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Oligocene combination/stratigraphic traps and their reservoir quality in Cuu Long basin, offshore Vietnam

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Summary

Cuu Long basin is a Cenozoic rift basin located in the Southeastern shelf of Vietnam with high potential of oil and gas. Up to date, most production in the Cuu Long basin is contributed from structural traps, making them more and more depleted after years of exploitation. Exploration activities in the Cuu Long basin, therefore, are shifting towards nonstructural traps including stratigraphic and/or combination ones.

By integrating exploration methods such as seismic sequence stratigraphy and seismic attribute interpretation, petrophysical and petrographical analysis, this article discusses the assessments of combination/stratigraphic trap types within the Oligocene section in the Cuu Long basin, including (i) identification of several trapping mechanisms and (ii) some evaluations of the trap's reservoir quality utilising the database of some 2D/3D seismic sections, several wells and unpublished reports. The research results show that the key forming factor for primary stratigraphic traps of sand body is lithology change and the one for pinch-out stratigraphic traps is tapering off of sand layers landward or toward the horsts. The reservoir quality of these traps ranges from moderate to good. Further detailed studies on reservoir distribution and sealing capacity of these trap types, however, need to be carried out to fully evaluate hydrocarbon potential of these stratigraphic/combination traps, and minimise risks in exploration drilling.

Key words: Stratigraphic trap, trapping mechanism, reservoir quality, Cuu Long basin.

1. Introduction

Cuu Long basin is a matured basin with high density of exploration and production activities. So far, it is the most important sedimentary basin which contributes greatly to Vietnam's annual petroleum production. The major targets for petroleum exploration and production in the Cuu Long basin have been Pre-Cenozoic fractured basement highs and sandstones in Oligocene as well as in Early and Middle Miocene time. Most of these Cenozoic targets are related to structural traps of tectonically formed anticlines.

In recent years, petroleum production from structural traps in the Cuu Long basin has been gradually declining, and exploration for new structural traps is facing technical difficulties, limited potential and commercial issues. Thus, petroleum exploration needs to focus on more potential but more complicated targets such as stratigraphic/combination traps.

Exploration and appraisal activities in recent years have increasingly discovered more hydrocarbons in the Oligocene section of the Cuu Long basin, thus showing a higher potential of Oligocene targets. Some of them were discovered in combination/stratigraphic traps, such as Ca Tam, Song Ngu, Kinh Ngu Trang Nam, etc. These demand further attention to explore the nonstructural traps.

There were several researches conducted in the Cuu Long basin to search for non-structural traps [1 - 4]. Some of them focused on the Southeastern part of the Cuu Long basin and showed that there existed pinch-out traps in Oligocene deposits along the Northwestern slope of Con Son swell. However, these traps were not paid sufficient attention in petroleum exploration due to low petroleum potential or insufficient petroleum

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system. As the result, these non-structural traps are ordinarily considered as secondary targets in exploration in the Cuu Long basin.

Recently, exploration activities in the Southeastern margin of the Cuu Long basin have identified several stratigraphic traps formed by appropriate changes in rock facies. Their existence has been confirmed through several wells. These are new exploration targets in the Southeastern part of the Cuu Long basin. These findings have opened up a new direction for petroleum exploration of potential stratigraphic/combination traps in the Southeastern part of the Cuu Long basin [5]. Nevertheless, prospecting these non-structural traps is a difficult task due to the complex distribution and the large range of exploration risks. Therefore, additional studies and assessments of recently discovered nonstructural traps need to be carried out in order to support future exploration and appraisal programmes in the Cuu Long basin.

This paper focuses on the identification of several trap types ascertained in the Oligocene section and their distribution as well as main risks in exploration using various methods of seismic stratigraphy and seismic attribute analysis in conjunction with well log interpretation and other geological data. Further discussions on reservoir's qualities of combination/stratigraphic traps are also mentioned with some examples in the Southeastern margin of the Cuu Long basin in order to support the exploration of non-traditional target and appraisal of the discovered structural traps in this area as well.

2. Geological settings

2.1. Basin evolution

Cuu Long basin is a Cenozoic rift basin located in the Southeastern shelf of Vietnam. The geological evolution of the Cuu Long basin is divided into three periods: pre-rift, syn-rift and post-rift [1, 6]:

First period (pre-rift): From Jurassic to Paleogene was the period of formation and uplifting of basement. This was the levelling period of the paleo-topography before creation of the Cuu Long basin [1].

Second period (syn-rift): This period took place from Late Eocene to Early Miocene. A series of NE-SW faults were formed due to vigorous subduction and extension activities [1]. The Cuu Long basin was formed during this period and underwent two rifting phases: true rift phase from Middle Eocene to Oligocene and late rift phase in Early Miocene [6].

Third period: Thermal subsidence from Middle Miocene to the Quaternary [1].

2.2. Structural elements

The Cuu Long basin has an oval shape, elongating along Northeast-Southwest direction and is divided into five secondary structural units including: Bac Lieu differentiated trough, Ca Coi differentiated trough, Cuu Long uplifted zone, Phu Quy uplifted zone (the extension of Con Son swell), and Cuu Long main trough [1]. Cuu Long main trough (secondary structure unit) is subdivided into smaller (tertiary) structural units including Northeastern trough, West Bach Ho trough, Northwestern monocline, Central high, Northwestern high, Eastern high, Northeastern differentiated zone, Southwestern differentiated zone, East Bach Ho trough, Opal - Amethyst high and Southeastern monocline (Figure 1).

2.3. Stratigraphy

Stratigraphic column of the southeastern area as well as the whole Cuu Long basin can be summarised as follows (Figure 2) [1]:

Pre-Tertiary basement: The Pre-Tertiary basement in the Cuu Long basin is mostly magnetic intrusive rocks with main lithologies of granite, granite - gneiss, granodiorite, diorite, adamellite, monzodiorite, gabbro, monzogabbro. The metamorphic rocks are also encountered in some places [1].

