8th Biennial International Conference
& Exposition on Petroleum Geophysics

"HYDERABAD 2010"

P-261

Speculative Petroleum System & Play Model of East Andaman Basin from Regional Geology and Basin Evolution Concepts: Addressing the Exploration Challenges of an Extreme Frontier Area

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Summary

For the remote location and unavailability of data, the Andaman deepwaters was never considered for hydrocarbon exploration until very recently. With hardly a few line kilometers of 2D data and no exploratory drilling, initial understanding of the region was rather poor. Exploration activities by the Eni-led consortium in the last few years have, however, revealed the presence of a completely unexplored rift set-up, much inline with the nearby North Sumatra and Mergui rift basins situated on the eastern side of Mergui Ridge. Current studies on regional geological correlation between the East Andaman Basin and analogous North Sumatra and Mergui Basins, coupled with 2D & 3D seismic data interpretation convincingly point out a close resemblance of tectonostratigraphy among them. These basins essentially evolved in a poly-phase setup (five phases were identified) through the Cenozoic in response to the subduction of Indian Plate below the Indochina-Burmese plate. Sedimentation in these basins therefore can be linked closely with each basin development phases.

Hydrocarbon occurrences in the North Sumatra and Mergui Basins typically exhibit rift-related petroleum systems which are proven to be quite prolific in parts. Since the East Andaman Basin is a virgin exploration area with no well control, a conceptual geological-thermal-source rock model was worked out to establish the petroleum system and play model. Following the similarity in basin development and sediment distribution with the analogous North Sumatra and Mergui Basins as documented in various dataset (published literature review, seismic and well data etc.), a credible analogy was drawn from them to the yet-to-beexplored East Andaman Basin. The petroleum system elements were simultaneously predicted after close correlation in order to establish the most plausible hydrocarbon play model. In broad scale, the petroleum system of East Andaman Basin can be prognosticated in the following four rift-related plays: 1) Pre-rift clastic play, 2) Syn-rift clastic play; 3) Early post-rift clastic / carbonate (?) play; and 4) Late post-rift clastic play.

The objective of this work is to make an appraisal of the tectonic evolution of the area, analyze sedimentation pattern and related petroleum system of a proven basin in order to extrapolate the results to a remote frontier basin. Establishment of petroleum system model in East Andaman Basin is a necessary step to define the future exploration strategy.

Introduction

East Andaman Basin is a frontier area located at the southeastern corner of Indian Territory in the Andaman Sea. Bounded by the volcanic Mount Sewell Rise on the West and the continental Mergui Ridge on the East (Fig. 1), this elongated basin is envisaged to have been originated during Late Eocene-Early Oligocene time due to the interplay between the Burmese Plate and north-moving Indian Plate. It covers an area over 50,000 km² with water depth ranging from 1000 to 3000 m.

The closure of Tethys at the present Sunda Subduction Zone caused back-arc extension along the margins of Sundaland to generate a number of rift basins. Western part of Sundaland now hosts roughly N-S/NNE-SSW trending basins (North Sumatra, Mergui, East Andaman etc.) which most likely originated during Late Eocene/Early Oligocene as pure extensional back-arc troughs. However, since Miocene, the oblique subduction at Sunda Subduction Zone added a right-lateral transtensional component into the existing stress regime (Curray 2005, Jha et al. 2008). The

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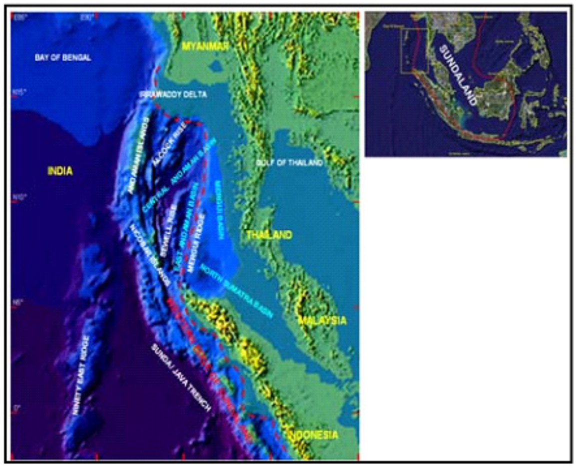

Fig. 1: Location of East Andaman Basin in Andaman Sea, along with other basins and tectonic features.

latest and most prominent manifestation of this pull-apart tectonics can be seen at the Central Andaman Basin, which is a nascent sea-floor spreading zone (Raju, 2005). The tectonic elements of the region have been illustrated schematically in Fig. 2.

