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Seismic Interpretation of the Nam Con Son Basin and its Implication for the Tectonic Evolution

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Abstract - The Nam Con Son Basin covering an area of circa 110,000 km^2 is characterized by complex tectonic settings of the basin which has not fully been understood. Multiple faults allowed favourable migration passageways for hydrocarbons to go in and out of traps. Despite a large amount of newly acquired seismic and well data there is no significant update on the tectonic evolution and history of the basin development. In this study, the vast amount of seismic and well data were integrated and reinterpreted to define the key structural events in the Nam Con Son Basin. The results show that the basin has undergone two extentional phases. The first N - S extensional phase terminated at around 30 M.a. forming E - W trending grabens which are complicated by multiple half grabens filled by Lower Oligocene sediments. These grabens were reactivated during the second NW - SE extension (Middle Miocene), that resulted from the progressive propagation of NE-SW listric fault from the middle part of the grabens to the margins, and the large scale building up of roll-over structure. Further to the SW, the faults of the second extentional phase turn to NNE-SSW and ultimately N - S in the SW edge of the basin. Most of the fault systems were inactive by Upper Miocene except for the N - S fault system which is still active until recent time.

Keywords: seismic, tectonic evolution, Nam Con Son Basin

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Introduction

The Nam Con Son Basin (NCSB) is located in the south-eastern continental shelf margin of Vietnam with an area of circa 110,000 km^2, bordered by Con Son swell in the northwest, Khorat - Natuna Arch in the southwest, and Tu Chinh High in the east (Figure 1).

Multiple institutions and geoscientist teams have been studying the basin, with many articles that have been published. However, there has not been any significant update on the tectonic evolution and basin history despite a large amount of newly acquired seismic and well data. This causes high uncertainties in the evaluation of petroleum system trap integrity and HC generation and migration. The probability of petroleum exploration success for commercial discovery in the basin is rather low (16% - unpublished data) probably because of the complex tectonic settings of the basin that has not fully been understood. In this article, the authors present a revised interpretation of the tectonic development in the basin scale based on the entire set of seismic and well data. Basin tectonic evolution is critical to improve understanding of the evaluation of petroleum system in the Nam Con Son Basin.

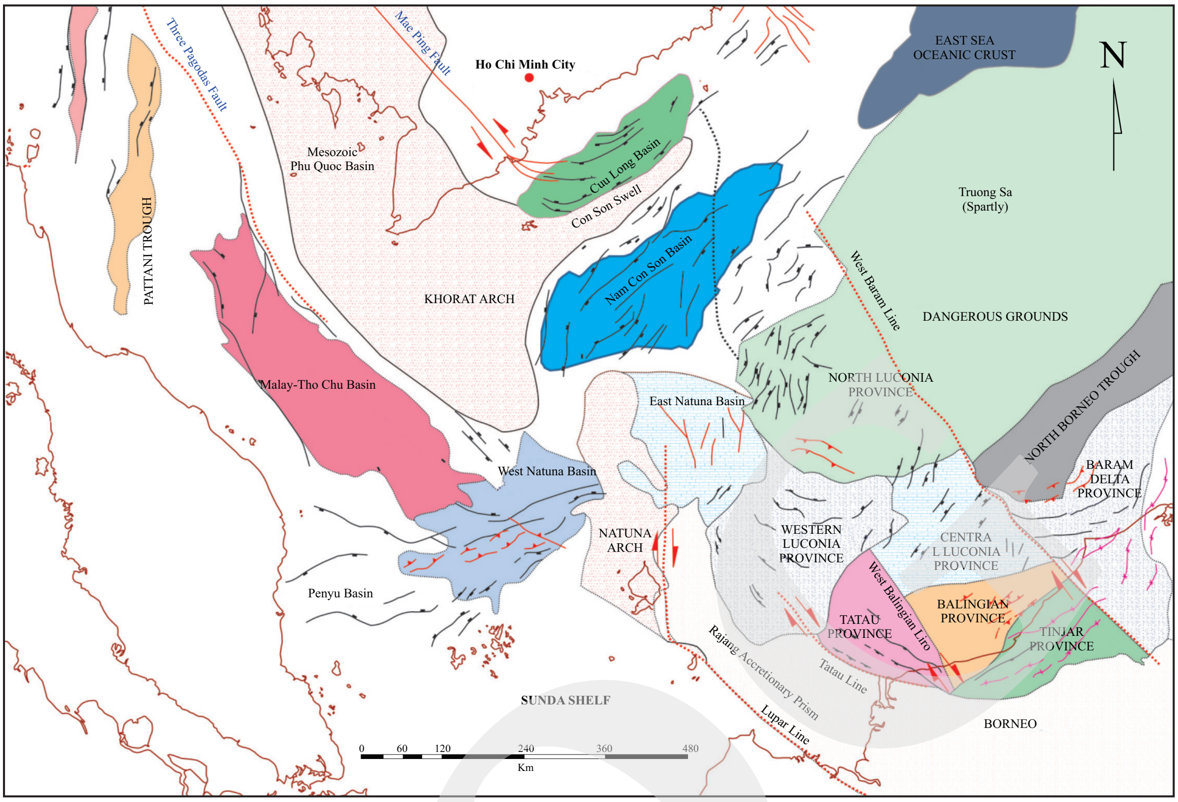

Figure 1. The main tectonic and structural features of the Nam Con Son Basin and adjacent areas.

