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Depositional environments of the Miocene sediments in northern Song Hong basin

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ABSTRACT

Northern Song Hong Tertiary Sedimentary basin is a classic case study of a pull-apart basin in southeast Asia, whose formation was controlled by the India-Eurasia collision, sinistral and dextral strike-slip motion of the Ailao Shan-Red River Shear Zone and Opening of the East Vietnam Sea during the Cenozoic. Unlike the central and southern parts of the basin, the northern Song Hong Basin experienced a very strong inversion during the Late Miocene. This rapid uplift of the region has led to significantly change in lithofacies and sedimentary environments, which are now still poorly understood. This uncertainty is considered one of the main challingings in prediction of the non-structural traps in the region. The recent results derived from well logging and 2D/3D seismic interpretation allowed us to define the Miocene formation in northern Song Hong basin, which are subdivided into three substrata, namely: the Lower, Middle and Upper stratum, which are characterized by typical characteristics of lithology and depositional environments. The Lower Miocene formation is dominated by deltaic environment at the bottom, transitioning to the overlying shelf environment. Lithology of the section varies from coarse-grained sediment (sandstone) to fine grained material such as shale and mudstone upward; The Middle Miocene stratum demonstrate sandier, coalic materials of the delta plain and delta front environments intercalated with swampy shale. In contrast, the Upper Miocene section is characterized by more fluvial and nearshore elements. It is illustrated by presence of the channel-filled sand bodies and mouth/longshore sand bars. These sand bodies demonstrate good porosity and horizontal permeability, which are considered to be good potential reservoir for both structural and non-structural traps in the Miocene formation.

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1. Introduction

The Song Hong Tertiary Sedimentary basin (Figure 1) is one of the classical pull-apart basins, which are closely associated with left lateral strike-slip motion along the Ailao Shan-Red River Shear Zone and opening of the East Sea during the Cenozoic (Tapponier et al., 1982). However, tectonic evolution of northern part is significantly different from central and southern parts of the basin. Previous studies indicated that the northern Song Hong basin had experienced a strong inversion period since the Middle Miocene while the similar event was not evidenced in the remaining parts of the basin to the south (Hoang et al., 2020).

It is noteworthy to note that the Song Hong basin is an interest area attracting a large number of geoscientists and oil and gas companies's attention due to its promising potential of hydrocarbons. Even though several small-scale hydrocarbon fields have been discovered, many exploration wells were unsuccessful due to the inappropriate interpretation of the geological model for the area.

As it was addressed in the upper sections, the Middle Miocene uplift triggered a strong erosion and deformation of the pre-existing sedimentary formations, making geological structure, stratigraphy correlation more complex. Numerous truncations and erosions during uplifting caused by inversion have led to

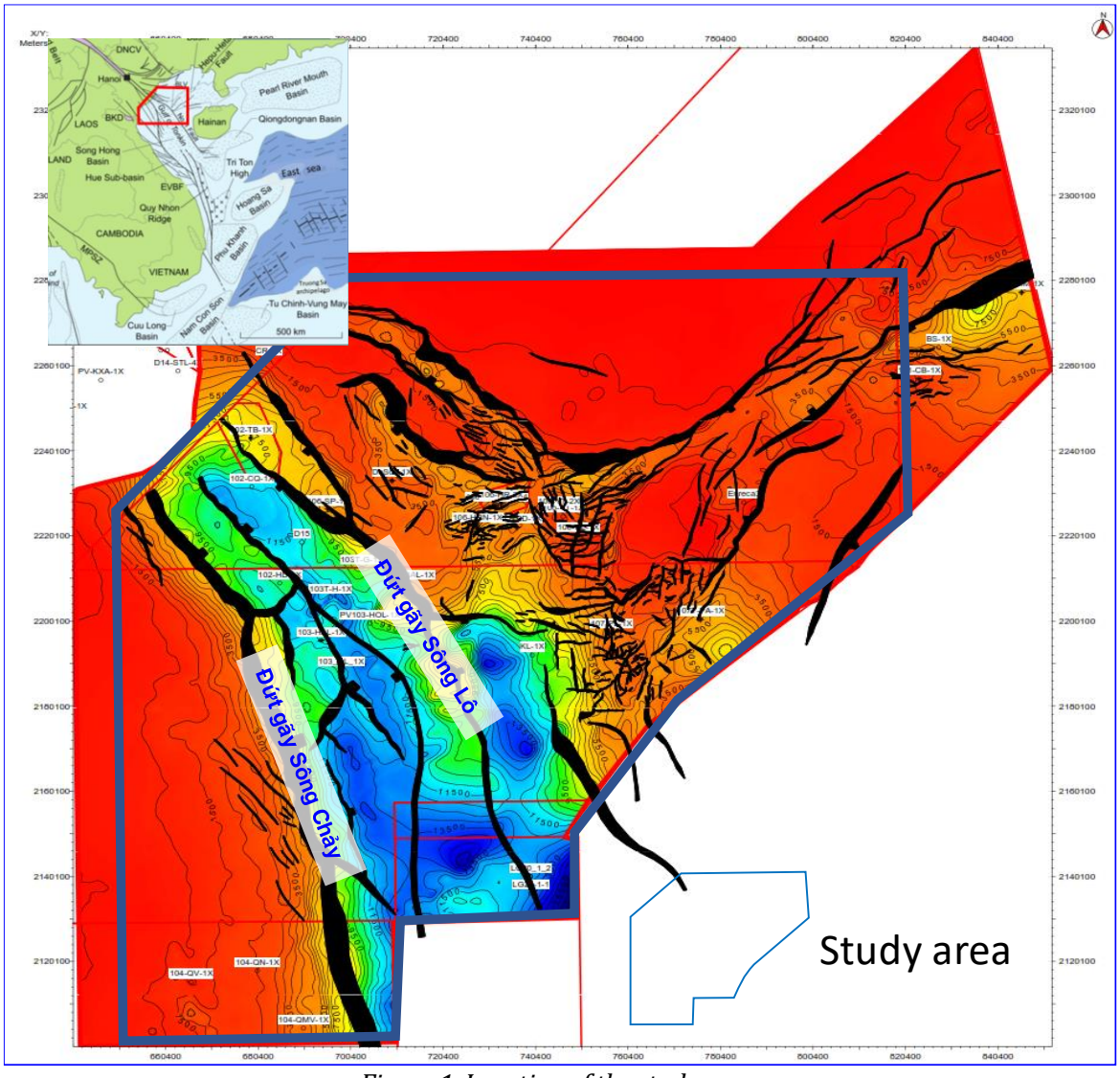

Figure 1. Location of the study area.

interpretation of sediment thickness and trend of changing in environments. These problems introduced various uncertainties in mapping lithofacies and depositional environments and hence cropping potential structural traps, especially non-structural traps are always challenging tasks.