As a consequence of this poly-phase development of the basins the structural evolution was quite complex, with phases of extension, inversion and subsidence controlling the sedimentation pattern in the area. However, all the basins broadly exhibit similar pattern in sediment succession related to passive margin – pericratonic rift (East Andaman) and intracratonic extension (North Sumatra & Mergui). The economic basement in North Sumatra and Mergui is of continental origin (Pre-Tertiary granitic /metamorphic rocks), but a transitional / stretched continental crust is predicted for East Andaman. Sedimentary successions on top of basement starts with Late Eocene/Early Oligocene fluvio-lacustrine and fluvio-marine clastic facies unconformably overlain by Late Oligocene-Early/Middle Miocene shallow marine sediments (both clastic and carbonate), and finally Late Miocene to Recent deeper water clastics occupying the top of the succession (Polachan & Racy 1994, Doust & Sumner 2007).

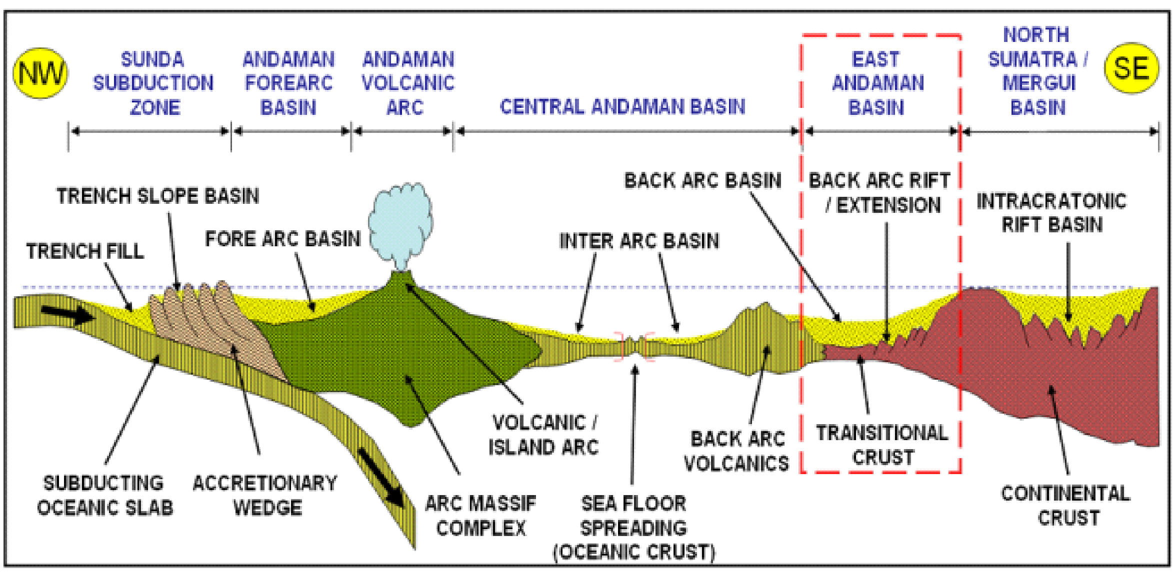

Fig. 2: Schematic geological section with major tectonic elements and basin locations along Andaman Sea (Figure not to scale).