Regional Geologic and Tectonic Settings of The Basin

In Southeast Asia, by Paleocene, the southeast extrusion of the Indochina Block and southward drift of the proto East Vietnam Sea associated with the collision of Luconia micro continent and Borneo caused a series of right-lateral transform faults in the East Vietnam Shelf extending to the East Luconia. This combination possibly derived N - S extension in the Sunda Shelf (Hall, 2002, 2009, 2013; Hutchison, 2004; Clift, 2008). Matthews (1997) and Fyhn *et al.* (2009) proposed the onset of rifting in the proto East Vietnam Sea (EVNS) as well as the NCSB initiated in the Eocene and lasted to the Early Oligocene (about 30 Ma). This rifting period is controlled by N-S extension, associated with E - W oriented faulting and deposition of rift-fill sediments in local W-E trending sub-basins (Figure 2).

The rifting phase in Eocene - Early Oligocene then was followed by the spreading of East Vietnam Seafloor, which propagated initially from E to W then WSW. At about 25 Ma, the axis of the seafloor spreading shifted from WSW trend to SW trend (Andrew, 2010; Morley, 2007; Pubellier and Morley, 2014).

At the end of Early Miocene, southwestward propagation of the seafloor spreading continued by a continental breakup, caused the second extension phase at the SW of the rift tip including NCSB, associated with NE - SW normal faults and deposition of syn-extension sediments in NE - SW grabens. The second extension phase is derived by NW - SE regional extension as a slab-pull of the SE drifting Dangerous Ground and the subduction of the proto EVNS beneath NW Borneo.

Well pronounced NW - SE central graben extension and accompanied progressive large scale listric faulting were probably initiated from the middle of the basin to its margins creating a unique depocentre with large scale roll-over structures with their crests in the middle of the grabens. The large scale faults penetrate the whole sedimentary cover to the basement.

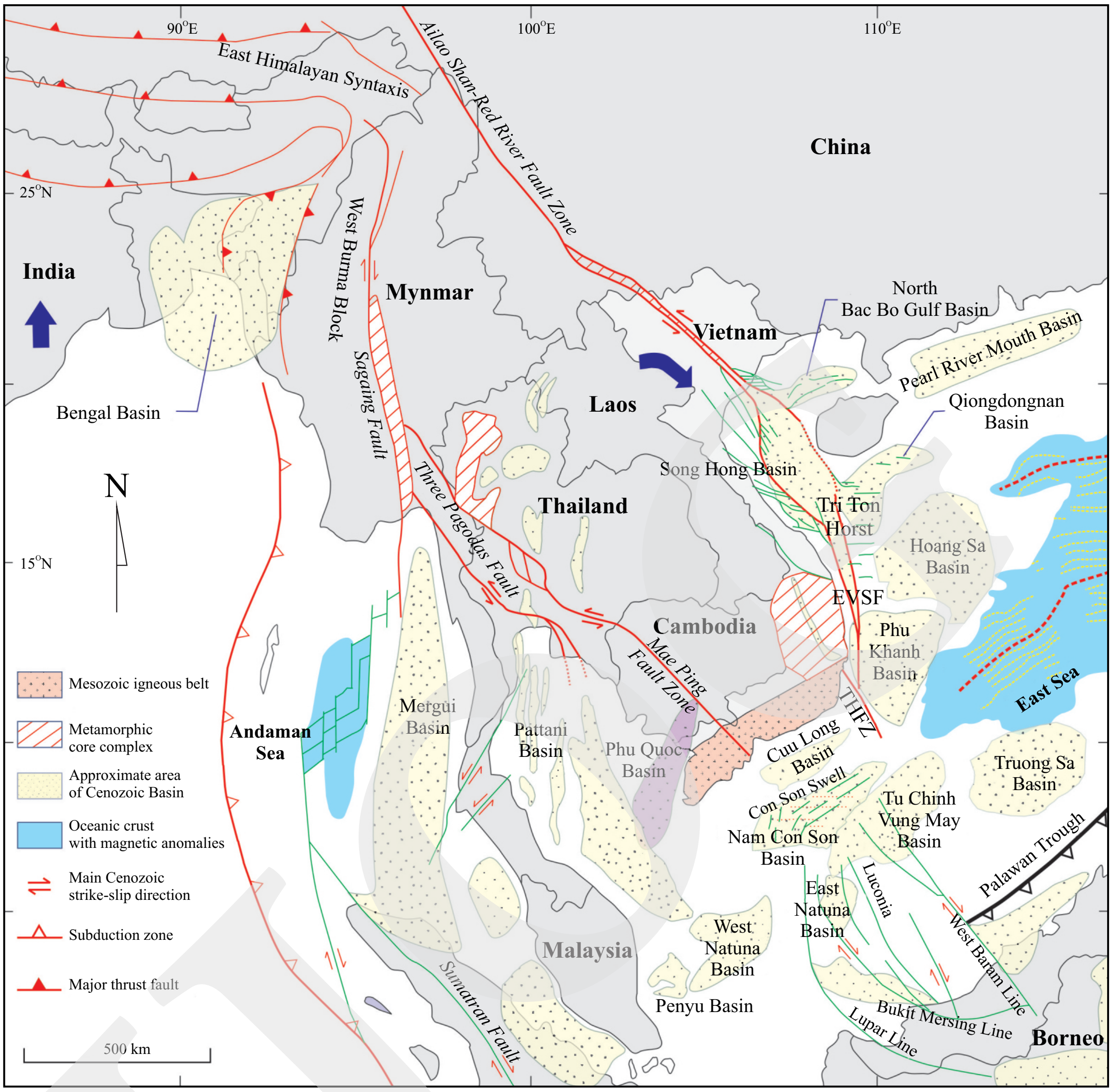

Figure 2. Regional tectonic map of SE Asia, modified after Fyhn *et al*., (2009), Andrew (2010) and Pubellier (2014). The studied area is marked by green curve. THFZ = Tuy Hoa Fault Zone, EVSF = East Vietnam Scarp Fault.