In order to improve the quantitative and reliable interpretations, the data derived from the recent exploration drillings together with 3D seismic data was used to update and define depositional environments for the Miocene sedimentary sequence in the northern Song Hong basin, aiming to the following objectives:

- Defining sedimentary compositions and stratigraphy of the northern Song Hong basin during the Miocene;
- Re-constructing and delineating distribution of the Miocene depositional environments in the region.

2. Regional geological setting and development

2.1. Tectonic framework

The Song Hong basin is a Tertiary pull-apart, north west - south east (NW-SE) trending basin associated with the south east (SE) extension of the Ailao Shan Red River Shear Zones, which was triggered by the India-Eurasia collision during the Cenozoic (Tapponier et al., 1982; Clift and Sun, 2006; Hoang et al., 2010). Formation of the basin were started and controlled by a series of transtensional faults during Eocene to Early Miocene. The western margin is controlled by the Song Ma and SE continuation of the Red River fault, which is known as the 110^0 longitude fault while the eastern margin is limited by the Song Lo fault/No. 1 fault (Figure 2).

Evolutionary history of the study area can be summarized in Figure 3. According to Clift and

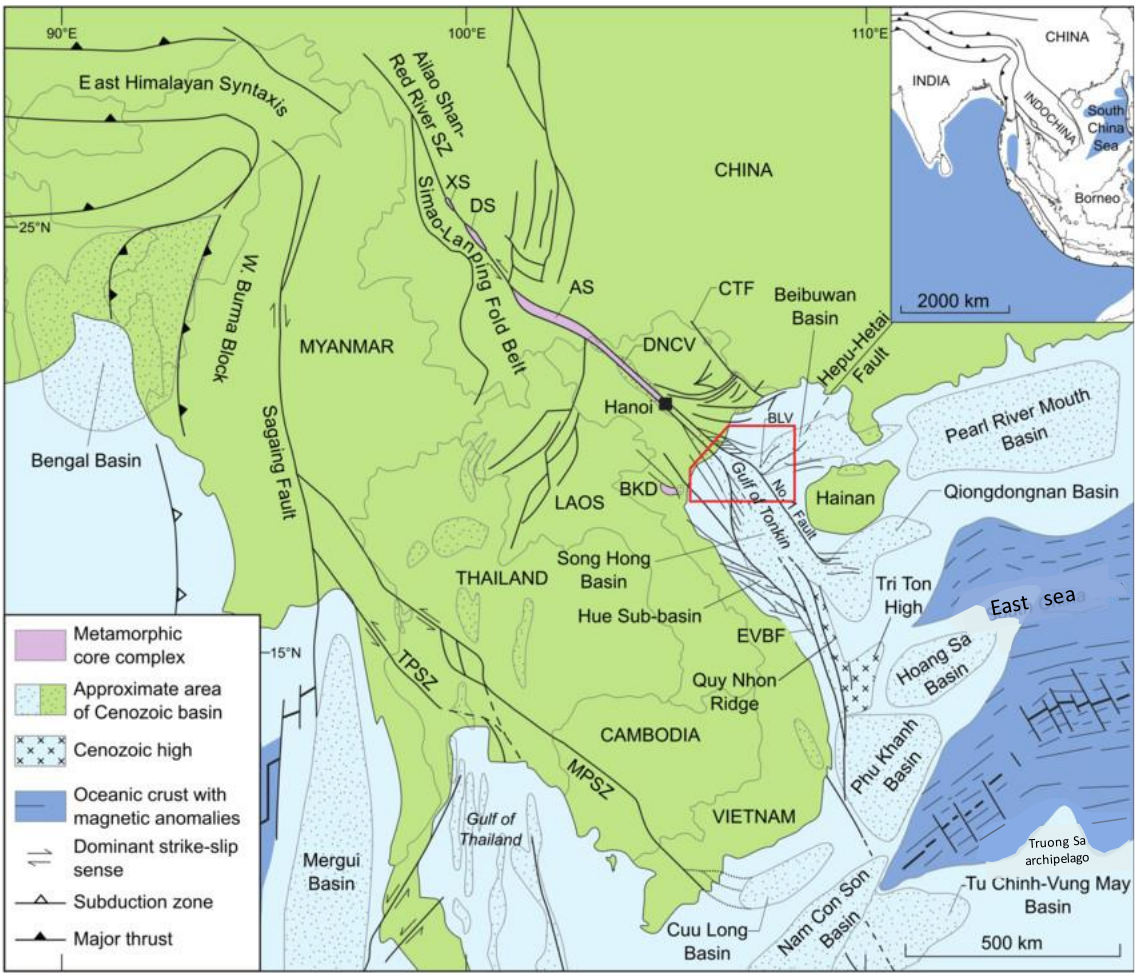

Figure 2. Red river basin and adjacent tectonic terranes (after Hoang et al., 2020).

Sun (2006), the basin was initially opened by transtension process, which was started at ca. 44 Ma. The extension along the margin was continued until ca. 22÷20 Ma. After a long and strong extension period and subsequent thermal subsidence, the basin was diachonously inverted during the 16÷10 Ma period. This tectonic uplift is clearly evidenced in the northern part by the presence of the reverse faults, overturn fold and erosion surfaces (e.g., U220, U210, U200 etc. seismic horizons in Figure 3).

The inversion reached a peak in the Late Miocene and was followed by a rapid subsidence after ca. 5.5 Ma., particularly during the Late Pliocene (Clift and Sun, 2006). The complex tectonic activities of the basin result in the formation of different structural units, which are now considered to be hydrocarbon potential structures. The basin has been filled with a huge volume of the Cenozoic sediments. However, the sediment distribution pattern is various from the north to the south. This change is illustrated by the migration of depocenter through time (Hoang et al., 2010). Due to shifting of the depocenter, the Miocene - Quaternary sediments in northern basin are much thinner than those in the central and southern parts. Total estimated thickness of the Cenozoic deposits based on seismic data is up to 13 km in the central part. General geometry of the basin demonstrates a NW-SE trending in the north and turning to NNW-SSE orientation in the south. During the early transtension, the Eocene - Oligocene sediments were filled within local troughs, which are dominated by sandstone, mudstone and shale intercalated with minor limestone thin coals seams. After a regional uplift at the End of the Oligocene, a strong subsidence took place during the Early Miocene causing a rapid transgression and hence marine sediments have unconformably onlapped over the pre-existing fluvial/lacustrine sediments prior to second regional inversion occurred in the Late Miocene.