Basin Evolution at Western Margin of Sundaland

Considering the poly-phase rift-related structural evolution of the area, five basin development stages can be recognized: a) Pre-rift passive margin, b) Intracratonic and pericratonic early syn-rift, c) Intracratonic and pericratonic late syn-rift, d) Early post-rift and e) Post-rift subsidence phases. However, all these phases are not equally reflected in the regional geology and seismic data.

a) **Pre-rift Passive Margin Phase:** Though the presence of the pre-rift sequences has never been reported in the North Sumatra and Mergui Basin, one cannot rule out the chances of encountering such sediments at least in East Andaman Basin. The western margin of Sundaland was probably a passive margin setting when the Tethys existed, much prior to the development of subduction zone and back-arc extension in the region. East Andaman Basin, being situated at the westernmost edge of this craton therefore had considerable possibility of hosting pre-rift shallow marine/paralic sequences. The genesis of North Sumatra and Mergui Basins are related to the intra-cratonic rifting of basement in response to the back-arc extension of Eocene/Oligocene age, hence this phase is least likely to be represented in those areas.

b) **Intracratonic and Pericratonic Early Syn-rift Phase:**
The Late Eocene- Early Oligocene rift and extensional blockfaulting phase created NNE-SSW trending half-grabens around Sundaland. On the intra-cratonic side this extension is characterized by the development of North Sumatra and Mergui Basins, while the western peri-cratonic margin of Sunda went into expansion phase with its thinned continental crust, marked by the present East Andaman Basin. The Mergui Ridge was acting as the separator horst in between them except on the northern and southern plunging edges, where the basins were probably connected with each other. Sedimentation was typically marked by thick sand-prone alluvial and fluvio-lacustrine deposits in the proximal setup, with gradual fluvio-marine facies development towards the basinal areas.

c) **Intracratonic and Pericratonic Late Syn-rift Phase:** During the Late Oligocene-Early Miocene, thermal subsidence caused marine flooding in the basins. The basin margin highs/ rift shoulders (horsts) though were completely not submerged and supplied large volumes of siliciclastic sediments into the basins. The fluvio-lacustrine/fluvio-marine system of early syn-rift phase gradually passed into more marine locally deep successions of the late syn-rift phase. However, due to the outer margin location of East Andaman Basin, the late rift sediments are expected to be of relatively open marine in nature than their eastern counterparts.

d) **Early Post-rift Inversion Phase:** During Early-Middle Miocene, the movement of Indian Plate and its oblique subduction caused rotation of the regional stress axis and the basins went into right-lateral transtensional phase. Numerous regional strike slip faults (roughly N-S oriented) developed, and as a consequence typical transpressional inverted structures and transtensional pull-apart sags were formed all along the region. Following this change in tectonic setting, the entire East Andaman Basin and northern part of Mergui Basin experienced considerable sea-level fall resulting in the numerous erosive channeling events and prograding deltas especially at basin margins. Later, southern part of the area (North Sumatra and major part of Mergui) was exposed to marine transgression which is evidenced by the widespread carbonate deposition on the structural highs and basin margins; basinal areas were filled with mixed sediments (shale, mud, marl etc.).

e) **Late Post-rift Subsidence Phase:** The late post-rift phase is characterized by renewal of clastic sedimentation all over the area in Late Miocene. Active delta progradations were again in place in North Sumatra and Mergui bringing enough clastics from existing highs (Mergui Shelf, Mergui Ridge and Malacca Shelf) into the system. The progradations at the margin occurred together with deepening of the depositional environment in the center of the basin, progressively bringing finer clastics into the deeper depocentres. Simultaneously, final amalgamation of Indian Plate with the Sunda Plate and continued transtensional rightlateral movement caused huge subsidence at the East Andaman Basin and North Sumatra Basin, with water depth rising as high as 3000m to 1000m respectively. In response to this, turbidites and mass flow sediments were deposited in the basins.