Moreover, growth-faults and related half grabens became progressively younger from the middle part of the basin depocentre.

As the East Vietnam Seafloor spreading totally ceased at about 17 - 16 Ma, regional sea level fell during the late Middle Miocene leading to the erosion (up to several hundred meters) of the central part of the roll-over structures.

The second rifting phase was then followed by a thick post-rift sequence (Upper Miocene - Pliocene - Quaternary) due to the increase in sediment supply with respect to onshore uplift and magmatism (Fyhn *et al*., 2009; Hall and Spackman, 2015, Nguyen Hiep, 2007; Tri and Khuc, 2011).

Stratigraphically, various rock sequences consisting of pre-Tertiary fractured granite and clastic sediments of Oligocene, Lower Miocene, Middle Miocene, and Upper Miocene age fill in the basin. Those Tertiary clastic sequences underlain unconformably by the pre-Tertiary fractured granite are source rocks and reservoir rock of potential hydrocarbon (Figure 3).

Datasets and Methods

This study is based on a number of reflection seismic profiles, totally 54,147 km. They cover

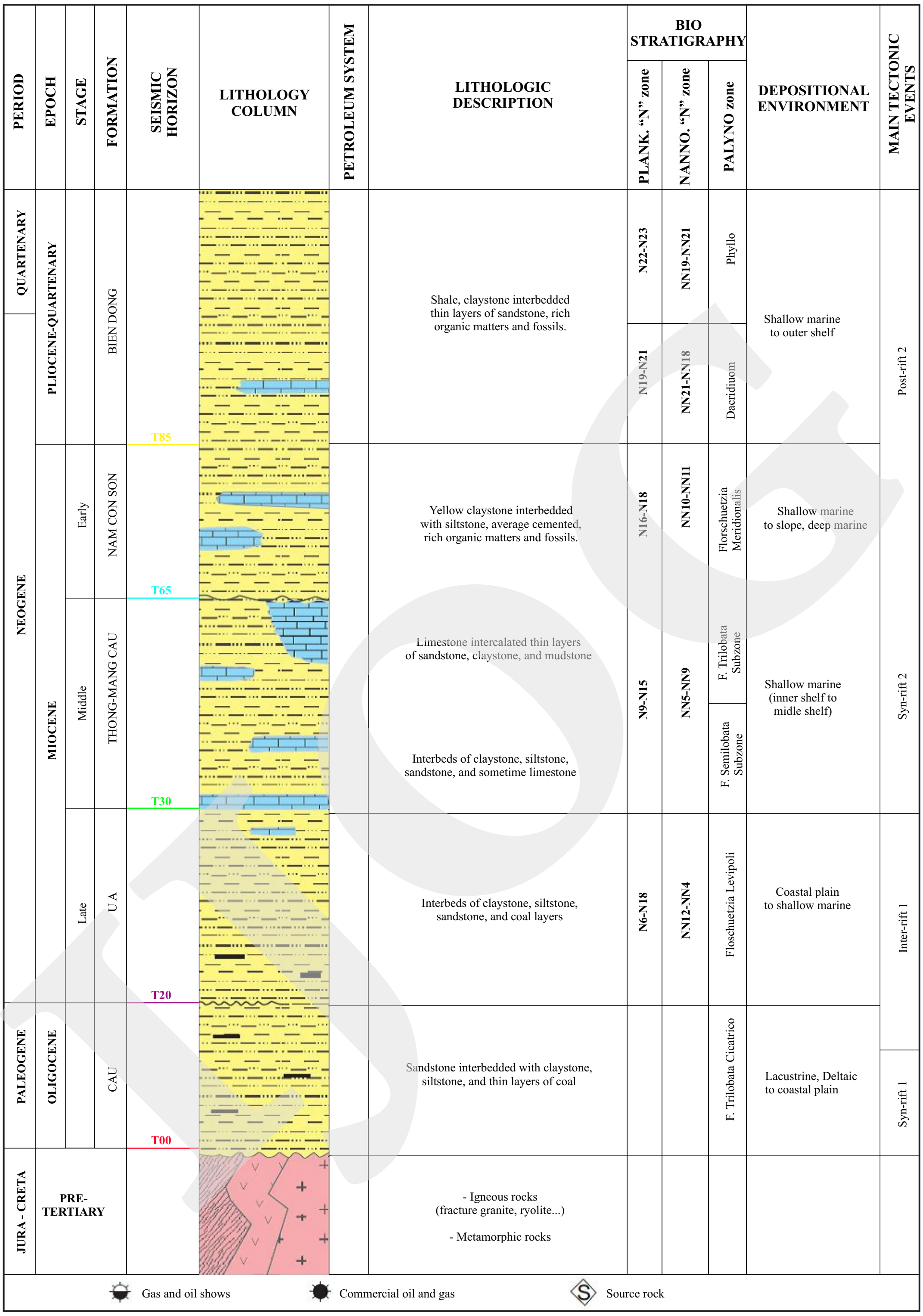

Figure 3. General stratigraphic column and petroleum system summary of Nam Con Son Basin.

the whole NCSB used for interpretation and reference (Figure 4). The quality of seismic data is fair to good in overall, with only a poor quality area around the central basin of Block 06-94, 05-2, and 05-3, where the basement is too deep. 3D seismic data available in Block 06-94, 05-2, and 05-3 were used to improve the quality of seismic interpretation in these areas.