2.2. Stratigraphy

Stratigraphy of the Song Hong basin has been studied for quite a long period of time, most of the works were conducted as a part of the hydrocarbon exploration projects. Based on microfossil data together with well logging and 2D/3D seismic data, stratigraphy of the northern

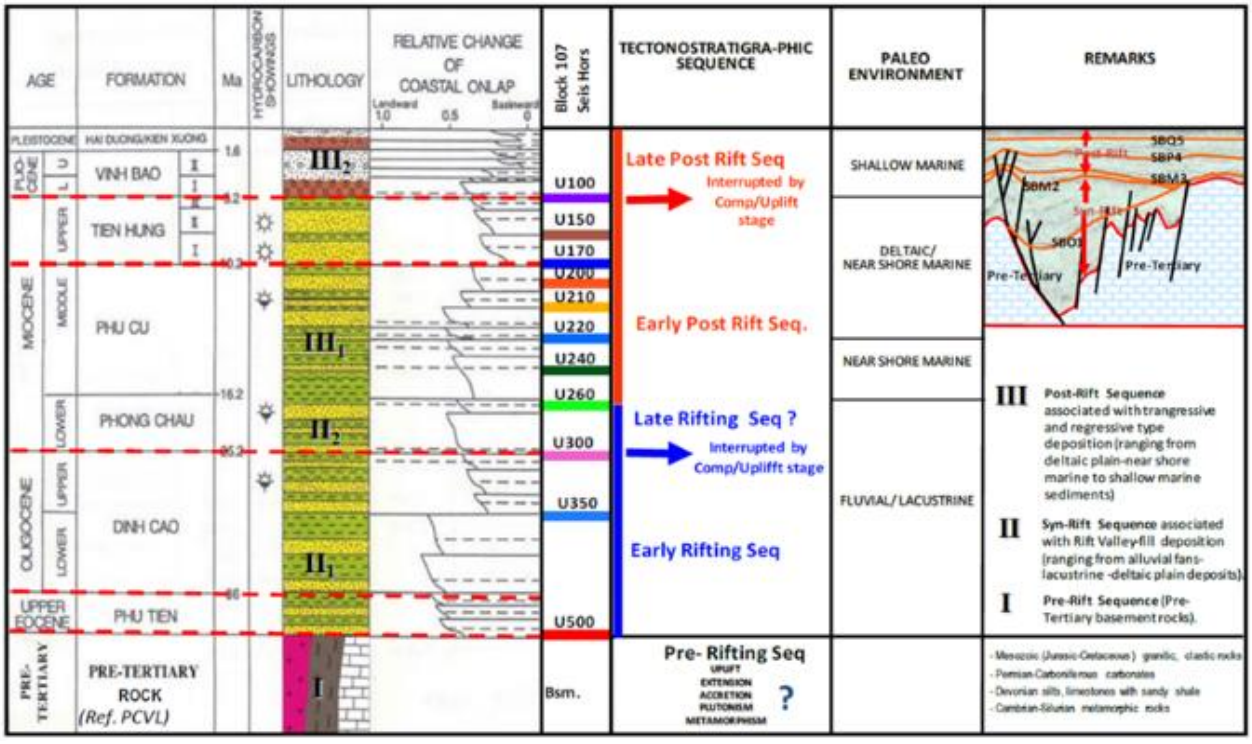

Figure 3. Regional tectono-stratigraphic framework of the North Song Hong Basin and seismic events (U500 - U100) (after Petronas Carigali, 2011).

Song Hong basin was established and briefly described as below:

Pre-Cenozoic basement

Although the distribution of the pre-Cenozoic basement rocks has not been well mapped, the data derived from exploration wells and onshore geology show that stratigraphy of the basement is diversified. It consists of metamorphic, intrusive/extrusive, carbonate and clastic rocks, whose ages vary from the Paleozoic to the Late Mesozoic time, formed in various environments.

Cenozoic sedimentary formations

Lower Paleogene - Phu Tien formation (E_2*pt*): This is likely the oldest formation in northern Song Hong basin and Hanoi trough. It is composed of brown-grey sandstone and siltstone intercalated with polymineral conglomerate. Depositional environments of the formation are alluvial and lacustrine.

Upper Eocene - Dinh Cao formation (E_3*dc*): The formation consists of light-dark grey sandstone, purple color in some places; intercalated with boudinage conglomerate; the upper section consists of blackish-grey, grey siltstone and shale. The sediments were deposited in the lacustrine environment.

Lower Miocene - Phong Chau formation (N_1^1 *pc*): The Phong Chau formation is characterized by alternative successions of the whitish grey, greenish grey bedded fine-medium grained sandstone intercalated with lenticular - very thinly bedded siltstone. Its major depositional environment is deltaic plain.

Middle Miocene - Phu Cu formation (N_1^2*pc*): It was subdivided into three sequences containing sandstone, siltstone, shale and coal seams. The sediments facies belong to the deltaic and nearshore environments.

Upper Miocene - Tien Hung formation (N_1^3 *th*): The Tien Hung formation demonstrates cyclic sedimentation fashion, which mainly consists of gritstone at the base and sandstone, siltstone, shale, coalic shale upward. The Formation was form in the deltaic environment.

Pliocene - Vinh Bao formation (N_2*vb*): it is separated from the upper and lower formations by regional unconformities. The main lithological compositions are grey, thickly bedded fine grained sandstone intercalated with lenticular conglomerate and become more fine-grained fraction upward. Environment for this formation is marine system.

Quaternary weakly unconsolidated - friable sediments: The Quaternary sediments were subdivided into the Hai Duong formation and the Overlying Kien Xuong formation. They are mainly weakly consolidated - unconsolidated conglomerate, sandstone, mudstone and loose clastic particles deposited in the deltaic and coastal zone environments.

3. Database and methodology

3.1. Input data

In order to conduct this study, we used bio-stratigraphic, lithological and geophysical logging data derived from 22 exploration wells together with 2D/3D seismic data within the 102, 103, 104, 106 and 107 Blocks in the Northern Song Hong basin (Figure 4).

