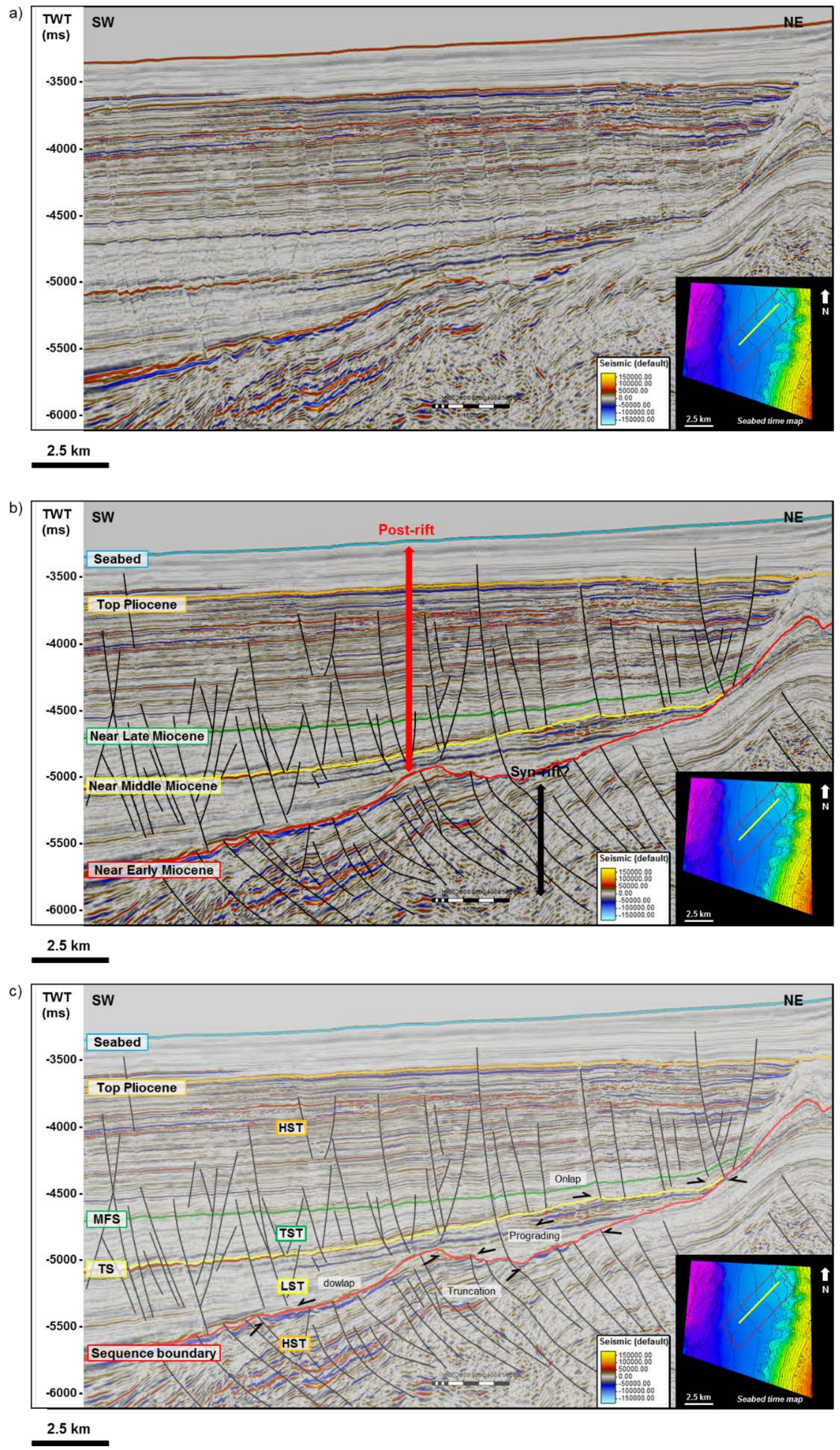

Figure 5: 3D seismic cross section a) without interpretation b) with interpretation and three main tectonic events in study area C) with interpreted seismic sequence stratigraphy related to the global sea level changes.