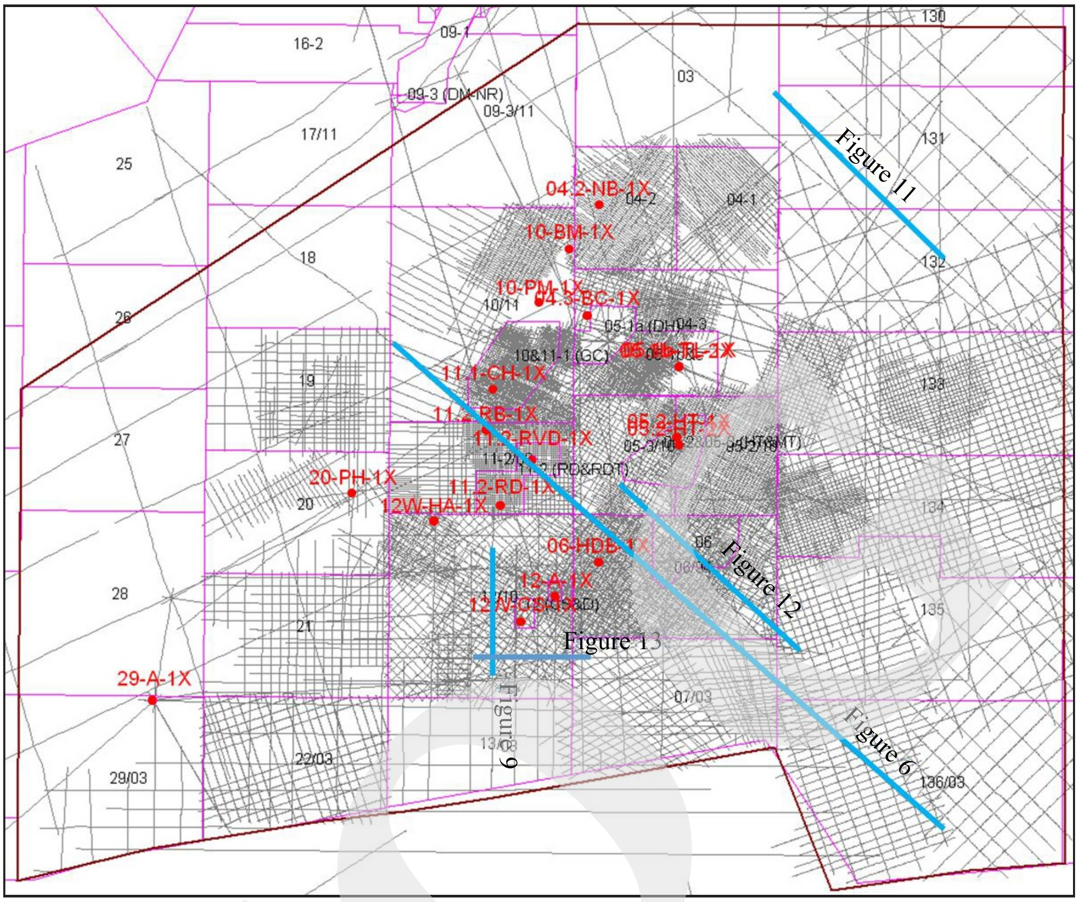

Figure 4. Blocks boundary map of NCSB showing the total seismic reflection data coverage analyzed in this study (gray lines). Blue bold lines show those lines presented in this paper. The red dots show the well locations used to provide bio-stratigraphic age control.

Age control is provided to the seismic stratigraphy through a biostratigraphy mode from selected wells located on the different blocks, as shown in Figure 4. These ages were transferred to the seismic profiles after converting drilling depth to two-way travel time (TWT) using the stacking velocities derived from processing the MCS data. Those dated horizons were then correlated across the entire study area. The oldest age pick from the biostratigraphic data was the top of Oligocene. The base of (?) Eocene-Oligocene strata is inferred by the top basement reflector, which can be followed over long distances across the study area. Age resolution is best for Miocene strata because a number of wells have penetrated these formations. In contrast, the Plio-Pleistocene was not cored by industrial wells, so there is no detailed date subdivision of those units.

Results and Discussion

The regional tectonic settings, data, and methods described above are the background guidelines for detailed data interpretation in this study. Five main seismic horizons have been interactively interpreted in time domain, namely Top Basement (T00), Top Oligocene (T20), Top Lower Miocene (T30), Top Middle Miocene (T65) and Top Upper Miocene (T85) sequences (Figure 5). After gridding, the time structure maps were generated, then were converted to depth domain. Several time depth conversion methods have been considered for generating depth structure maps of key sequences in the basin. After a careful quality test, the depth structure maps of these key sequences have been generated from the time interpretation by the layer cake method. Four structure maps of Top Basement, Top Oligocene,