Lower Tra Tan - Tra Cu formation - Oligocene E: This continental sediment consists of shale, siltstone and sandstone which were deposited unconformably on the Pre-Tertiary basement. It is distributed widely across the southeastern area and divided into two sub-units:

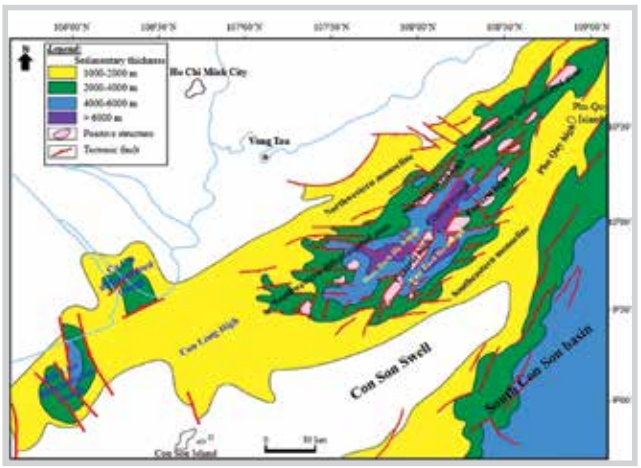


Figure 1. *Structural provenances of Cuu Long basin [1].*

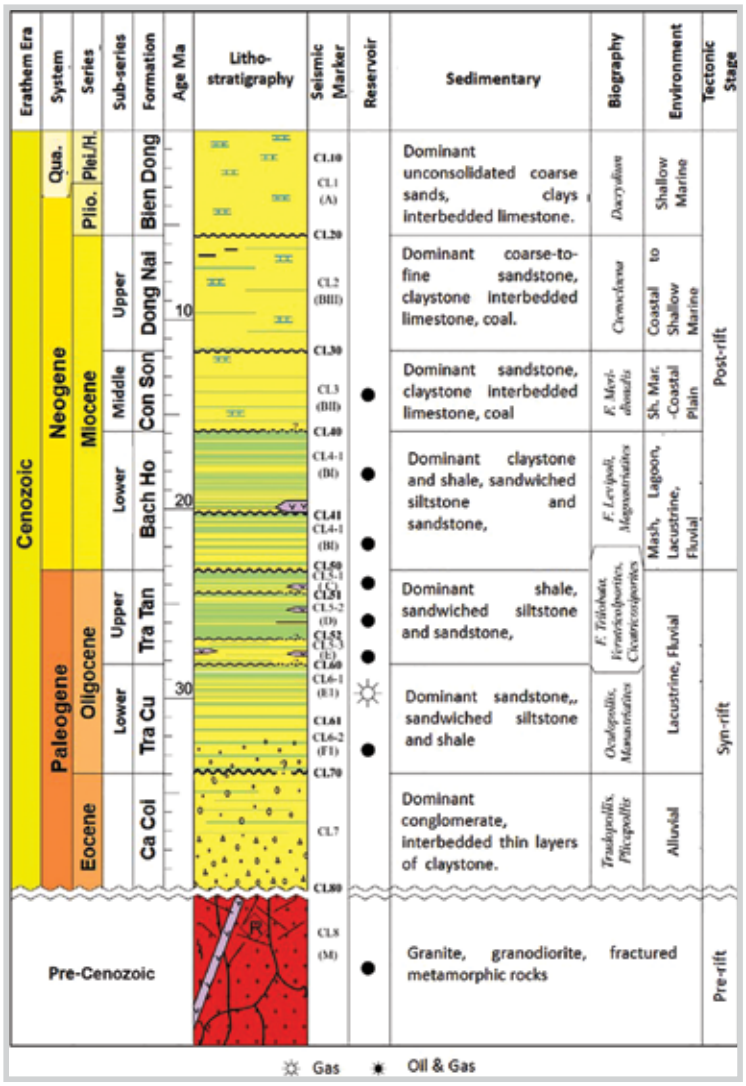


Figure 2. *Generalised litho-stratigraphic column of Cuu Long basin [1].*

Oligocene E Lower in the lower part and Oligocene E Upper in the upper part. The lower one is dominated by medium- to coarse-grained sandstones composed of mostly granitic fragments and feldspars, interbedded with hard organic-rich black shale layers. The other one is composed majorly of fine to medium grained sandstones interbedded with gray shale layers. In addition, magma intrusions such as dykes, composed majorly of andesite/basalt were found occasionally [1].

Upper Tra Tan formation - Oligocene D: It is majorly organic-rich brown shale deposited in lacustrine environment, occasionally interbedded with local layers of coal or sandstone [1]. However, toward the Eastern boundary of the sub-basin (close to Con Son swell), thick layers of sandstone were deposited on top of Oligocene D shale.

Upper Tra Tan formation - Oligocene C: This section is the mixtures of fine-grained sandstones and lacustrine brown shale [1].

Bach Ho formation - Miocene BI: This stratigraphic sequence is divided into two sub-units Miocene BI.1 (lower part) and Miocene BI.2 (upper part). Miocene BI.1 is composed mainly of sandstone-dominant fluvial-deltaic deposits with small intercalation of shale deposited in floodplain or some brackish environments, while Miocene BI.2 is composed mainly of sandstone interbedded with shale/claystone, occasionally shallow marine siltstone and limestone. The top section of Miocene BI is Bach Ho shale, a thick and continuous shale layer, acting as a regional seal for the whole Cuu Long basin [1].

2.4. Petroleum systems

Two matured source rocks in the Cuu Long basin are shales in Lower Oligocene + Eocene (?) and in Upper Oligocene [1]. The reservoirs in the Cuu Long basin are fractured granitoid basements and Cenozoic sandstones aged from Early Oligocene to Early Miocene. Besides, there could be Middle Miocene sandstone reservoir in the Eastern area of the Cuu Long basin [1]. The seals in the Cuu Long basin are confirmed to include five shale layers. The most important one is Rotalia shale in Bach Ho formation. The other four are shales in Con Son, Bach Ho, Tra Tan (C and D sequences) and in Tra Cu formation [1]. In the Cuu Long basin, the traps are defined to be structural, stratigraphic and combination ones. They were mostly formed during syn-rift and early post-rift periods. Migration timing of Lower Oligocene source rock started in Early Miocene and reached max in late of Middle Miocene. The migration timing of Upper Oligocene source rock started in Late Miocene. These timings occurred later than those of trap formation, thus making it favourable for hydrocarbons to be trapped [1].

3. Data and methodology

3.1. Database

This research was accomplished utilising several 2D/3D seismic surveys and petrophysical data from some wells in the Cuu Long basin. Data of regional geology and results of some unpublished reports were also included as database for this research.