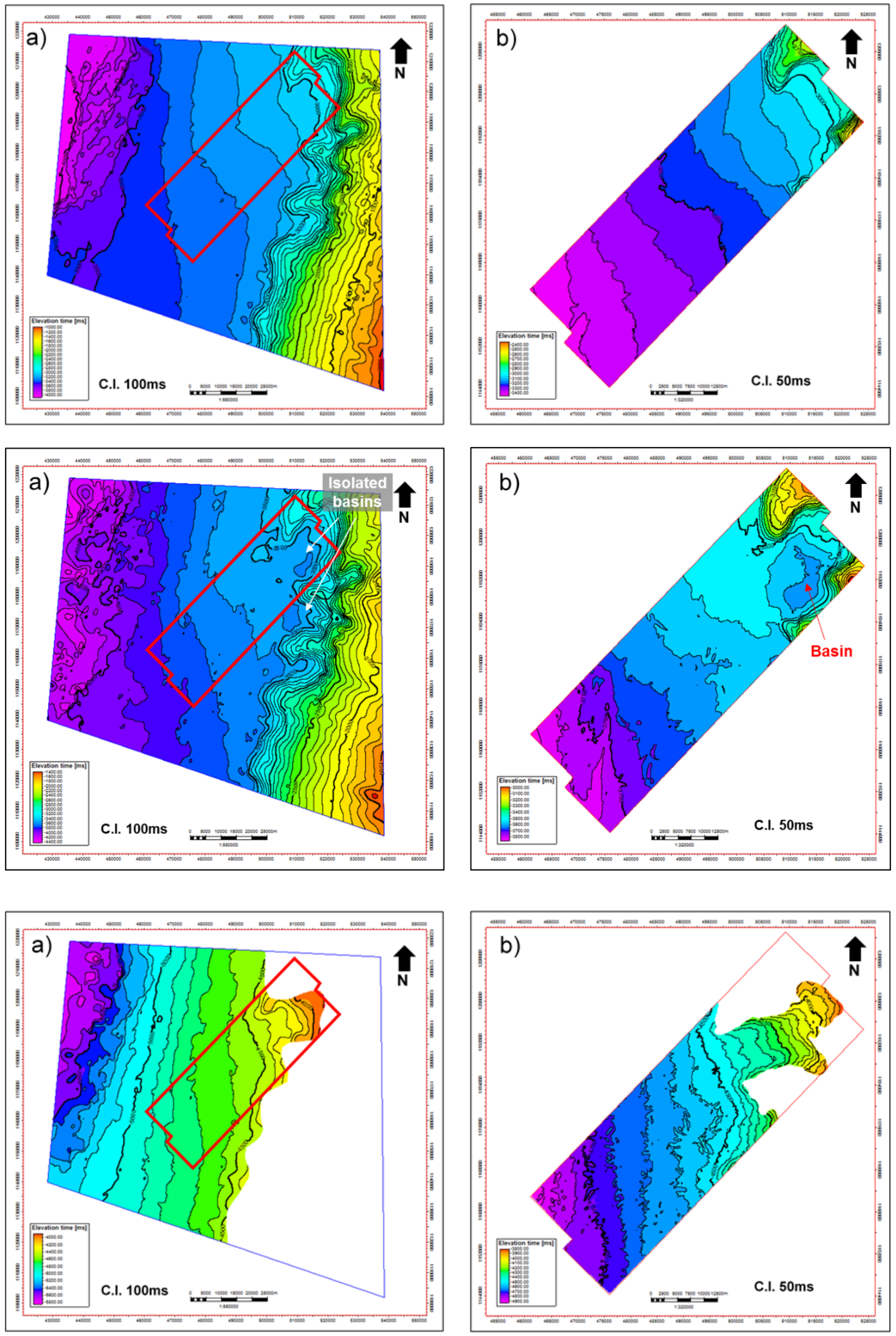

Figure 6: Time structural maps of Seabed, Top Near Pliocene and Near Later Miocene on a) 2D seismic data with 3D seismic boundary in red box and b) 3D seismic data. C.I. = Contour interval