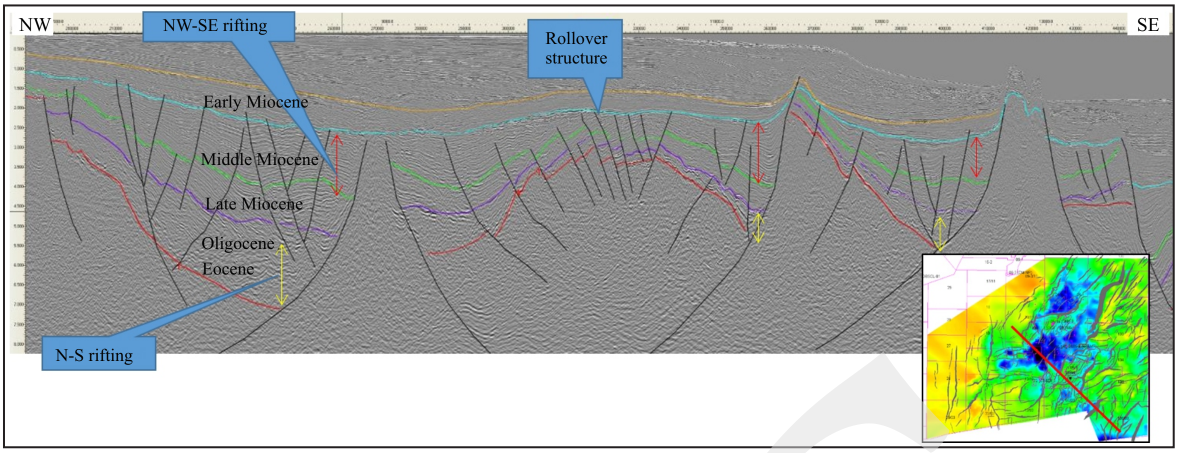

Figure 5. NW - SE seismic line from the Con Son Swell across Central Basin and further SE showing extension feature and the two distinct rift stages of NCSB. The interpreted horizon in red is top Basement, violet is top Oligocene, green is top Lower Miocene, blue is top Middle Miocene and yellow is top Upper Miocene. Several normal listric faults dipping to the WNW were recognized and associated with rollover anticline structure on the hanging wall side.

Top Lower Miocene, and Top Middle Miocene sequences were displayed on Figure 6.

To reconstruct the tectonic evolution of the basin, the fault systems have been interpreted with great attention. Fault heaves and fault timing were carefully determined to accurately reflect their development. As a result, four major fault trends developing at different time intervals can be recognized and described as follows (Figure 7):

1. The E - W trending fault system dominated in the southern and centre parts of the Nam Con Son Basin. The faults have extensional features that are clearly evidenced on the top crystalline basement, but mostly buried by the Late Oligocene and Early Miocene sediments (Figure 8). The growth sequence of Early Oligocene to the top basement against the E - W trend faults suggests that the timing of E - W faulting activities is about Eocene (?) - Early Oligocene during the first regional rift stage described in the previous section. This observation is also supported by the isopach map of the Oligocene sequence which shows clear E - W trend of the sediment thickness controlled by E - W trending fault (Figures 6 and 9). The E - W fault trend in Nam Con Son Basin during the Eocene-Early Oligocene is consistent with the oldest magnetic lineation (~32 Ma) oriented ~E - W in the East Vietnam Sea caused by the slab-pull from the southward movement of Dangerous Ground due to the proto East Vietnam Sea subducting beneath Borneo (Hall, 2013).
2. The NE - SW trend faults developed strongly in the northeastern part of the basin with listric geometry during the Middle Miocene sequence as a consequence of SW propagation of East Vietnam Seafloor spreading (Figure 10). In the central part of the NCSB, the NE - SW faults gradually bend to:
3. NNE - SSW trend implying that the faults was influenced by a N - S previously existed basement rock fabric. We suggest the weak basement fabric possibly formed earlier than the first rift phase in NCSB as exhibited in the tectonic model proposed by Hall (2009). The model implies that in the Early Eocene, the Sundaland region went into regional N - S compression as Australia attempted to move north. As a consequence, approximately E - W extension caused N - S basement fabric to form (Hall, 2009). Most of the normal listric faults in the basin dipping to the NW until WNW, implies that during the second rift phase the basin extended to the SE. The Con Son swell to the NW of the basin acted as a rigid block prohibiting further basin propagation to the W and NW (Figure 2). These faults created grabens, half grabens, and roll-over structures which are typical and easy to recognize on

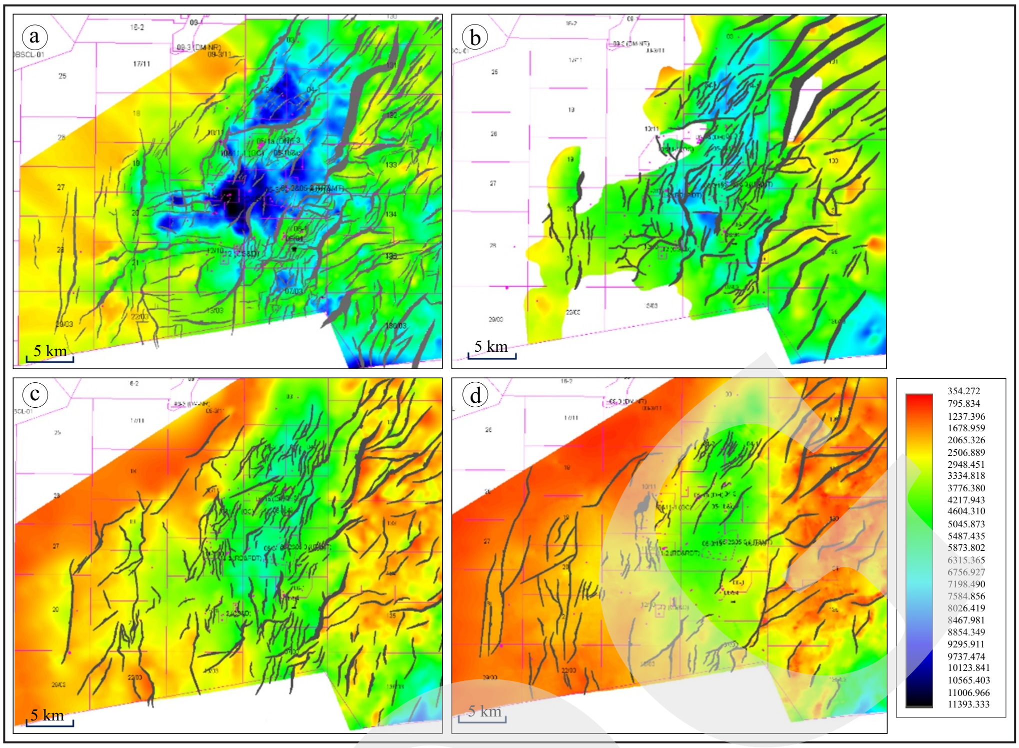

Figure 6. Total sediment thickness to seabed generated for (a) Top Basement, (b) Top Oligocene, (c) Top Lower Miocene, (d) Top Middle Miocene (Tung, 2015).