3.2. Study methods

Biostratigraphy

The bio-stratigraphical constraint for the northern Song Hong basin was based on analytical data of micro fossil such as foraminifera, spore and pollen collected from the core and/or cutting samples in exploration wells. The samples were pre-processed prior subject to examination under microscope. Distribution of the fossils was subdivided into different zones corresponding to each age interval. Finally, biomarkers were defined to be referencing age markers in each well.

In addition, microfossils are also important proxies for interpreting depositional environments of each sedimentary formation.

Lithological logging

Lithostratigraphy of each well was logged by on-site direct description of cutting samples under hand lens and/or microscope, detail examination of mineral composition was done using artificial thin sections under polarized microscope in the Lab.

Geophysical logging

As conventionally, geophysical properties of the rocks penetrated by exploration wells within the study area were recorded for various parameters such as gamma intensity, density, resistivity, etc. These well logs were subsequently interpreted for rock typing, stratigraphical correlation and assisting seismic interpretation.

Seismic interpretation

Major seismic horizons were picked across seismic profiles based on basic seismic termination configurations such as onlap, downlap, toplap, erosion etc. terminations, which were introduced by Dix (1955), Veenken (2007) and Vail et al. (1977). Horizons running across the biomarkers were also picked up for age constraining purpose. Seismic data were furthermore subjected to facies analysis supporting interpretation of the lithofacies and associated depositional environments.

All of the analytical data, including well logging, biostratigraphy, lithology, seismic stratigraphy/facies etc. were integrated for finally defining depositional environments for the Miocene section within the study area.

The workflow to interpret the Miocene depositional systems of the study area is briefly described in Figure 5.

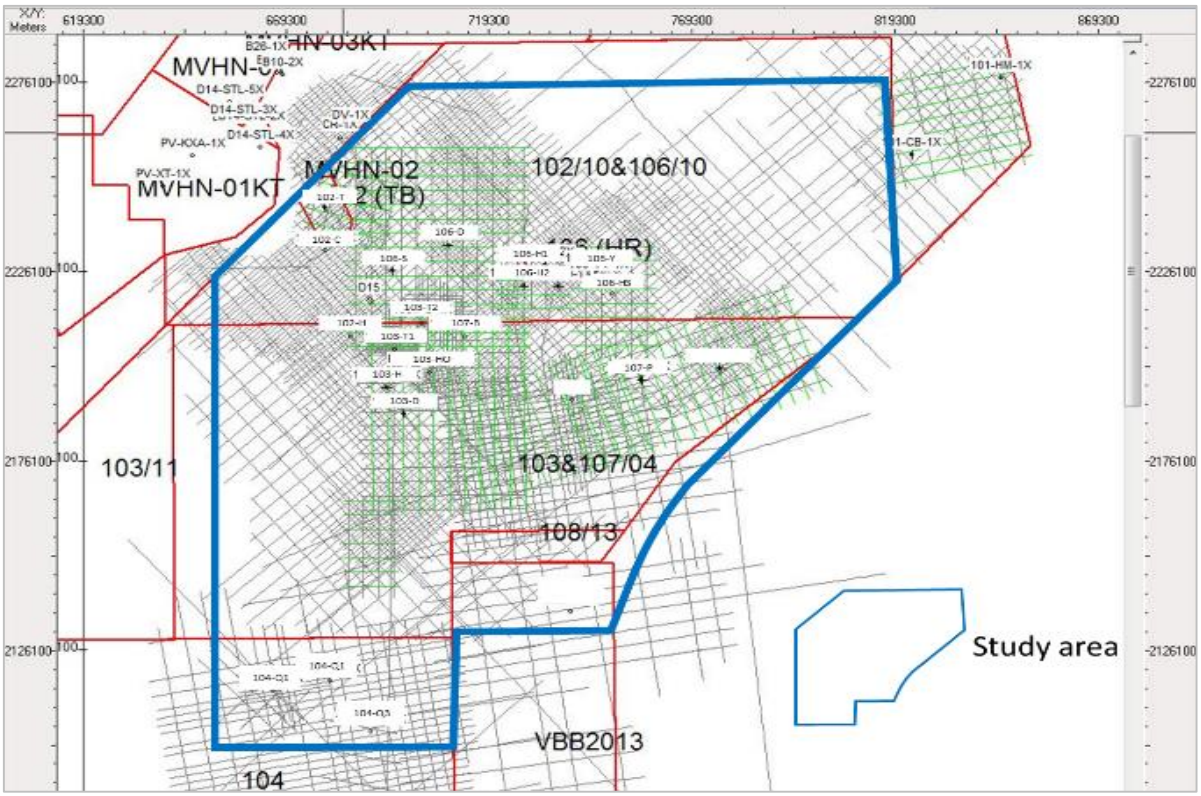

Figure 4. Location of exploration wells and seismic data used in this work.

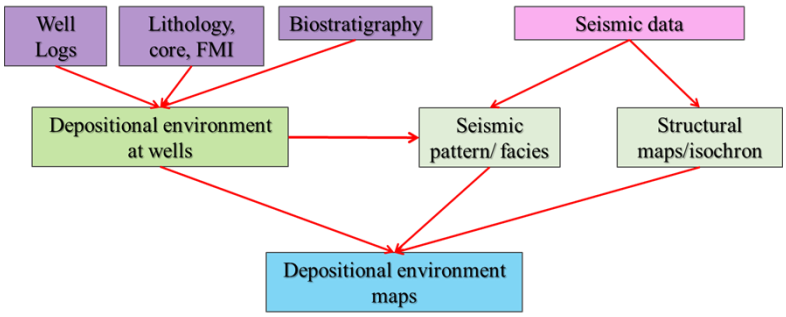

Figure 5. General workflow and data applied for this study.

4. Interpretation of lithofacies and depositional environment

Having applied the aforementioned approach (Figure 5), results of studying depositional systems of the Miocene sedimentary formations was obtained. Detail characteristics of each typical environment are described as follow.

4.1. Lower Miocene stratum

The well-log interpretation allowed us to define two distinctive sections for the Lower Miocene sequence (Figure 6). The lower section contains successive lignite and shale while the upper section is dominated by foraminifera-rich shale facies.