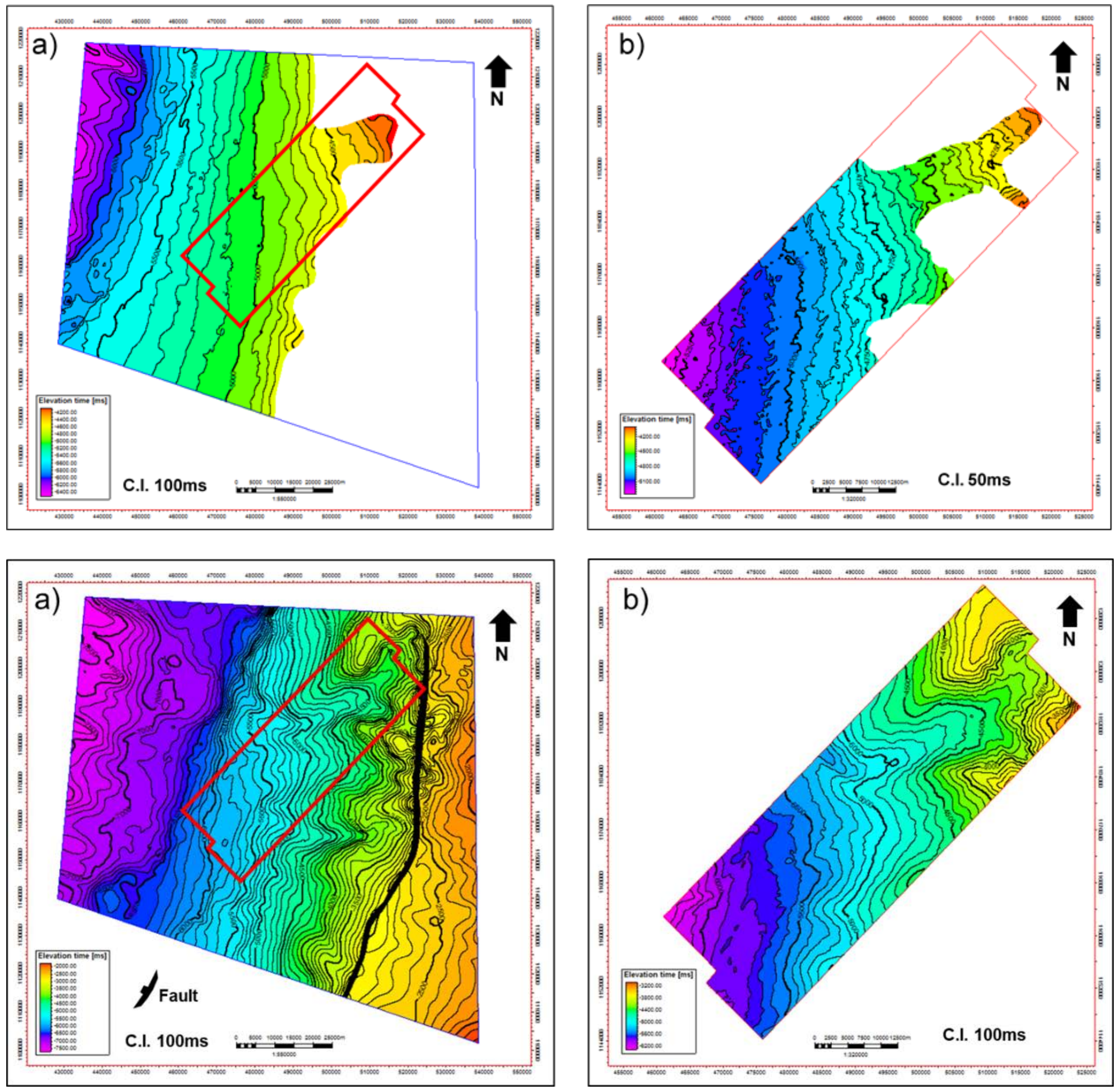

Figure 7: Time structural maps of Near Middle Miocene and Near Early Miocene on a) 2D seismic data with 3D seismic boundary in red box and b) 3D seismic data. C.I. = Contour interval

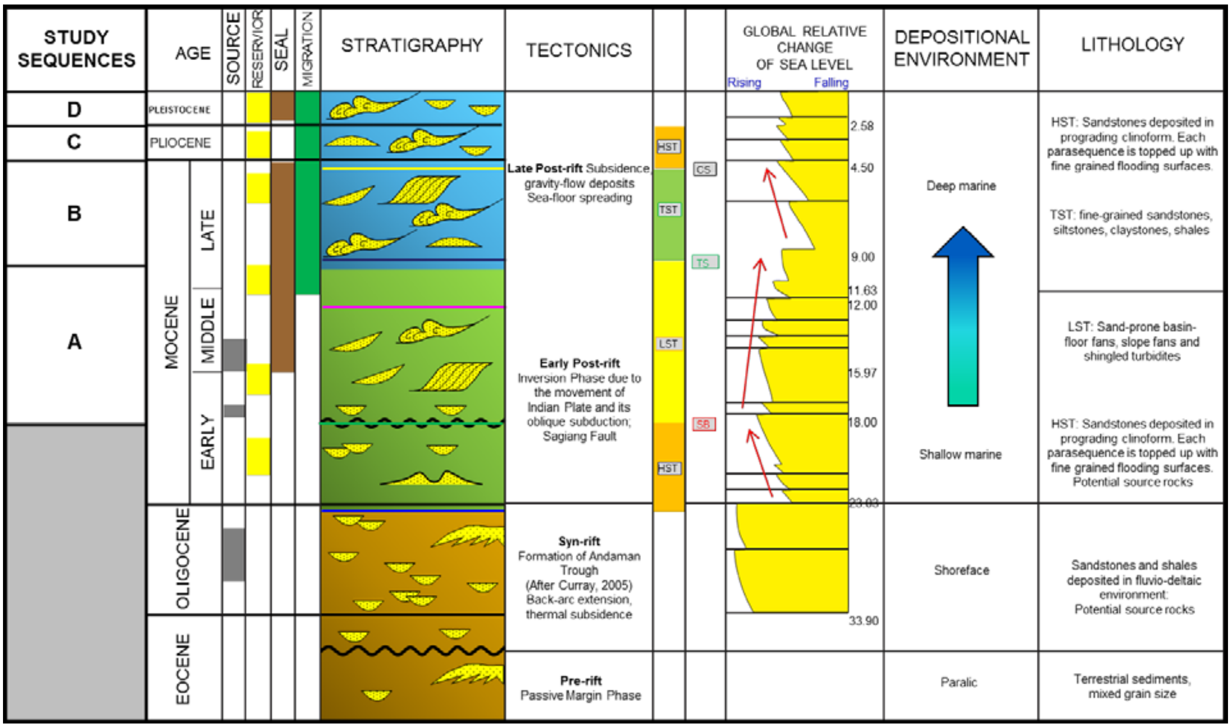

Figure 8: Lithostratigraphic column of East Andaman Basin (modified from PTTEP, 2018

At this time, a relative sea level rise towards the shelf area and accommodation space shifted to slope area. The rate of accommodation increases faster than the rate of sediment supply, resulting the onlapping feature over TS. Therefore, it was interpreted as TST. The MFS defines the top of TST, and then it gradually transcends into the highstand system tract (HST).

Sequence C (Near Late Miocene to Pliocene)

The sequence C was defined from Near Late Miocene (MFS) to Pliocene surface (Figure 11). Seismic character in this sequence shows the aggradation feature with bright reflections with moderate to high amplitude and moderate to low continuity, and downlapping onto the MFS. This sequence was interpreted as highstand system tract (HST).