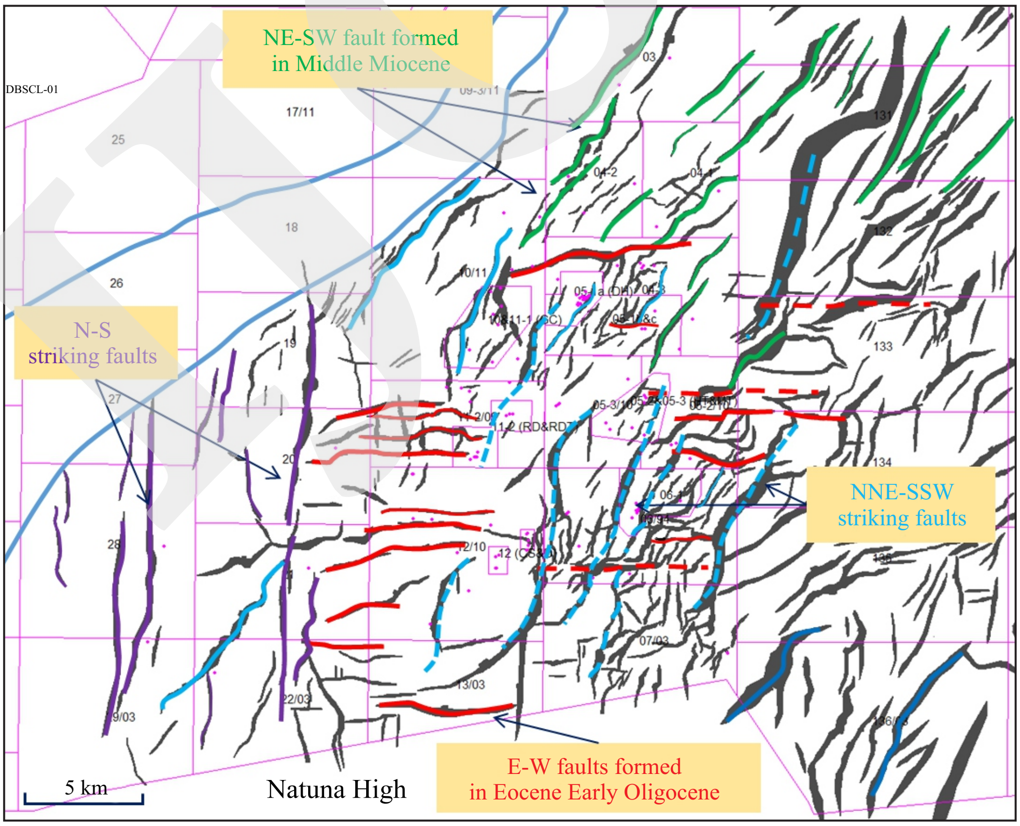

Figure 7. Fault map of the NCSB. Four major fault systems were recognized. The W-E faults initiated in Eocene – Early Oligocene, associated with E-W trending grabens and are buried beneath the Early Miocene sequence.

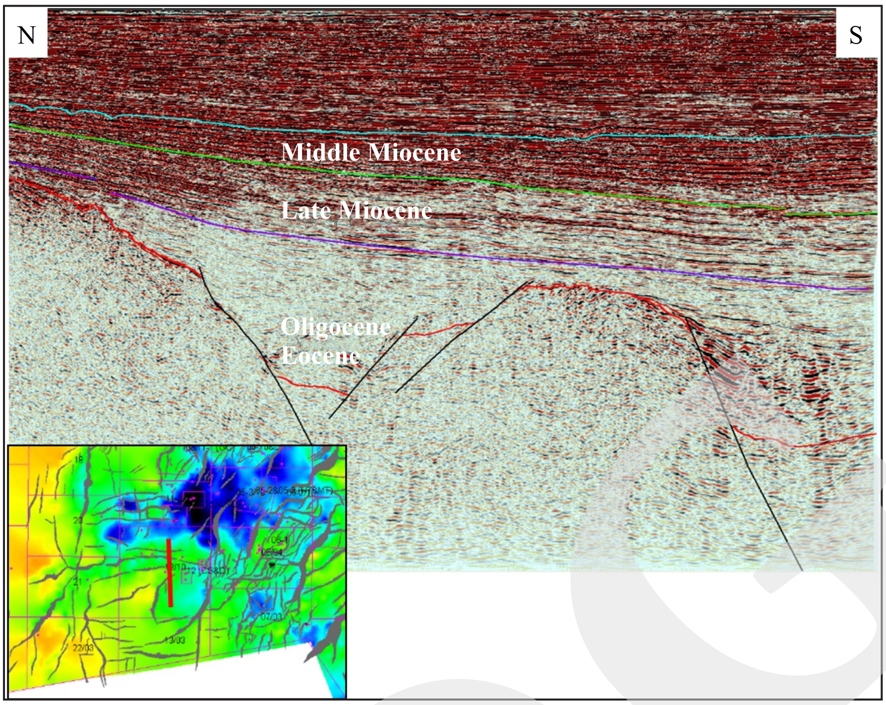

Figure 8. N-S seismic line to the S of the basin showing the E-W fault system. The fault ceased to be active by the middle of Oligocene time. The interpreted horizon in red is top Basement, violet is top Oligocene, green is top Lower Miocene, and blue is top Middle Miocene.