These two lithofacies are also identified basing on their typical seismic reflection configuration and attribute (Figure 6). The lower part of the sequence is characterized by high amplitude seismic reflections while the upper section demonstrates transparent seismic reflections, which could be attributed to formation of shale. The high amplitude seismic zone in the northeast of Song Lo fault is likely indication of shale deposits interbedded with coal as they were confirmed in Well 102-S (Figure 6). Most of the areas to the north are covered by transparent reflections except for the central location, where it is dominated by high amplitude and continuous seismic reflections.

The paleo-depositional environment of Lower Miocene sequence was interpreted as a transition from the deltaic to shelf environment. The upper shale facies indicate a rapid transgression at the end of the Early Miocene period, which has led to the shift of depositional environment from the deltaic environment in the lower part to shallow marine environment in the upper part of the sequence. In addition, the lower part is dominated by mangrove swamp sediments, which are now known as the source rock in 102 Block. This type of source rock abruptly disappeared due to a rapid marine transgression to Hanoi trough, forming an overlying marine shale. This marine shale is widely observed and hence it is likely a regional seal rock for the study area.

4.2. Middle Miocene stratum

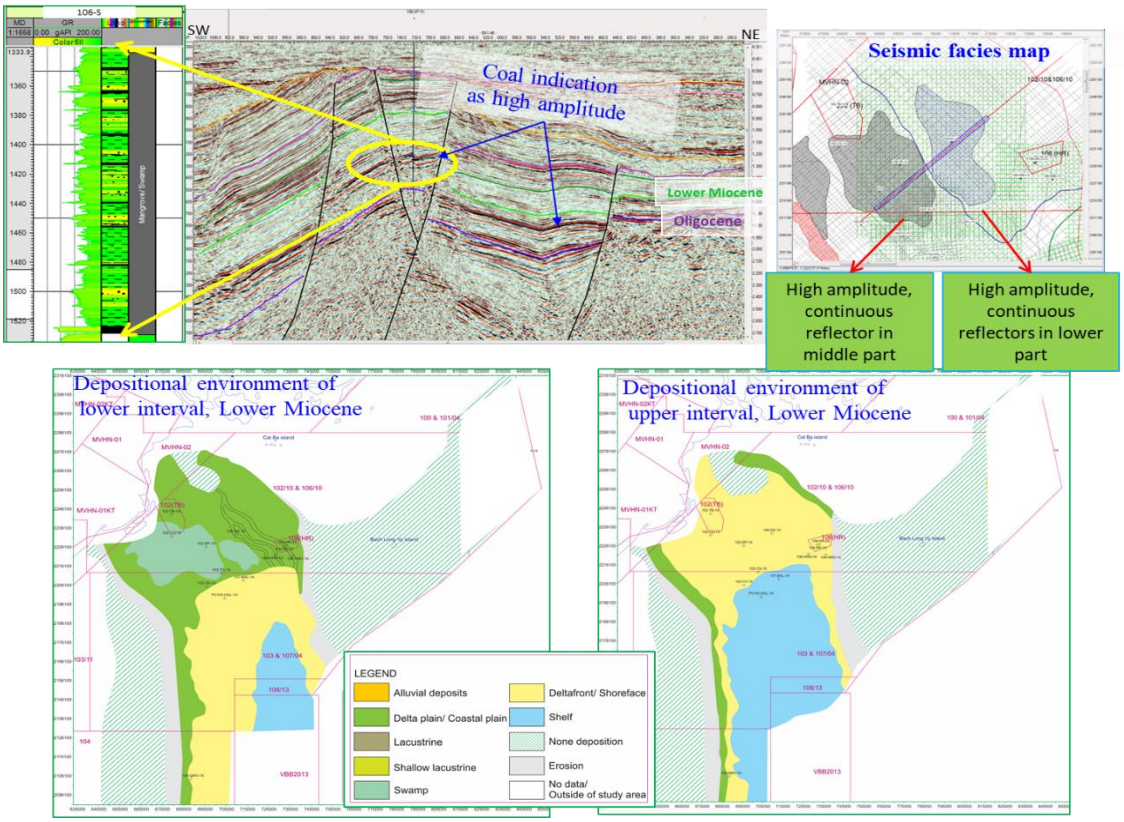

Figure 6. Seismic/well interpretation and depositional environment of the Lower Miocene stratum.

Due to multi-phases up-lift of the northern Song Hong basin, the Middle Miocene sequence demonstrates various patterns of the logging curves and seismic facies. The Lowest section of the Middle Miocene sequence shows aggradational stacking patterns with cyclic coarsening/fining-upward order as they are shown on the Gamma ray curve. Depositional environment of this section translates from the delta plain to the delta-front environment, in which the delta plain facies become more common upward. The presence of brackish water plant fragments and coalic shale shows that the mangrove swamp environment is widely distributed to the northwest and it is clearly identified by typical morphology of the log response in exploration the wells (102-C and 102-T) within the area. Extension of the high amplitude seismic reflection zone implies a deposition of coal seams in swamp depositional environment. Furthermore, the progarding reflections (Figure 7) are an indication of the delta extension, transitioning from the delta plain to the delta front. This interpretation is also supported by the presence of the delta front facies in the well 107-B.

Well-log characteristics are recorded as aggradational to slightly progradational stacking patterns (Figure 6) suggesting that the Middle interval of the Middle Miocene stratum has been strongly influenced by the marine process. The delta plain environment was still dominant in the northwestern location as Coalic material and plant fragments of mangrove Swamp were recorded only in 102-C and 102-T wells (Figure 8). The delta-front deposit observed in exploration well penetrates the middle position of the area, which indicates the increasing influence of the marine process from the west to the east of study area. Whereas, the point bar, flood plain and distributary channel facies were occasionally observed in all wells. Seismic reflections showing progradation and downlapping to the SE suggest that the sediment supply has been likely released from the NW, which revealed the major direction of the Paleo-Red river (Figure 9). The downlapping reflections nearby the 107-B and 106-H wells in the center of the 106 block indicates a possible transition boundary between