After Late Miocene, minor fluctuations in sea level represent the HST. The rate accommodation becomes less than the rate of sediment supply.

Sequence D (Pliocene to Present-day)

The sequence D was defined from Pliocene surface to the Seabed (Figure 12). Seismic character in this sequence is characterized by continuous, low amplitude with horizontal or very low angles of dip. This may results from low sedimentary supply and /or rapid rise in sea level to favor deposition and preservation of this sequence on the shelf-slope break. According to the seismic facies and well reports in this region, it can be inferred to the deposition of shale-rich sediments in a relatively low-energy sedimentary regime. The isochron map shows the thickness trend is thinner towards the southwest.

Summary

Based on 2D and 3D seismic data, five key horizons were interpreted which consists of Seabed, Near Top Pliocene, Near Late Miocene, Near Middle Miocene and Near Early Miocene. The post-rift seismic sequence stratigraphy in this research area can be divided into four-sequences (A to D). Each sequence was defined by using seismic character, seismic termination combined with seismic attributes and was integrated of global sea level change information.

Discussions

Potential turbidite reservoir

Potential turbidite reservoir was observed in sequence A. It was interpreted as LST which was deposited in slope canyon as a stack channel. The reservoir was also interpreted as

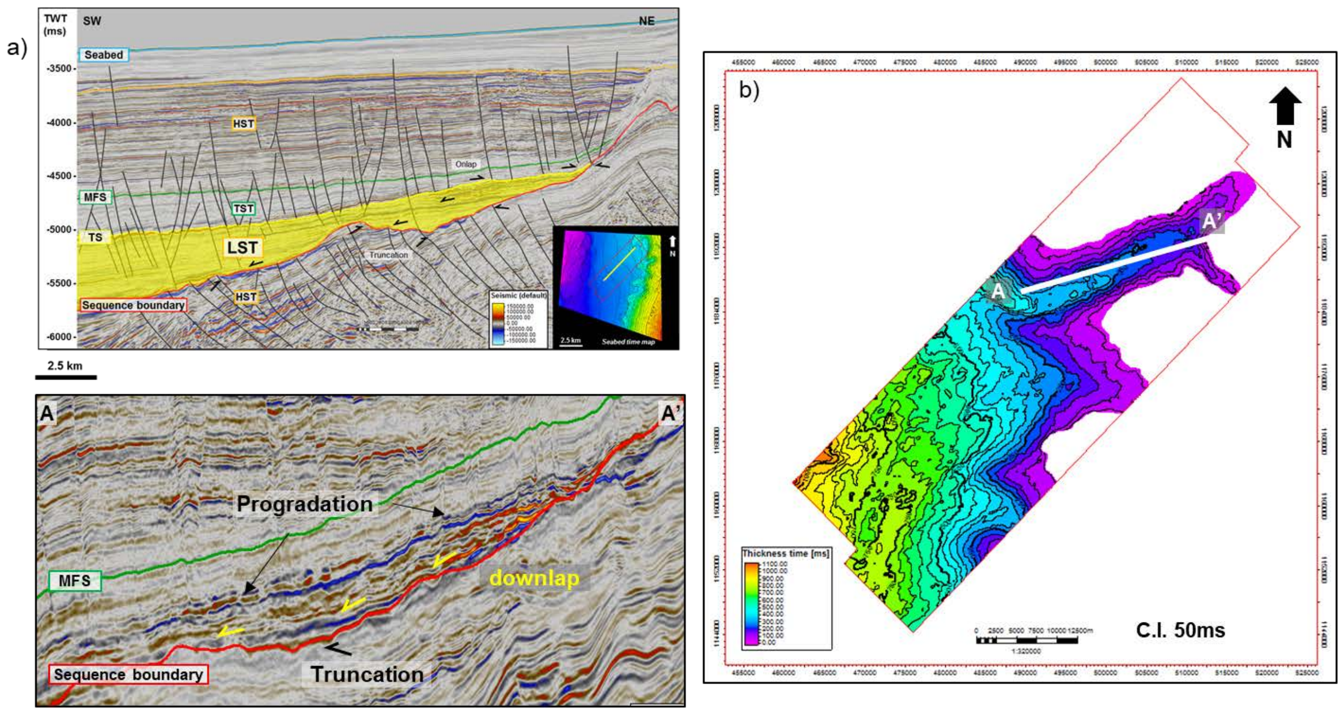

Figure 9: a) Seismic cross section show the prograding feature in sequence A and b) Isochron map of sequence A which is a lowstand system tract. C.I. = Contour interval.