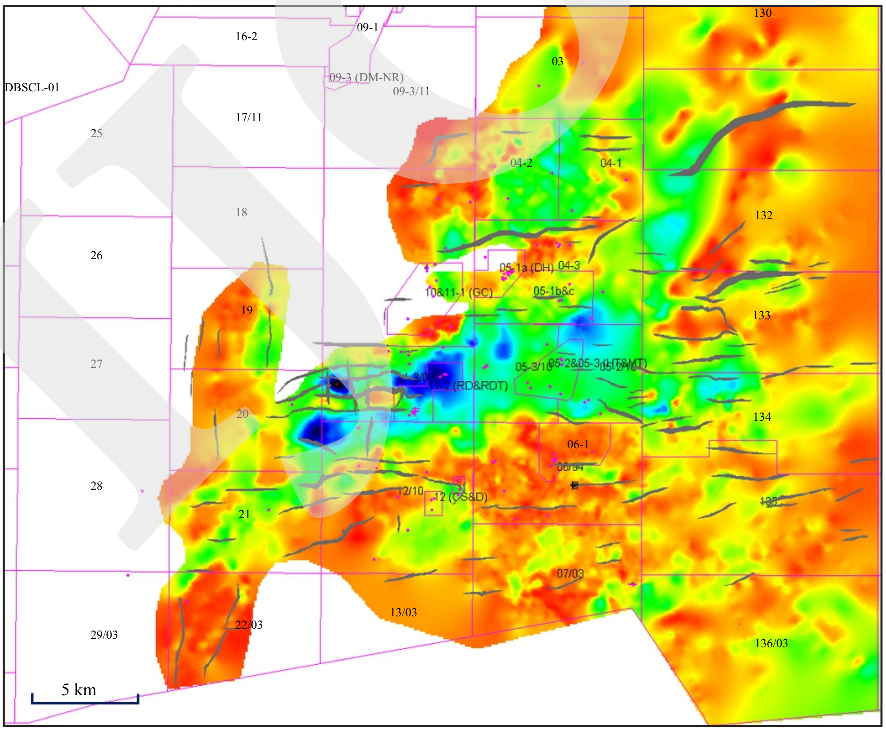

Figure 9. Isopach map of Oligocene sequence with overlay of faults activated during the first extentional phase in Eocene - Early Oligocene time. The basin was likely E -W orientation, which is consistent with E - W trending faults.

seismic sections as well as on structure maps (Figure 11). The last major fault system is of:

4. N - S trend which is mostly recognized in the western part of the basin. These faults

mainly developed during the second extensional phase in Early - Middle Miocene, but being further to the west their trends reflect the reactivation of pre-existing weak fabric and not affected by the main trend of the East Vietnam Seafloor spreading like the fault systems in the east of the basin. Several of them are still being active until today which make N - S faults distinctive from the rest (Figure 12).

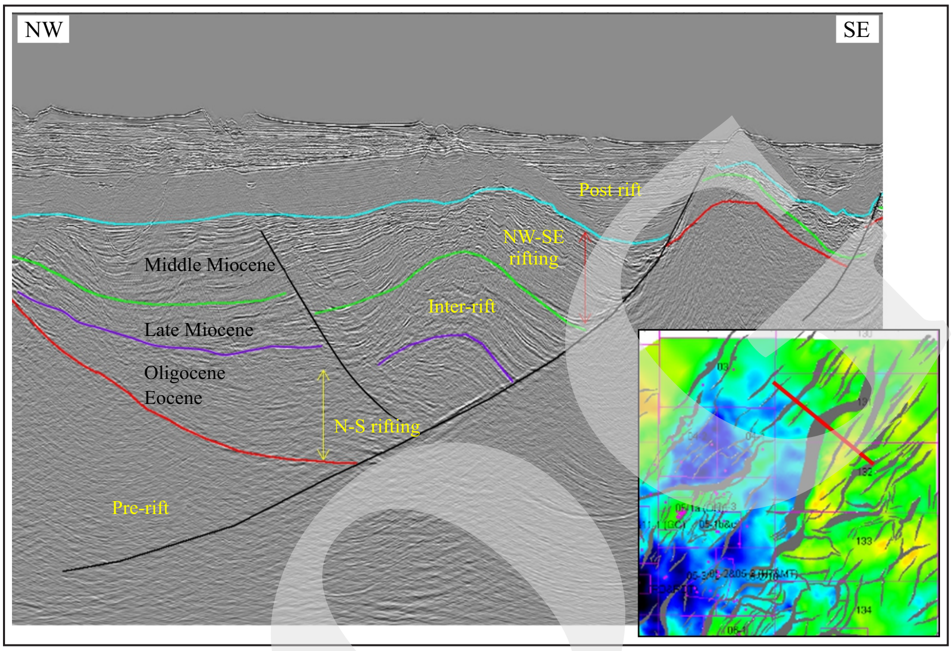

Figure 10. NW - SE seismic line in the NE of basin showing NE-SW fault system, which was active during the second extensional phase and terminated by Late Mioncene time. The interpreted horizon in red is top Basement, violet is top Oligocene, green is top Lower Miocene, blue is top Middle Miocene.