3.2. Methodology

In this article, we utilise an integrated approach of different exploration methods to assess various Oligocene traps in the Cuu Long basin. These methods are seismic sequence stratigraphy, seismic attribute analysis, petrophysical interpretation, petrographical analysis, and biostratigraphy, etc. Seismic sequence stratigraphy is based on analysis of patterns of seismic reflectors and analysis of sequences and system tracts [7, 8]. Seismic attribute analysis is based on the application of different attributes to enable the interpretation of depositional environment as well as the identification of internal patterns in stratigraphic units [9, 10]. Petrophysical analysis allows detailed interpretation of geologic sections and provides information on lithology, facies, reservoir characteristics as well as sequence stratigraphy [11]. Other supporting methods including petrographic analysis and paleo-biostratigraphy play an important role in the interpretation of depositional environments.

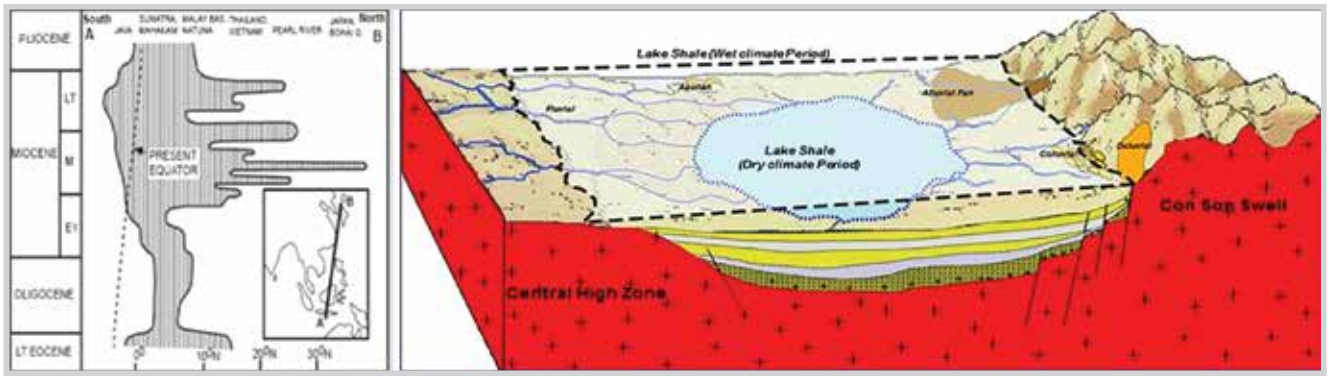
3.3. Depositional model in the study area

The Cuu Long basin is a continental rifting basin during the Oligocene epoch [1, 12]. Various researches show that tectonics and climate are two of the factors controlling the sedimentary and petroleum systems in rift basins [13, 14]. Tectonics also affects the trap types formed in these basins. Several authors [15, 16] have indicated that climate during Oligocene time in the Cuu Long basin was seasonal with more arid conditions in Early Oligocene and more humid ones in Late Oligocene times (Figure 3a). The depositional model for sedimentary system in the study area is illustrated in Figure 3b [13]. During wet seasons, the water level rose and caused most of the area to submerge (possibly up to dashed black line in Figure 3a), then creating opportunities for shale layers to form and act as both source and seal for traps at the East-Southeastern margin of the Cuu Long basin. During dry seasons, the water level felt back low making the lake's area retracted (light blue area in Figure 3a). The area between the highest and the lowest water level had sedimentary facies of fluvial deposits, mudflats, sandy alluvial fan that were detrital-deposit reservoirs of different trap types in the research area. In some locations on the slope less affected by post-depositional tectonic activities, these deposit materials could form potential stratigraphic traps. In the areas that were affected by post-depositional tectonics without truncation, the traps formed would be structural type. Other conditions could cause combination traps to be formed.

4. Results and discussion

4.1. Trap types, forming mechanisms and their distributions

A series of hydrocarbon fields and discoveries in the Oligocene section have been identified by exploration and appraisal drilling in the Cuu Long basin. They appear to trend in the main axis of the Cuu Long basin. Integrated studies and oil and gas exploration in recent years have shown that oil and gas accumulations exists in both structural and stratigraphic traps such as facies change, pinch-outs or truncations. These traps have different trapping mechanisms, risks and different distributions in the Cuu Long basin. Detailed delineations of the structural ones could be found in various papers. This section reviews several trap types and forming mechanisms as well as their main risks in the Cuu Long basin, focusing on the stratigraphic/combination traps.



(a) (b)

Figure 3. *Illustration of Cuu Long basin's eastern sub-basin depositional model under wet and dry paleo-climate conditions [15] (a); Schematic and simplified distribution of tropical rain forest climate in SE and East Asia during Tertiary [13] (b).*