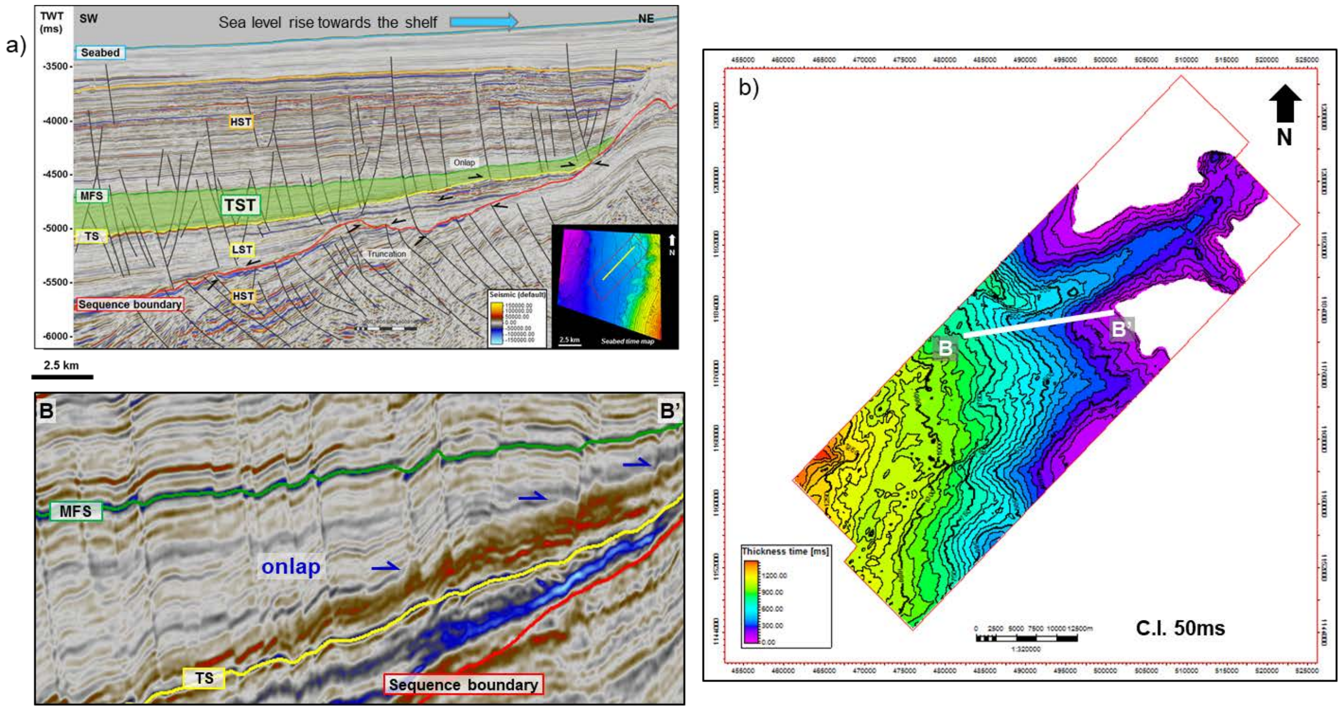

Figure 10: a) Seismic cross section show the onlap feature in sequence B and b) Isochron map of sequence B which is a transgressive system tract. C.I. = Contour interval.

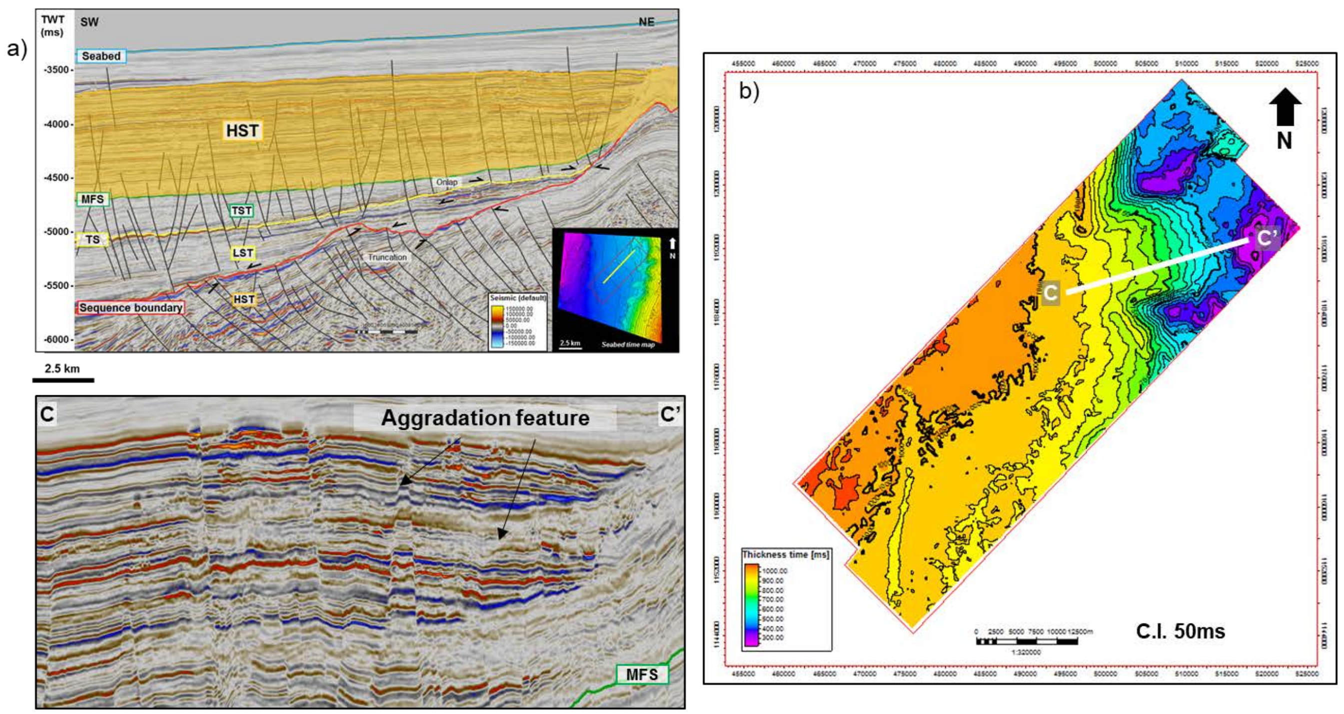

Figure 11: a) Seismic cross section show the aggradation feature in sequence C and b) Isochron map of sequence C which is a highstand system tract. C.I. = Contour interval.