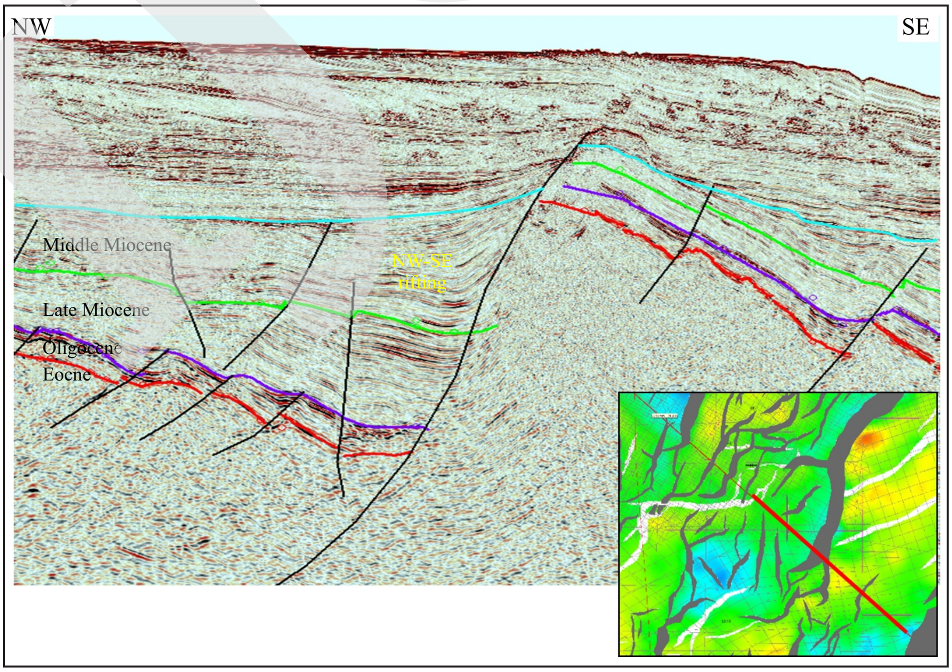

Figure 11. NW - SE seismic profile showing the NNE-SSW fault system, which was also active in Early to Middle Miocene and terminated by Late Miocene.

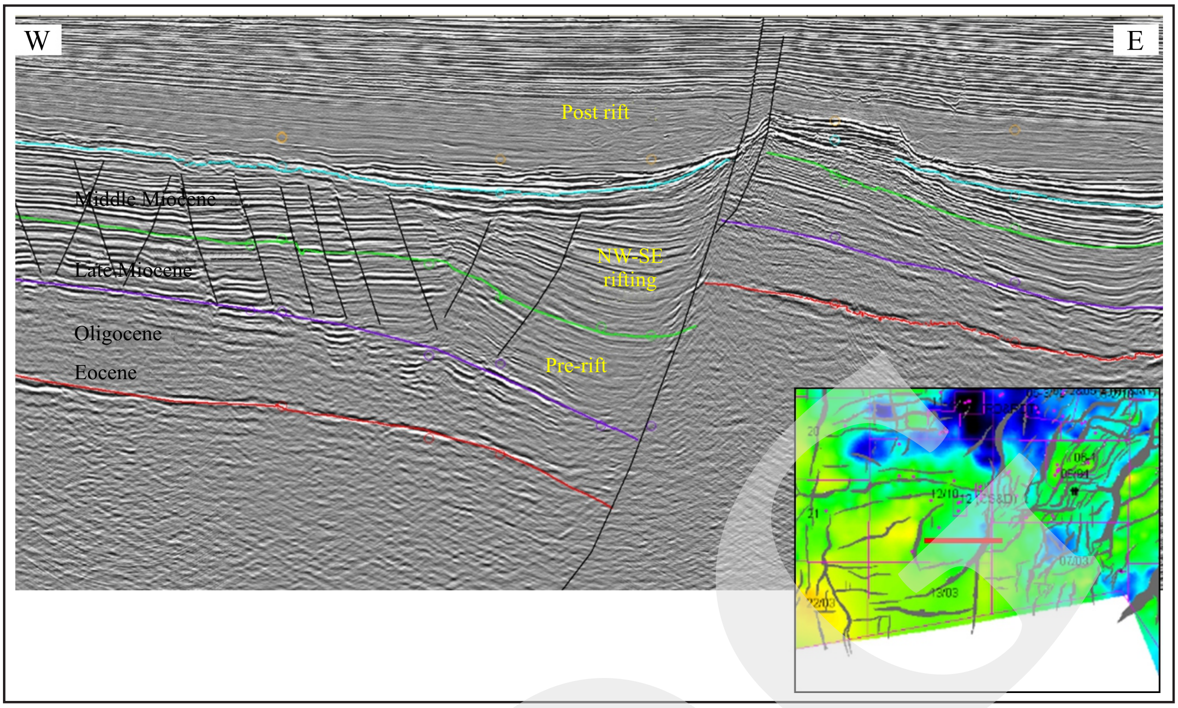

Figure 12. The W - E seismic line in the south of the basin showing the N - S fault system.

Conclusion

From the systematic interpretation of seismic data and its integration with the major geological history of Nam Con Son Basin, it can be infered as follows:

1. The preceding morphology of the NCS area underwent a regional erosion until the first rift phase happened in Eocene - Middle Oligocene. The N - S extentional force caused E - W fault system with local E - W grabens and half-grabens to develop in the whole basin area. In the Inter-Rift Phase (Late Oligocene - Lower Miocene) the NCSB was relatively quiet probably because all extensional effects were accomodated by the NW - SE opening of East Vietnam Sea.
2. The second extensional phase (Middle Miocene) resulted from the southwest propagation of the NE - SW seafloor spreading zone, due to the proto East Sea subducting beneath Borneo. This phase is believed to be the cause of the NE - SW, NNE - SSW, and N - S fault systems in the NCSB.
3. The post rift sequence (Upper Miocene - Recent) is associated with an onshore uplift causing an increase in sediment supply to the basin depocentre. NCSB has tectonically been quiet, only the weak N - S fault system continues to be active in some areas of the basin.
4. The significant Eocene - Early Oligocene rifting episode resulted in the deposition of ~ 5 km of sediments in E - W trending grabens. At a regional scale the N - S trending basement fabric, which is oblique to the regional extension direction (NE - SW), has been reactivated resulting in an oblique rifted basin. At a local scale within the basin, the Eocene - Oligocene structure has passively controlled the deformation by creating heterogeneity within sedimentary covering sequences.

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