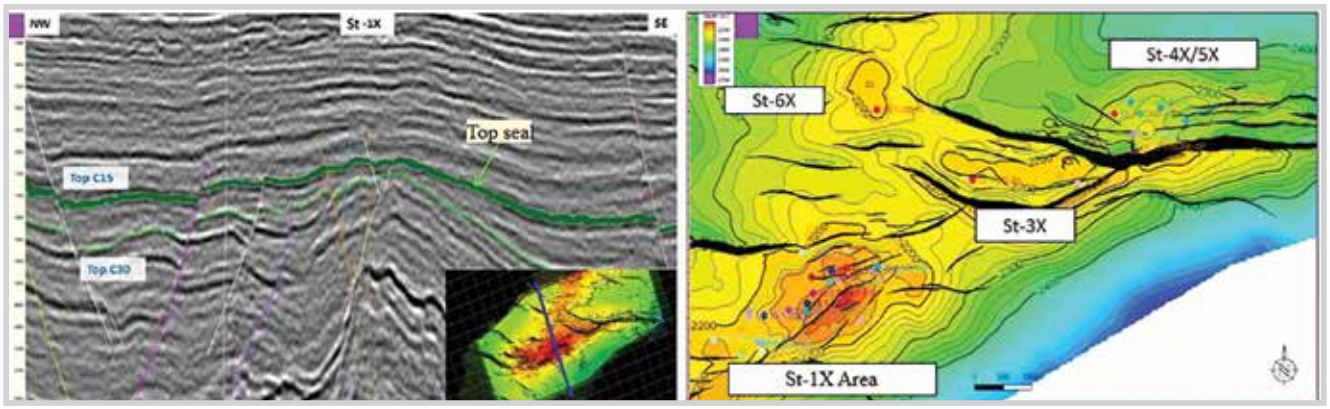
4.2. Structural traps

These trap types developed mainly over the pre-rift basement highs (Figure 4a). The trap forming mechanism is determined to be the consequences of post-depositional tectonic activities forming anticlines or draping over the existing topography highs. Tectonic inversion can be a favourable conditions for structural traps to form. These traps are sealed at the top by a number of overlying shale layers (Figure 4a). Lateral seals of these structural traps are 4-way closure types or fault-dependent trap types in which a tectonic seal is created on the downdip of the structures (Figure 4b). The structural traps distribute widely in the Cuu Long basin but mostly in the centre of the basin. Main risks in exploring these trap types are mostly related to sealing, especially fault seal. In some places, source rock and migration complexities could add additional risk into prospecting these trap types due to long distances from the source areas in the Cuu Long basin.

4.3. Stratigraphic traps

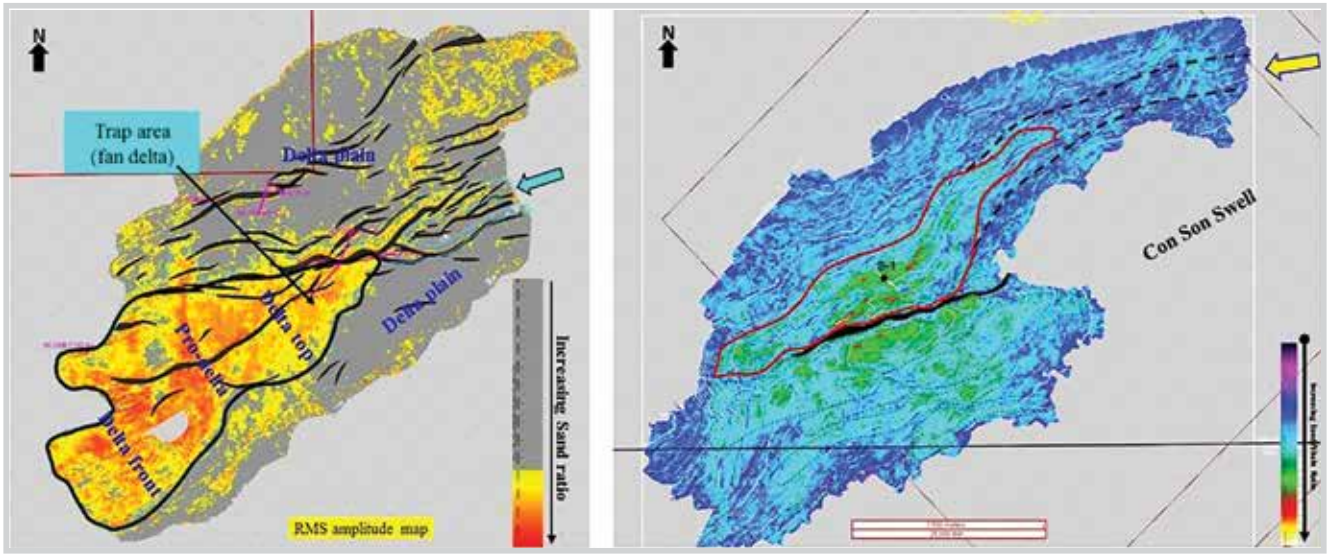
4.3.1. Facies change

This kind of stratigraphic trap was identified in some places in the southeastern areas of the Cuu Long basin such as Kinh Ngu Trang Nam (in Oligocene C sequence), SoN (in Oligocene D sequence) and Ca Tam (Oligocene D) [5, 17]. The trap is interpreted to be sand bodies that could be sand fans as the case in KTN prospect or channel sands as in SoN case (Figure 5). Lithology changes from coarse-grained to contemporaneously deposited fine-grained sediments are the key factor to form these stratigraphic traps.



(a) (b)

Figure 4. *Seismic section though an anticline formed by post-depositional tectonics (a); Depth map of a structural trap showing four-way closure (b).*



(a) (b)

Figure 5. *Interpretation of stratigraphic traps in Block 09-2/09: Fan trap deposited in deltaic environments during lowstand stage of water level (a); Channel sands deposited during high-stand stage of water level (b). The trapping mechanism is interpreted to be lithology changes from coarse-grained sediments to fine-grained sediments.*

The overlying fine-grained sediments that were deposited during the highstand stage of water level act as top seal for these traps. Lateral and bottom seals for the traps are fine-grained sediments (Figure 6).

Well data analysis shows that the overlying strata of the trap consist mainly of shale/clay interbedded with minor sandstones with thickness of more than 17m deposited in flood plain environment (Figure 7) [5]. The underlying strata consist of very thick brown shale layers deposited in lacustrine environment. These Oligocene D shales are believed to be very good seal in the Cuu Long basin. These analyses show that both top and bottom seals for this stratigraphic trap are interpreted to be the best type.

Seismic attribute analysis is applied to predict the distribution of seals for this trap. It could be inferred from seismic attribute map (Figure 8) that there is high possibility of shale distribution of both overlying and underlying strata over the trap area. This reveals that the trap has good sealing capacity at both top and bottom positions.