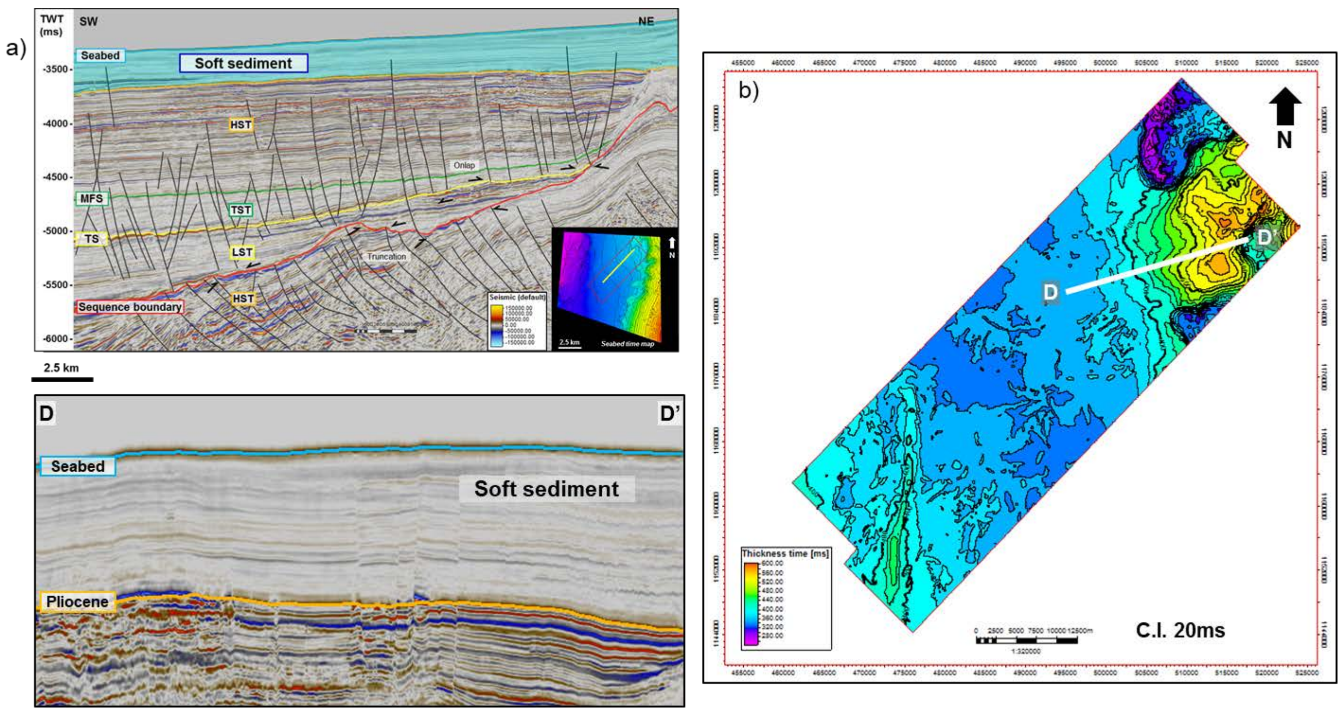

Figure 12: a) Seismic cross section show the low amplitude feature when compare with sequence C and b) Isochron map of sequence D which is a highstand system tract. C.I. = Contour interval.