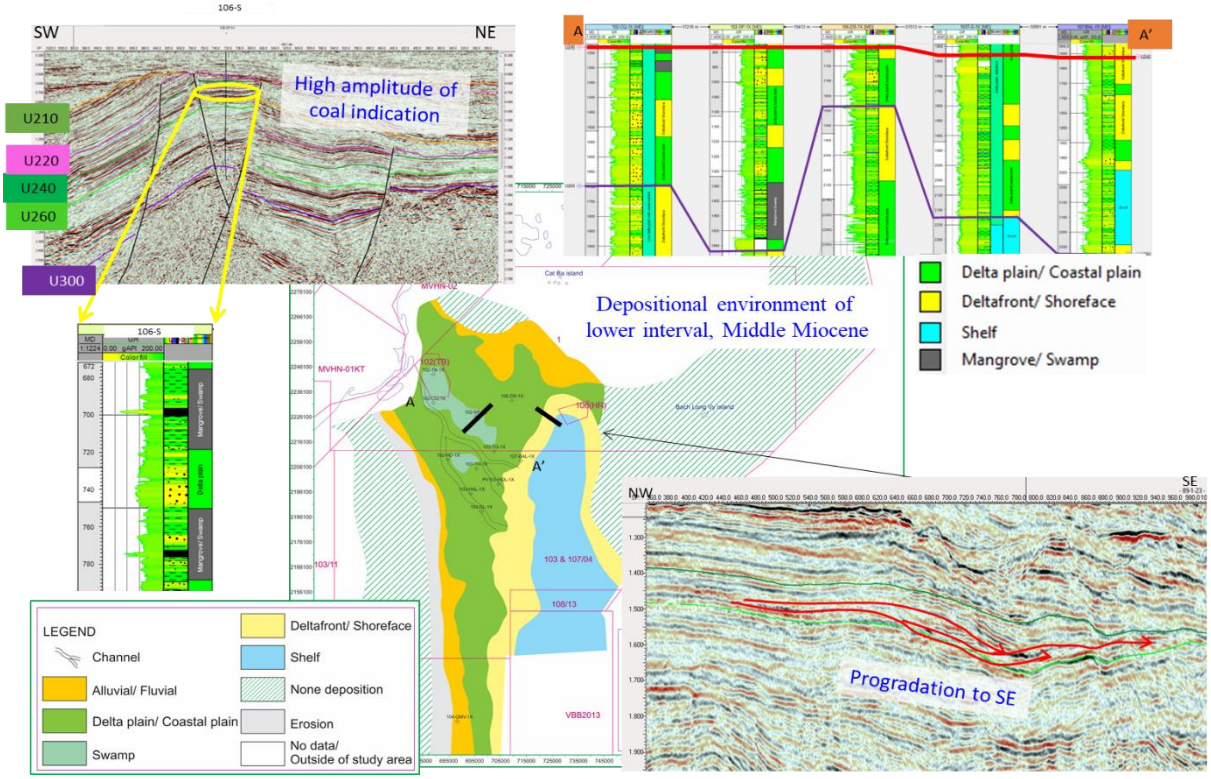

Figure 7. Seismic and well interpretation and depositional environment maps of the Lower section of the Middle Miocene stratum.

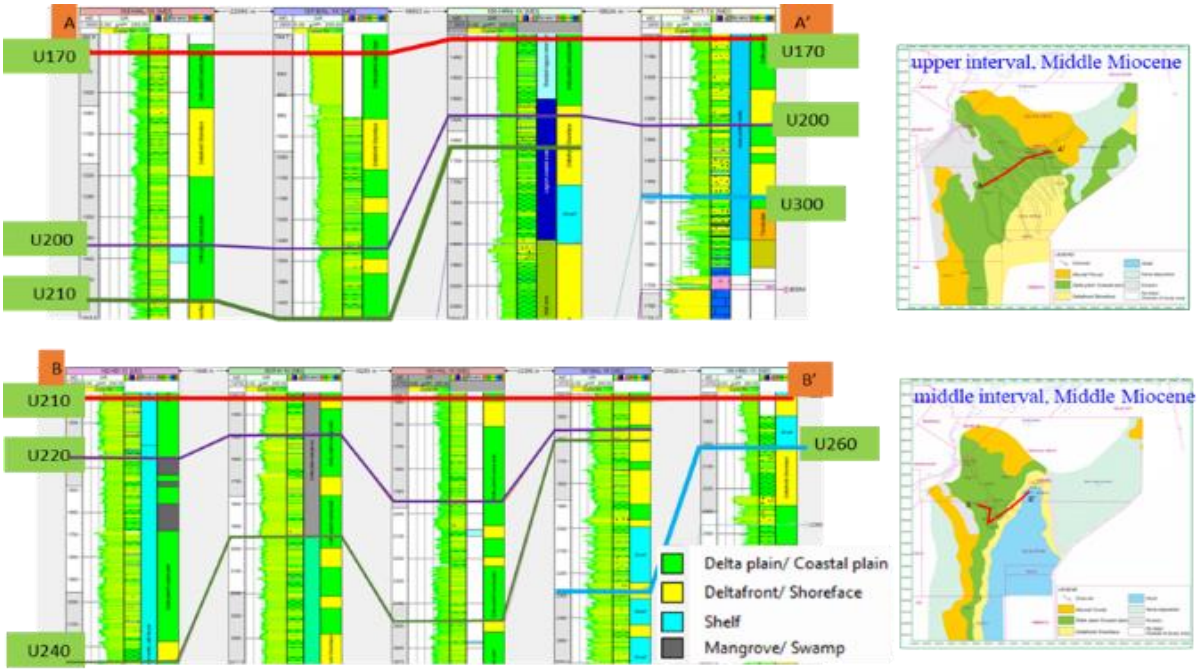

Figure 8. Environment interpretation in logs and correlation of middle and upper intervals of the Middle Miocene stratum.

the delta plain and delta front. It is noteworthy to note that the parallel, onlapping and pinching out of the seismic reflections to the east of the basement high (Figure 7) suggest a period of subsidence of the sub-basin relatively to the adjacent basement highs. Many stacked channels were identified on seismic profiles as deep erosional surface incised into the older/underlying strata during the rapid regression period.

Different incised-channel systems observed on seismic profiles of upper section of Middle Miocene (Figure 9) suggest that the area has been subjected to different periods of subaerial exposion as the relative sea-level has retreated. The channels show strongly meandering and variable in length and shape with NW-SE, N-S and NE-SW development directions. The seismic facies of the sequence indicate that most of the northwestern parts of Song Hong basin during this period were strongly subjected by fluvial influence. Wireline characteristics through most of the wells in this location prove the domination of fluvial delta plain environment (Figure 8). Meanwhile, biostratigraphic analysis of southeast well PL clarifies that the section was controlled by the marine environment. However, deposition has occurred in shallow marine - near shore condition due to the strong development of channels in most of the 107 Block.