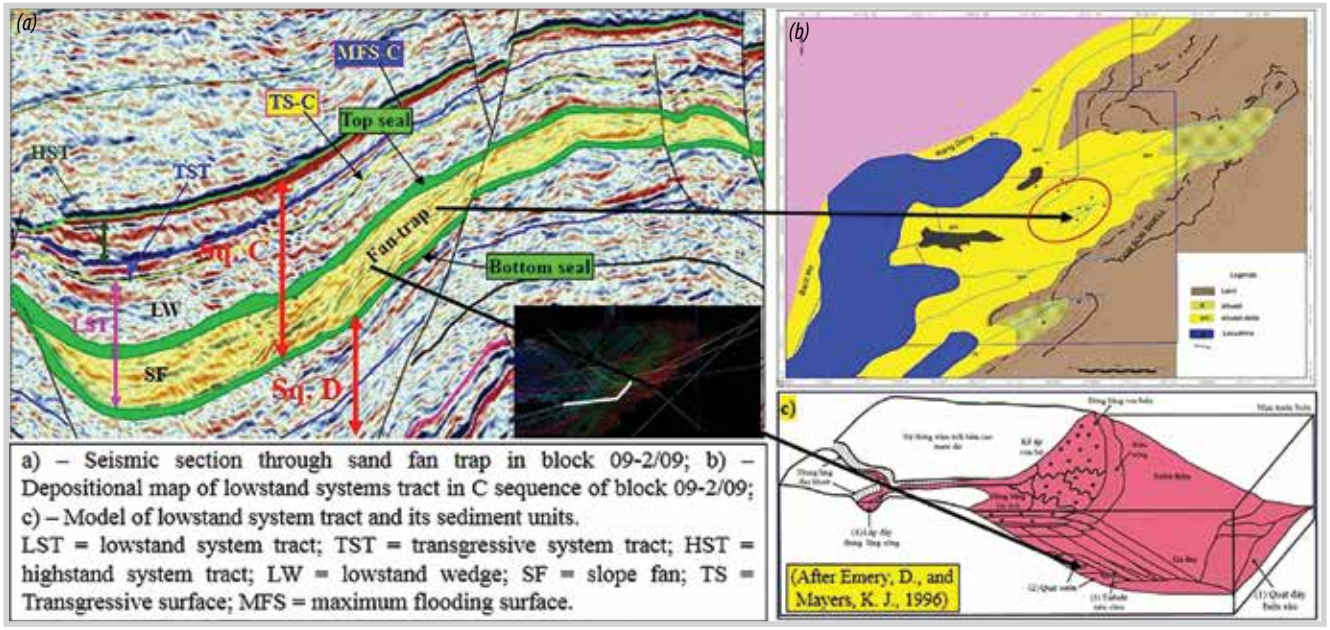


Figure 6. *Seismic section through a stratigraphic fan trap that is interpreted to have formed during lowstand stage of water level in deltaic environment (a); Depositional environment map of lowstand systems track in C sequence (b); Model of lowstand systems track and its sediment units (c).*

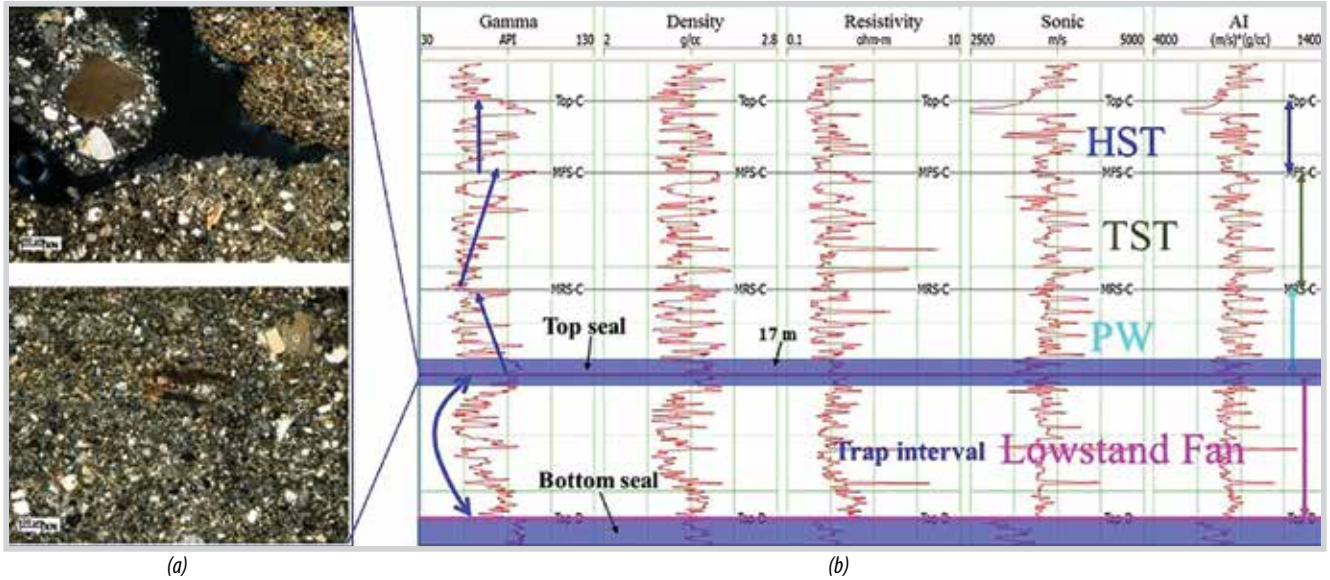


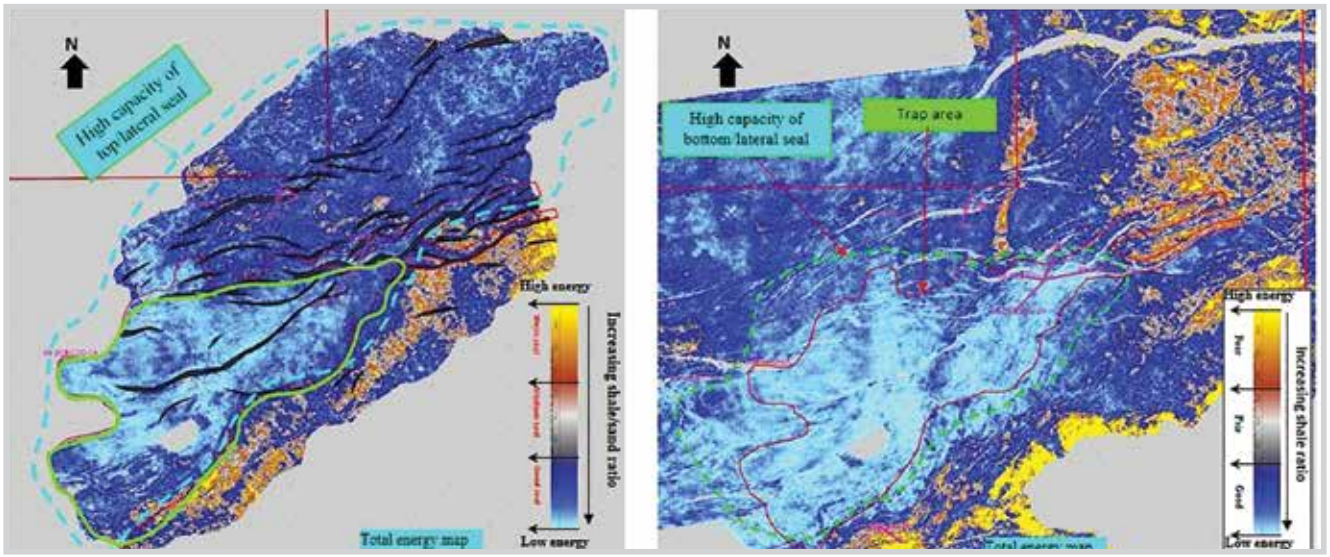
Figure 7. *Well data analysis of stratigraphic fan trap in Block 09-2/09: Petrographical analysis of overlying strata showing mostly shale/claystones interbedded with minor sandstones (a) [18]; Petrophysical interpretation showing about 17m top seal and thick Oligocene D shale acting as bottom seal (b).*