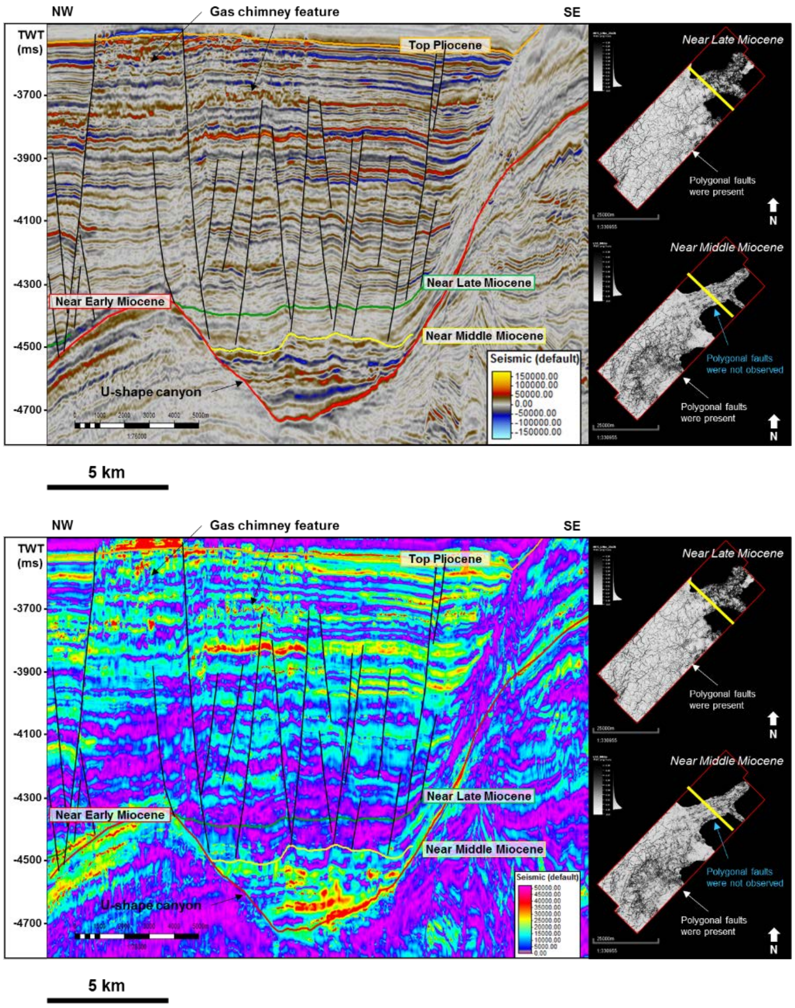

Figure 13: Seismic cross section of crossline 5840 without and with RMS attribute that present the stack channel sand reservoir deposit in slope canyon overly on Near Early Miocene Unconformity. Canyon architecture display in U-shaped cross sections (confined canyon). The variance seismic attribute (right side) show polygonal fault feature in mud-rich area. Gas chimney was presented in shallow part along fault migration.

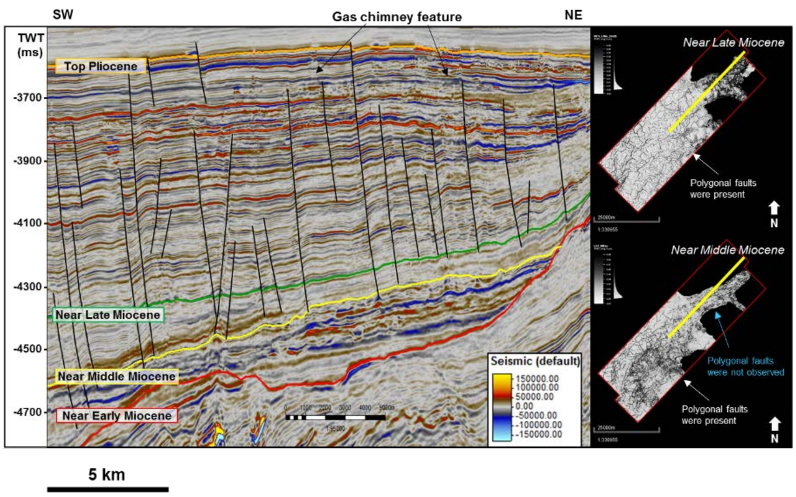

Figure 14: Seismic cross section of inline 2840 that present the stack channel sand reservoir deposit in slope canyon overly on Near Early Miocene Unconformity. The variance seismic attribute (right side) show polygonal fault feature in mud-rich area and gas chimney was presented in shallow part along fault migration.

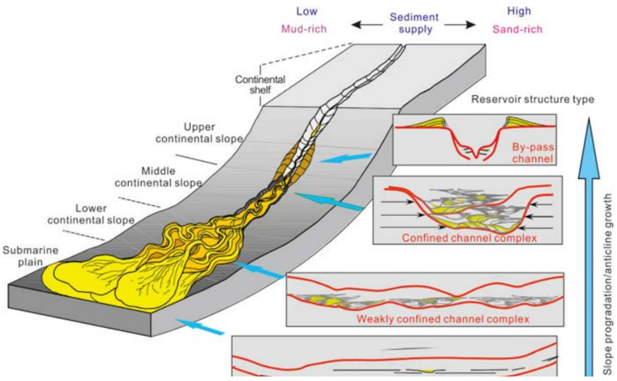

Figure 15: Sedimentary model of turbidite fan showing that the incised valleys and by-pass channels are developed in the continental slope and the upper slope; the confined channel complexes and weakly confined channel complexes are developed in the middle slope and the lower slope; and the lobes are developed in the submarine plain (Huang, 2018)

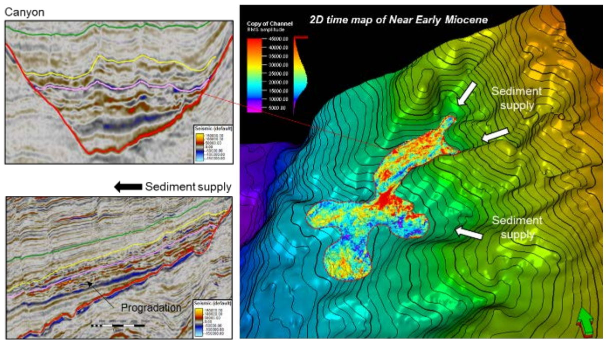

Figure 17: 3D model of the deepwater turbidite stacked channel that show the high amplitude anomaly in slope canyon. Show the progradation dowlap on Near Early Miocene unconformity which can imply to direction of sediment supply.