4.3. Upper Miocene sequence

Due to a strong uplift triggered by the turning from sinistral to dextral strikeslip motion along the Song Hong Faults at the End of the Late Miocene, the top sediment succession of the Upper Miocene stratum has been strongly truncated and deformed at central location of the basin. It was agreed that truncation is the most common feature of the Top of the Upper Miocene formation. Prograding, wedge-shaped seismic reflections in the Upper Miocene section allowed us to interpret the relationship between this stratal unit and the shelf-break depositional environment, which are widely observed in the southwest (Figure 10). Further to the east, chaotic and high amplitude seismic reflections were supposed to be formation of the basin-floor fans or turbidites in the deep water depositional environment. Characteristics of the wireline logging also support for seismic facies interpretation by the dominance of the coastal plain environment through wells (Figure 10).

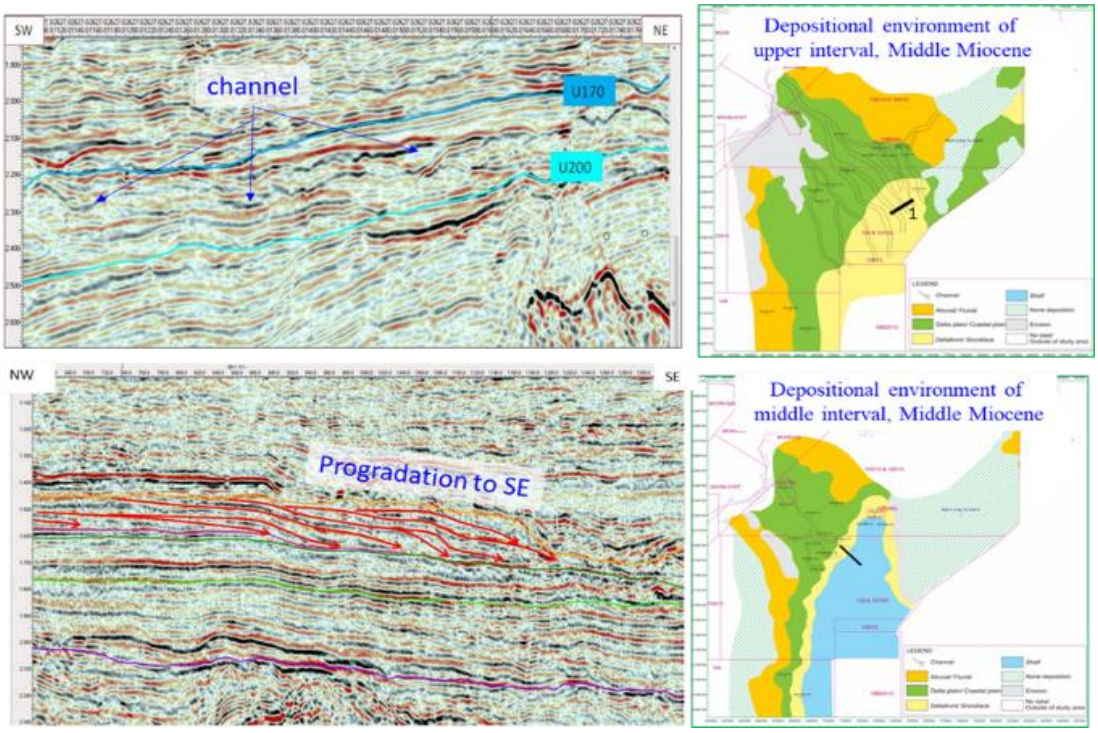

Figure 9. Seismic facies interpretation and depositional environment maps of middle and upper intervals, the Middle Miocene stratum.

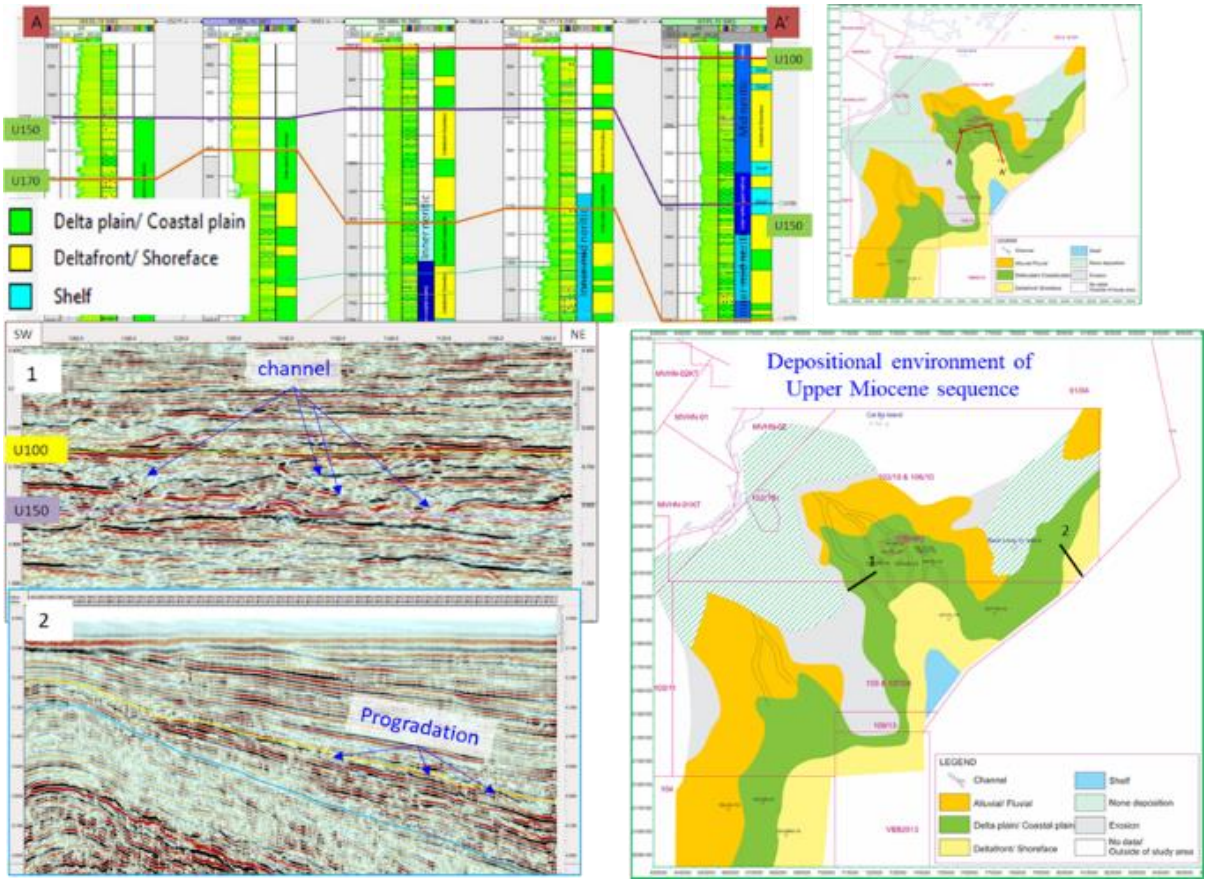

Figure 10. Seismic, well interpretation and depositional environment maps of Upper Miocene stratum.