Based on evidence derived from seismic data analysis (Figures 9a and b), this stratigraphic trap is predicted to be distributed along the Eastern margin of Cuu Long basin where there is a steep slope (Figure 9c). To discover this type of trap, explorationists need to predict thoroughly a number of significant factors including depositional environmental and lithological changes as well as evaluate the petroleum system with great care for the lateral and bottom seals.

4.3.2. Other stratigraphic traps

- Pinch-out traps

This kind of stratigraphic trap was identified in some places at the southeastern margin of Cuu Long basin. They were formed due to the tapering off of sand layers landward or toward the horsts. These sand layers were overlain by finer-grained sediments deposited in during the highstand stage of water level that acted as top seal for these traps. The bottom seal is determined to be the underlying shale layers or the ones in Oligocene D sequence. The lateral seal could be facies change into contemporaneously fine-grained sediments or tectonic sealing such as fault sealing or structural closing (Figure 10a). For the latter case, the trap becomes



(a) (b)

Figure 8. *Sealing capacity prediction for top seal (a) and bottom/lateral seal (b) for the stratigraphic fan trap in Block 09-2/09 using seismic attribute analysis. Both seismic attribute maps show that there is high possibility of shale distributions over the trap area represented by low total energy anomalies.*

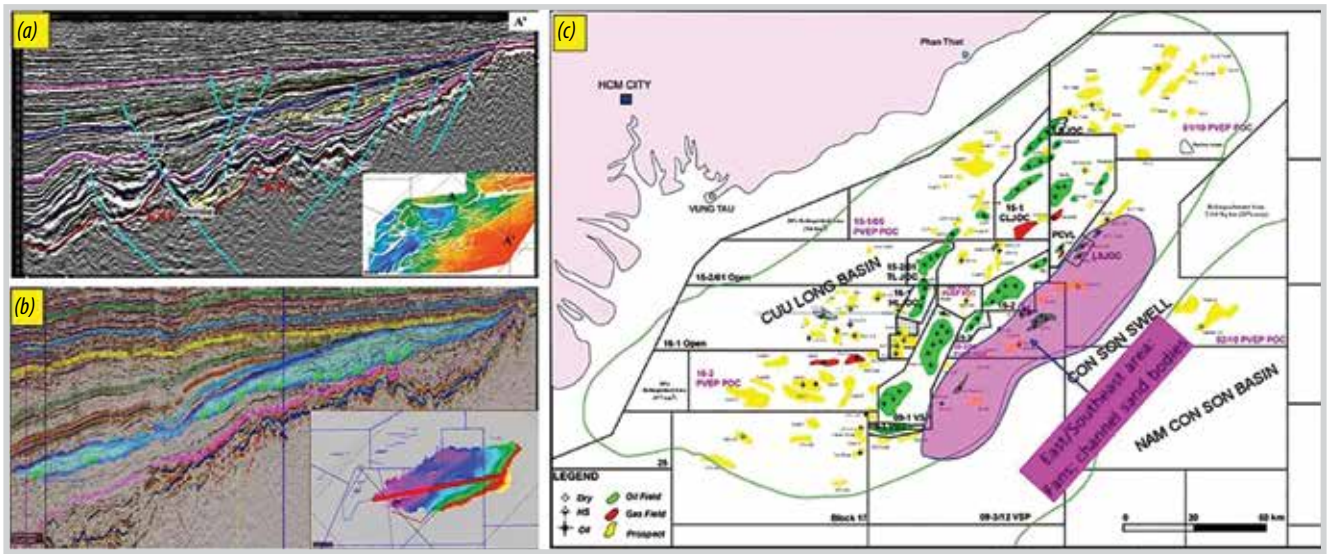


Figure 9. *Possible distribution of stratigraphic traps in southeastern margin of Cuu Long basin. NW-SE seismic section showing progradation of reflections toward the basin centre (a); E-W section showing seismic characteristics that could be related to prograding deltaic depositions (b); Predicted distribution of fan-shaped traps in Oligocene section of Cuu Long basin (c).*

the combination trap. These traps often have better reservoir heterogeneity and clearer reservoir boundaries than facies-changed stratigraphic traps. Therefore, this trap normally has good reservoir quality. This kind of stratigraphic traps is interpreted to distribute at the eastern margin of the basin as well as areas close to the basement highs (Figure 9c). It is, however, necessary to have a concrete prediction about lithology changes as well as to evaluate the petroleum system with great care on lateral and bottom seals just the same as facies-changed stratigraphic traps.

- Unconformity-related trap (truncation)

Beside the above-mentioned stratigraphic trap types, it is possible to identify the unconformity-related stratigraphic trap in the study area. By applying seismic analysis, this kind of stratigraphic trap is interpreted to be truncation trap (below unconformity). Seismic data analysis shows that strong erosion of highstand system tract (HST) of D sequence occurred in the eastern part of Block 09-2/09. These sandy sediments of HST in D sequence were then overlain by fine-grained sediments acting as top seal (Figure 10b). The bottom/lateral seal for the trap is determined to be fine-grained sediments in transgressive system tract of D sequence. Exploring these traps could be performed in the erosional areas of Oligocene strata adjacent to Con Son swell. However, further detailed studies focusing on top and lateral seals, reservoir distribution and hydrocarbon potential should be carried out in order to reduce risks in exploration activities.