deepwater turbidite stacked channel which deposited at the middle continental canyons (Figures 13, 14 and 15). Therefore, the reservoir model can be defined by canyon architecture

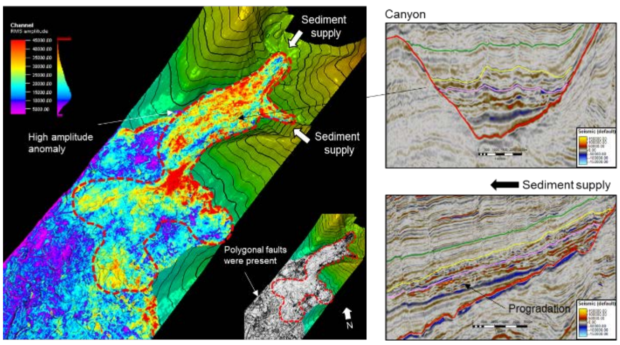

Figure 16: High amplitude anomaly along the deepwater turbidite stacked channel in slope canyon and show progradation feature.

which is characterized by steep-walled with U-shaped cross sections (confined canyon) (Figures 13 and 15). The sediment deposited as thick sheet which supply from shelf on eastward. This is a stratigraphic play type which interpreted to be deposited in the lowstand systems tract. Due to it showed progradation feature onto an erosional surface (unconformity surface) along the basin margin. The deepwater turbidite stacked channel was identified based on its high amplitude seismic reflection and fairly continuous (Figure 16). The vertical stacking of deepwater turbidite channels can be expected in the steeply dipping container. At weakly confined setting, lateral migration of channel- levee system can be expected in low-moderate gradient canyon. Further to base of slope or on the basin floor, channel-levee and lobes are disperse trough the low gradient area (Figure 15).

The transgressive shale in Late Miocene period (TST) was interpreted as a regional vertical and lateral seal. This Late Miocene deepwater shales deposited by mud-rich turbidity current, which later produced polygonal fault feature and promoted leakage along this faults (Figures 13 and 14). Therefore, the stacked channel reservoir is expected to be trapped by Early Miocene Unconformity in the lateral and Late Miocene deepwater shales is trapped in the vertical. Moreover, it can be observed gas chimney above the stacked channel as migrate by fault that cut into the stacked channel (Figures 13 and 14). Based on the petroleum system in this study, the stacked channel is a potential turbidite reservoir but should work with some caution of leakage along the fault zone.

Analogue field

Due to the main potential reservoir in this research area is a deepwater turbidite stacked channel reservoir which is a stratigraphic play type. A good analogue field in term of similar reservoir type is the Jubilee field. The Jubilee field is a world class reservoir that is an oil field located approximately 60 km offshore Ghana between the deepwater Tano and West Cape in the South Atlantic Ocean. The field is a late

Cretaceous combination structural- stratigraphic trap associated with topography created by the transform tectonics during the opening of the Atlantic. The Jubilee appraisal wells were drilled and confirmed a 250 m average gross interval of stacked, amalgamated turbidite channel and fan sands with RMS amplitude extraction support. The net pay interval ranging from 20 – 100 m TVD. The recoverable reserves of the Jubilee field are estimated at over 600 million barrels.

Although, no wells have been drilled in the research area, and the age of potential deepwater turbidite reservoir between analogue field and research area are different.

Anyway, Gas Chimney which is a good DHIs was observed above a deepwater turbidite stacked channel through fault cut. Moreover, there is the RMS amplitude extraction support of potential turbidite stacked channel reservoir as shown in Figure 17. Therefore, it can imply that the petroleum system in research are quite expectable.

Conclusions

Regional geological understanding and seismic interpretation results indicate that the post-rift event of the East Andaman Basin shows the deposition of shallow sediment and deepwater sediment throughout the research area.

Therefore, the major potential plays in this area are related to deepwater petroleum system. Based on the existing seismic data present that potential reservoir was deposited in the slope canyon and it was interpreted as deepwater turbidite stacked channel reservoir.

The post-rift seismic sequence stratigraphy in this research area can be divided into four sequences (A to D). Each sequence was defined by using seismic character, seismic termination combined with seismic attributes and was integrated of global sea level change information. It represents the variation of depositional and erosional process.

The variation of seismic facies are related to changes in lithology and the energy of deposition. The slope canyon feature and LST fill deposited which was deposited during a relative sea level fall and slow relative sea level rise. Whereas, TST in Near Late Miocene was deposited during a relative sea level rise.

Main potential reservoir area deepwater turbidite stacked channel which deposited at the middle continental canyons (confined canyon) during Early to Middle Miocene age. It was interpreted as a lowstand systems tracts with high amplitude anomaly supported.

Late Miocene deepwater shale deposited by mud-rich turbidity current as show the polygonal fault feature in wide spread. S0, it can imply that it is a main trap/seal in this research area.

Based on this seismic dataset, it can be observed gas chimney above the stacked channel as migrated by fault cut. Therefore, it can imply that the petroleum system in research are quite expectable.

Due to a lack of well information so, a deep well exploration in this basin is needed for stratigraphic calibration.

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