Speculative Petroleum System

The North Sumatra Basin is a proven and mature petroliferous basin with around 28 TCF of gas, 2300 MMbl of oil and 900 MMbl of condensate (IHS Energy, 2007) that are found in its rift-related petroleum system. The majority of hydrocarbon pools are found to be concentrated at two stratigraphic levels: I) the top of syn-rift, sealed by the transgressive early post-rift Late Oligocene-Early Miocene transgressive shale/mud, and II) the early post-rift Middle Miocene deltaic-near shore clastics and carbonate reefs, sealed by late post-rift Upper Miocene deep marine shales of the subsidence phase. Some of the world-class fields that exist in this area are Arun (14 TCF gas and 750 MMbl condensate), Kuala Langsa (5.5 TCF gas), NSO (3 TCF gas), Rantau (850 MMbl oil) with in-place reserves. The prospect in Mergui basin and deep-water North Sumatra area is not so bright with only a few minor discoveries; however it still remains a highly potential area considering limited exploration efforts.

The complex tectonic history of this region is well manifested in the sedimentary successions and four distinctive types of thermogenic petroleum systems are found to exist, namely early syn-rift, late syn-rift, early post-rift and late post-rift (Doust & Sumner 2007). However, latest information on East Andaman Basin indicate towards the possibility of another additional system, the pre-rift petroleum system, which is likely to be locally present as suggested by the new seismic data. The East Andaman Basin is still a completely unexplored area as no wells have been drilled so far. The nearest wells present in the area, i.e. in North Sumatra and Mergui Basins are located too far away (in order of hundreds of kilometers) to bring any close correlation in terms of petroleum system parameters. Since these basins are timeequivalent and have similar genetic history with a few minor differences, a possible analogy among them can be drawn to suggest the petroleum system model of the East Andaman Basin. A brief portrayal of the major petroleum system elements are discussed below.

• **Source Rocks:** The exact source facies intervals and their characteristics are rather speculative even in North Sumatra and Mergui, since these sequences are not penetrated by the wells at the deepest depocentres. In general, hydrocarbon discoveries in the North Sumatra can be correlated to the source rocks deposited as fluvio-lacustrine deposits (kerogen type II-III) in the deeper parts of the early syn-rift half grabens. The East Andaman Basin accordingly indicates the presence of good quality source within its thick early syn-rift sequences. Alternatively, Early Miocene marine fluvio-deltaic shales and clays containing Type II-III kerogen is another contender if sufficiently buried. However, especially in Mergui Basin, these source rock intervals are generally found to be early mature/ immature because of shallow burial.

• **Reservoir:** The target reservoirs in the region, in general terms, are represented usually by fluvio-marine and shallow-marine clastic sediments of syn-rift and post-rift stages. Within the early post-rift phase, a prolific carbonate play is also present (namely Arun, NSO & Kuala Langsa of North Sumatra), but its extension in the East Andaman is not well supported by the current geological model. Based on the studies, the following reservoir intervals are expected to be encountered in East Andaman.

I) Shallow marine / paralic clastic facies deposited during the pre-rift phase along the passive margin of Sundaland, which presently lies in the East Andaman Basin. Reservoir quality of these rocks though is doubtful.
II) Syn-rift fluvial coarser clastics reservoirs that were deposited with the onset of extension and subsequent rifting and deltaic/ shelfal clastics that were gradually introduced into the system following the marine incursions at the late syn-rift phase. These have been sparsely penetrated by wells though and are likely to be present widely with fair to excellent reservoir qualities.
III) Mixed facies development (clastic and carbonate) after regional flooding during earliest post-rift phase, where basin margin deltaic clastic sediments were deposited in response to the transgressive-regressive cycles and at the same time carbonates grew on top of the shallow structural / basement highs. This interval represents some of the most prolific reservoirs to be found in the entire area. However with present geological understanding of East Andaman Basin, availability of carbonate reservoir is uncertain.
IV) Mass flow deposits and deepwater turbidites in East Andaman Basin that developed during the late stage of

postrift, when the basin was inundated following the huge regional subsidence.

• **Seal:** In the East Andaman Basin, regional data combined with current seismic interpretation suggest the possibility of effective vertical sealing. Presence of at least three regional/ local efficient seals can be anticipated to be present: the deeper reservoir (prerift/early synrift) is likely to be sealed by intra-formational shales; synrift reservoirs to be capped by late syn-rift/early post-rift transgressive shales; early postrift reservoirs and youngest post-rift reservoirs are expected to be sealed by regional deepwater marine shales/clays. In addition, pore pressure studies in East Andaman Basin also predict an over-pressured syn-rift sequence which can enhance the sealing capacity of the intraformational units.