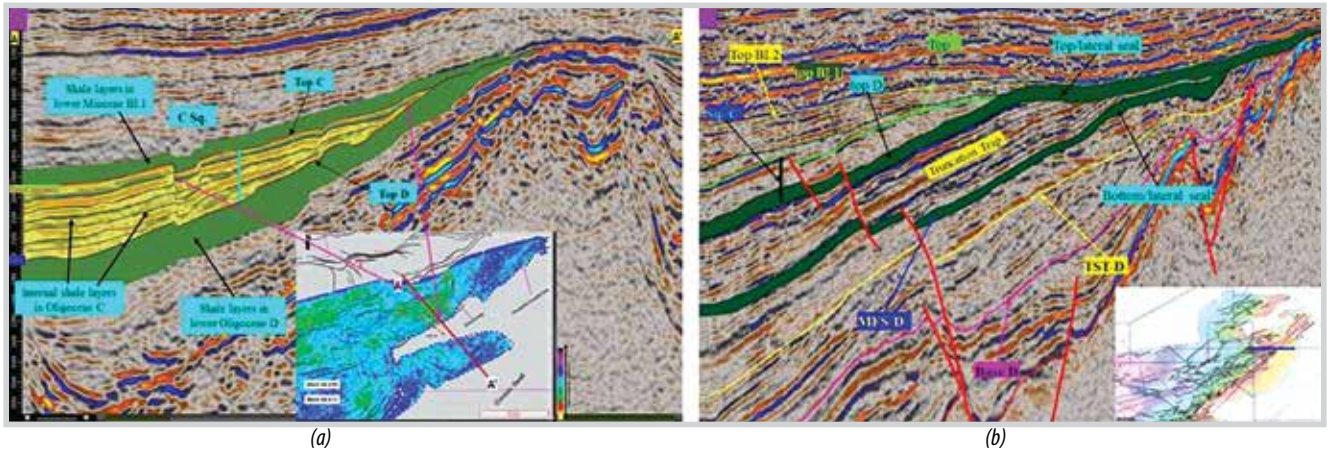
5. Reservoir quality of stratigraphic/combination traps

As mentioned earlier, several kinds of stratigraphic/combination traps have been identified in the Oligocene section in the Cuu Long basin, most of which are located in the Southeastern areas of the basin. Some of them are confirmed by exploration drilling. This section shall focus on some evaluations of reservoir quality of the discovered stratigraphic/combination traps in the Southeastern margin of the Cuu Long basin.

5.1. Facies change traps

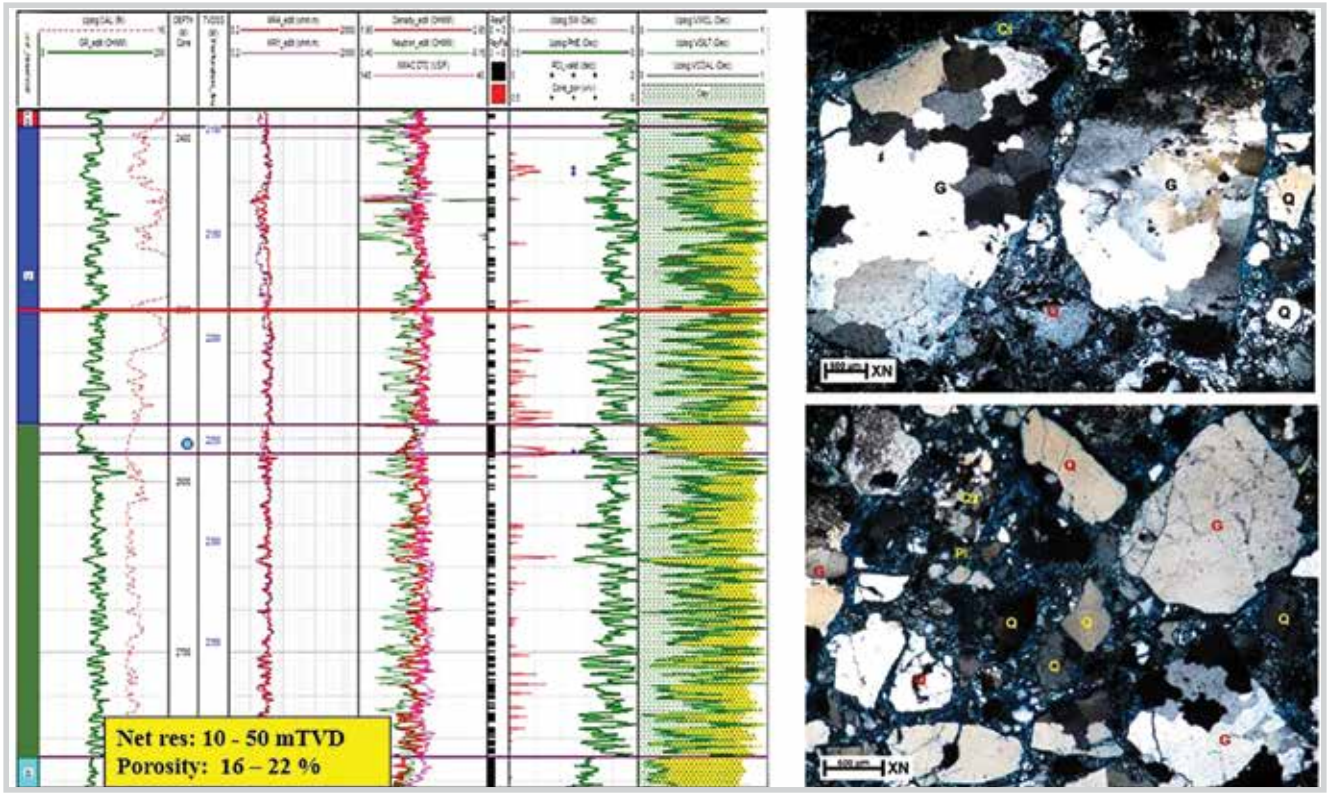
This kind of stratigraphic trap was confirmed by drilling in several places such as KTN (in C sequence) and SoN (in D sequence). In KTN wells, the reservoir interval has moderate to good oil shows while drilling [5]. Petrophysical interpretation shows that the reservoir interval is 20 - 30m thick with porosity ranging from 16 to 22 percent (Figure 11a) [5]. Results of petrographical analysis indicate that the lithology of reservoir interval consists of sandstones interbedded with shales and claystones. Sandstones are coarse - very coarse grain, poor - very poor sorted, subangular, subrounded to rounded. The rock composition is composed of mostly granitic fragments, quartz and quartzite, showing that the sediment supply is from nearby basement highs (Con Son swell). In addition, grain size is quite large (0.5 - 5mm), showing that the reservoir was formed in shallow water environment with high energy (Figure 11b) [18]. These analyses of well data reveal that the reservoir has moderate to good quality.