Two different sub-sequences can be established within the Upper Miocene unit in northeastern, at the end of the region (Figure 10). The lower part is characterized by high frequency, moderate to high amplitude and continuous seismic reflections whereas the upper part is dominated by channelized, discontinuous with chaotic reflections, which could relate to high energy fluvial environment.

5. Discussion

This work was carried out based on the well logging data and seismic interpretation using facies model classification introduced by Walker and James (1992); Selley et al. (2005), aiming to define distribution and potential of the reservoir in the Miocene strata in northern Song Hong basin. However, the hardest challenging task is to predict characterizing sand body distribution as it depends not only on the sedimentary environment but also on sediment supply, paleoclimate and tectonic subsidence/uplift.

The Lower Miocene section affected by rapid trangress, which is evidenced by common stacked channels within this section. The widely distributed longshore and mouth bars probably contain much carbonate cement with poor to fair porosity as reveal in the 107_B well. The porosity and permeability analysis indicated that the longshore bar is better than mouth bar in terms of reservoir quality owing to abundance of the clean sand body. They are more homogenous and bear good connectivity (vertically and horizontally), resulted from the reworking and concentration of the river-born sediments by wave action. The mouth bars deposited at the seaward, the end of distributary channels, where sandy sediments have been transported as bedload mechanism when current velocities decreased. Significant development of marine shale in upper interval of Lower Miocene could provide good potential of regional seal for the Oligocene - Lower Miocene reservoirs.

Channel-filled sandy deposits demonstrate good horizontal but poor vertical connectivity due to the interbeding of the flood plain mud or mud flat. These well-developed channels in Middle Miocene section show good porosity with about 10% of matrix as analyzed in well samples. The main composition of cement is clay minerals. The upper part of the Middle Miocene and Lower part of the Upper Miocene accumulate thicker channel-filled sand bodies. Although the amount of matrix and cement is quite high, porosity of those reservoirs varies from fair to good as they have not been subjected to strong compaction during the diagenesis.

The transgression during early Miocene period has resulted in deposition of the onlaping shallow marine sands in the eastern part of the study area. This onlapping zone can provide potential stratigraphic trap for hydrocarbon accumulation. Other pinch-out and onlap stratigraphic traps are also observed within Middle and Upper Miocene sections. In general, they are deposited mostly on the western and eastern flanks of the basin.

6. Conclusion

Depositional environment of the Miocene formations in northern Song Hong basin have been studied using well logging and seismic interpretation. The obtained results were reliable basis for defining depositional environments and associated lithofacies during this period. These results allowed us to draw the following conclusions:

During most of the Early Miocene period, the region was influenced by the marine process, the fining upward and shale-dominant deposit shows trend of the marine trangression.

Coal formation was only observed in the lower part whereas incised channel systems were strongly developed in the upper part of the Middle Miocene section. These results suggest that the depositional environments vary from the fluvial to the shelf.

In the Late Miocene, fluvial delta plain becomes dominant. These characteristics of depositional environment imply potential of stratigraphic trap in area, such as sand bar, channel and pinch-out, locating along channel/eroded zones of delta plain and on the western and eastern flank of the basin.

Contribution of authors

Cuong Duy Tong - generated major ideas and wrote manuscript, interpreted seismic data; Long Van Hoang - finalized the checking of manuscript;

Dung Viet Bui - created environment maps; Huyen Dieu Thi Pham - analysed well logs and made their correlation; Tung Thanh Nguyen - also contributed ideas and contents to the study.

References

Clift, P. D., Sun, Z. (2006). The sedimentary and tectonic evolution of the Yinggehai-Song Hong basin and the southern Hainan margin, South China Sea; implications for Tibetan uplift and monsoon intensification. *Journal of Geophysical Research* 111 (B6, 28).

Dix, C. H. (1955). Seismic velocities from surface measurements. *Geophysics*, 20, 68-86.

Hoang, B. H., Fyhn, M. B., Cuong, T. D., Tuan, N. Q., Schmidt, W. J., Boldreel, L. O., ... & Cuong, T. X. (2020). Paleogene structural development of the northern Song Hong basin and adjacent areas: Implications for the role of extrusion tectonics in basin formation in the Gulf of Tonkin. *Tectonophysics*, 789, 228522.

Hoang, L.V., Clift, P. D., Schwab, A. M., Huuse, M., Nguyen, D. A., & Zhen, S. (2010). Large-scale erosional response of SE Asia to monsoon evolution reconstructed from sedimentary records of the Song Hong-Yinggehai and Qiongdongnan basins, South China Sea. *Geological Society, London, Special Publications*, *342(1),* 219-244.

Lee, T. Y., Lawver, L. A. (1994). Cenozoic plate reconstruction of the South China Sea region. *Tectonophysics* 235, 149-180.

Petronas Carigali. (2006)., Sequence Stratigraphy of Blocks 102&106, Song Hong basin. In-house study report.

Selley, R. C., Cocks, L. R. M., & Plimer, I. R. (2005). *Encyclopedia of geology*. Elsevier Academic.

Tapponnier, P., Peltzer, G., Le Dain, A. Y., Armijo, R., Cobbold, P., (1982). Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. *Geology 10(12):* 611-616.

Vail, P. R., Mitchum, R. M., & Thompson, S. I. I. I. (1977). Seismic stratigraphy and global changes of sea level, part 3: relative changes of sea level from coastal onlap. vol. 26, (eds.) C. E. Payton. *American Association of Petroleum Geologists,* 49-212.

Veenken, P. C. H. (2007). Seismic Stratigraphy, Basin Aanlysis and Reservoir Characterisation, 37, 1st ed. *Elsevier*, Oxford, 509 pp.

Walker, R. G., & James, N. P. (1992). Facies models: response to sea level change: *Geological Association of Canada*, St. John's, Newfoundland.