• **Trap:** The hydrocarbon fields in North Sumatra Basin indicate that the structural traps are the best contenders for effective trapping, along with the carbonate build-ups which can be considered as stratigraphic ones. Pure stratigraphic traps are not commonly found and usually work along with some structural element in post-rift plays. Structural traps are mostly found along the pre-existing basement highs (horst features derived from rifting), as well as the inverted anticlines and positive flower structures (generated by strong strike-slip movements). Seismic data of East Andaman Basin confirms the presence of such structural features and therefore can be considered as possible traps. Structuration essentially took place at the late syn-rift stage soon after the thermal sag phase (Late Oligocene to Early/Middle Miocene). Post-rift structural traps are the drape-over structural features on preexisting highs and also could work with stratigraphic trap elements (like delta sands, channels etc.) in combination. Post-rift deepwater turbidites can also be considered as stratigraphic traps.

• **Generation & Migration:** The earlier publications on the area (Hall 2002, Doust & Sumner 2007, and International Heat Flow Commission) show that the area is under a very high heat flow regime. Available data also suggest that the heat flow in this region varies from 1.4 to 2 BHU and the geothermal gradient from 3.5°C/100m to as high as 5.5°C/100m. The computed heat flow map at the present day changes parallel to the NNE-SSW trend of the continental margin (considering western edge of Mergui Ridge) and increases gradually toward west and north west from 1.5 to >1.9 HFU within the East Andaman Basin area. This increase can be associated with the Oligo-Miocene volcanic emplacements at the western boundary of East Andaman, and the current sea-floor spreading activity since Late Miocene. As the onset of hydrocarbon generation is fixed about at 0.55 Ro (%) vitrinite reflectance (though it depends on the kerogen type), the hydrocarbon window is expected to lie around 3000-5000 m from burial.

Generation of hydrocarbon in East Andaman Basin probably started as early as at Latest Oligocene; however, hydrocarbon expulsion timing is not very definite but can be estimated to have started by Early Miocene. The Early Miocene/ Middle Miocene inversion tectonics though might have slowed down the continuous expulsion before having been resumed during Late Miocene and most likely continuing till date. It is expected that the hydrocarbon migration took place by both primary and secondary migration processes. Presence of numerous faults in the system, created during the structuration and that too before the expulsion phase, are likely to enhance the migration efficiency of the whole system.

Play Model for East Andaman Basin

The play model is based on the similarity with surrounding analogue basins (North Sumatra, Mergui) and hydrocarbon occurrences in these basins typically exhibit rift-related petroleum system that are proven to be quite prolific. In broad scale, the whole petroleum system of East Andaman Basin can be summarized in following four plays (Fig. 3):

1) Pre-rift clastic play (conceptual for East Andaman, not proven in the region), 2) Syn-rift clastic play (least explored in the region); 3) Early post-rift clastic/ carbonate (?) play (very prolific all over the area), and 4) Late post-rift clastic play. The common risk component of this play model lies in the presence and effectiveness of the source rock.

1) **Pre-rift clastic play:** Seismic signatures in the East Andaman area indicate possible presence of a deeper pre-rift sequence. This play can be related to pre-subduction passive margin sediments of Sunda shelf margin. Pre-rift reservoirs of shallow marine/paralic facies are likely to be charged by the earliest syn-rift terrestrial-prone source intervals. However, reservoir presence and quality could be

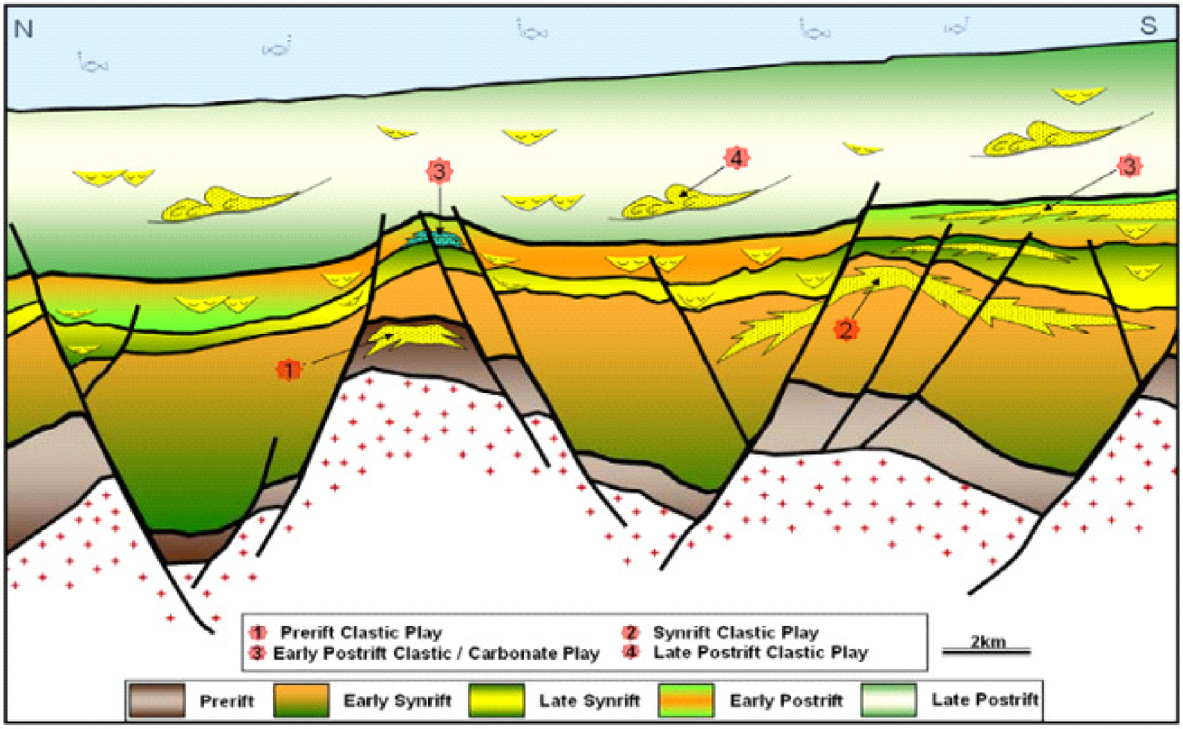

Fig. 3: Schematic seismo-geological section of East Andaman Basin showing the postulated play model (vertically not to scale).

of concern, coupled with trap formation. Sealing is dependent on Intra-formational shale/claystones.

2) Syn-rift clastic play: Typical fluvio-deltaic high quality clastics reservoirs are expected to be charged by the early synrift fluvio-lacustrine source intervals and finally being effectively sealed by the late syn-rift / early post-rift marine transgressive shales. As evident from seismic data, some of the biggest traps are found to exist within this sequence as late syn-rift inversion anticlines, tilted fault-blocks and/or unconformity related traps.

3) Early post-rift clastic / carbonate (?) play: Extensive shallow-marine deltaic sands of the early post-rift are likely to be sourced from the syn-rift lacustrine shales of early syn-rift stage and probably by the shallow marine transgressive shales of early post-rift once sufficiently buried. Both intraformational and post-rift thick deep marine shales can act as the seals. Traps are usually the drape-anticlines over existing highs/ tilted fault blocks inversion anticlines. Regional presence of post-rift reef carbonates on top of existing highs and / or tilted blocks within the early post-rift sequence can act as another reservoir, though it is not very conclusive.

4) Late post-rift clastic play: This youngest play can be envisaged with the late post-rift gravity and fan deposits that can be charged by the early post-rift transgressive marine shales when sufficiently buried. However, chances of biogenic gas play cannot be ruled out completely.

Conclusions

The East Andaman Basin remained a completely unexplored area till very recently mainly due to its remote location (south-eastern most edge of India), data paucity

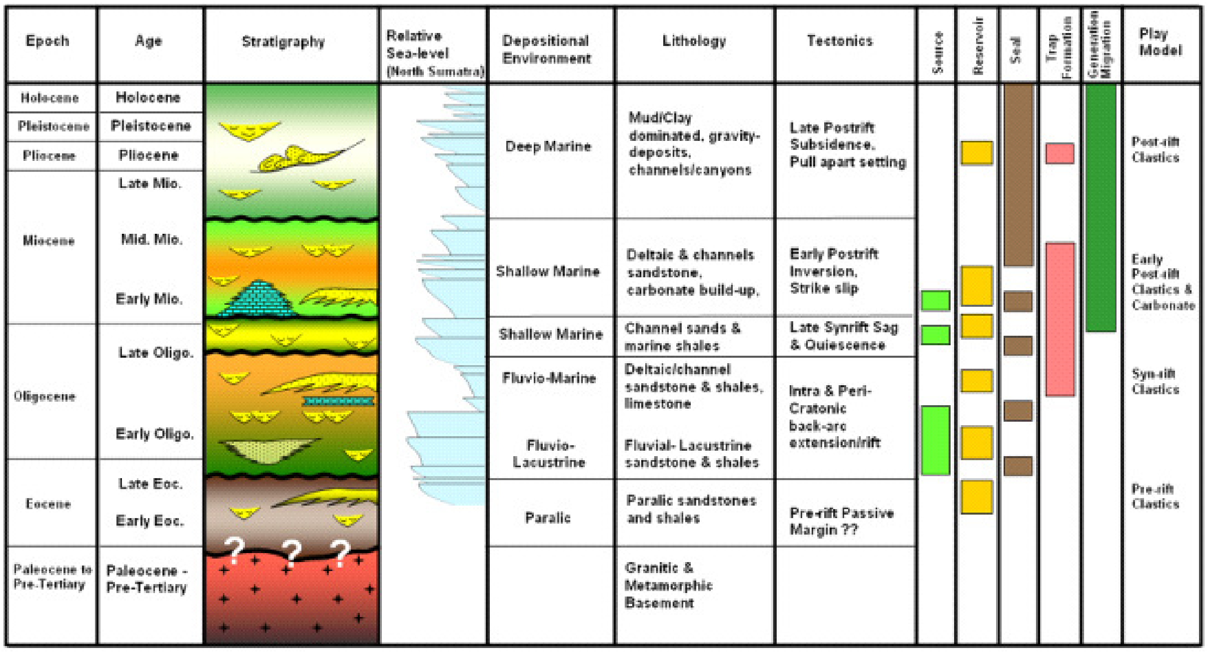

Fig. 4: Proposed tectono-stratigraphic chart, petroleum system and play model of East Andaman Basin

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and operational constraints (water depth hovering around 2500m or more). Present studies on regional geology, seismic interpretation and petroleum system model (Fig. 4) clearly bring out the fact that East Andaman basin in every possible way is time-equivalent to the North Sumatra and Mergui Basins, if not slightly older. All of them developed due to the back-arc extension of western Sundaland in response to the subduction of Indian Plate under the Indochina-Burmese Plate in the Cenozoic. The region later went into a right-lateral transtensional mode and currently is under the same tectonic setting.

These three basins also exhibit comparable characteristics in sedimentation pattern during the basin building processes.

The initial syn-rift fluvio-lacustrine and fluvio-marine sedimentation gradually became shallow marine/shelfal in late syn-rift before entering the deep-water in late post-rift stage. Under these tectonic circumstances, North Sumatra Basin is known to hold significant hydrocarbon reserves in its riftrelated plays. This in fact adds confidence about the presence of a plausible working petroleum system in East Andaman Basin in a similar rift-related play model.

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Acknowledgement

The authors are grateful to Eni management and JV partners for the permission to publish the material contained in this paper and express their special thanks to exploration colleagues of Eni for their kind review and comments.