Seismic attribute analysis integrated with well log interpretation shows that the stratigraphic trap has fan-shaped distribution of more than 88km^2 (Figure 5a). The reservoir porosity of the trap is predicted by applying artificial neuron network theory using database of both seismic attributes and well log data. The result shows that the predicted porosities of trap's reservoir are from 12%



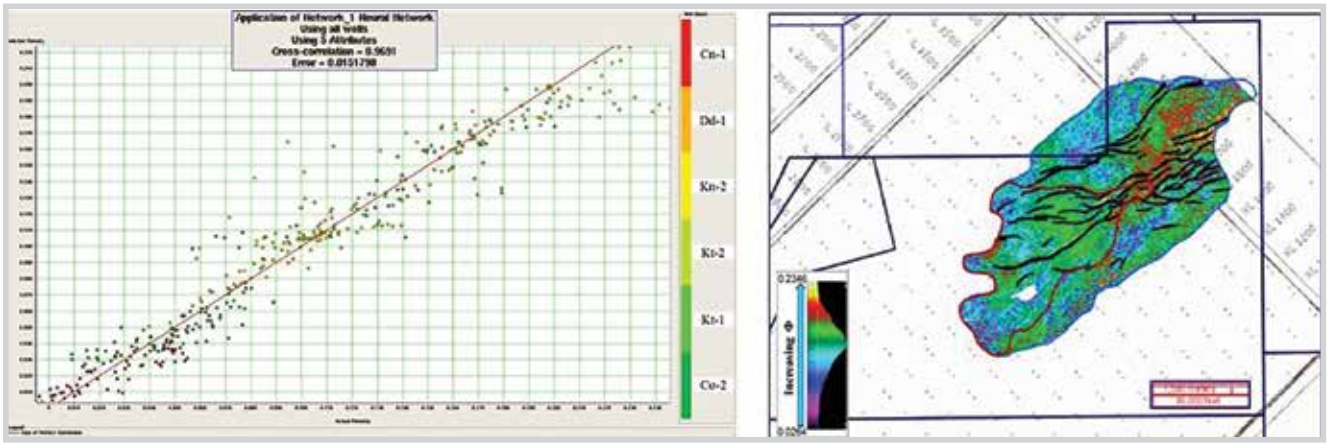
(a) (b)

Figure 10. *Interpreted seismic sections through the stratigraphic traps in the southeastern margin of Cuu Long basin: Pinch-out trap formed by the tapering off of sand layers landward or toward the horsts (a); Truncation trap formed by tectonic uplifting and truncation of underlying strata and later draping of fine-grained sediments over the trap (b).*



(a) (b)

Figure 11. *Reservoir characteristics of the fan trap in Block 09-2/09 on Kn-2 well data: Petrophysical interpretation (a). In Kn wells, the trap reservoir is interpreted to have about 10m to more than 50m reservoir and porosity from 16% to more than 20%; Petrographical analysis in reservoir interval showing mostly of coarse-grained and poor sorted sandstones (b) [18].*



(a) (b)

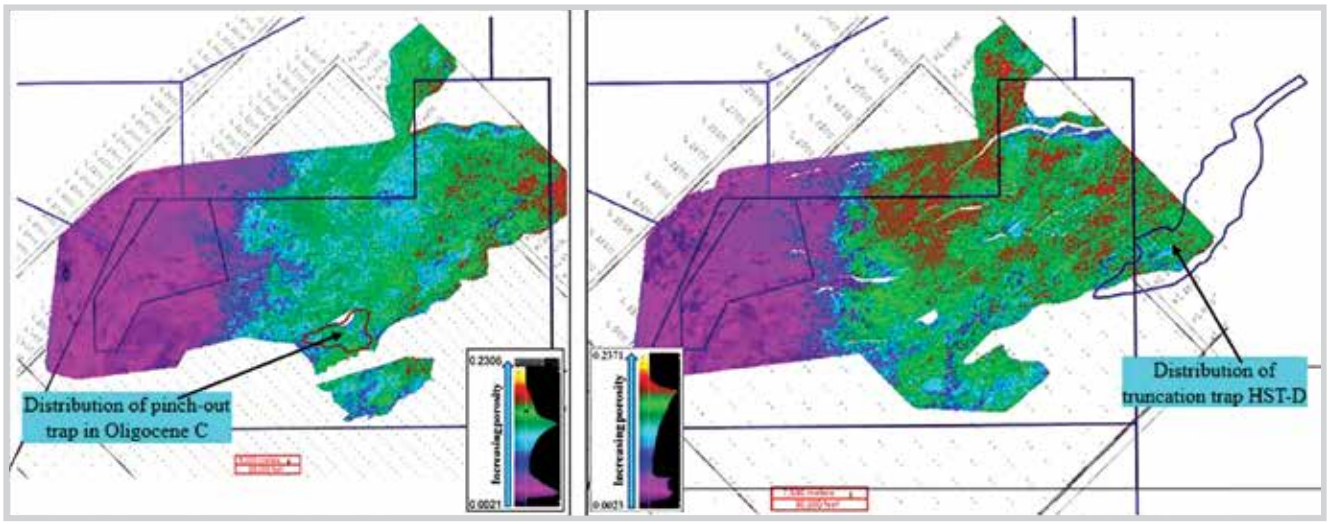
Figure 12. *Prediction of reservoir porosity of stratigraphic fan trap in Block 09-2/09. Correlation between the predicted porosities and the actual porosities (a); Predicted porosity map of the trap's reservoir showing that the predicted porosities are from 12 to 19%, consistent with those derived from well log interpretation (b).*

to 19%, consistent with the calculated porosities derived from well log interpretation (Figure 12). This means that the porosity prediction for the trap's reservoir using seismic data is highly reliable.

5.2. Other stratigraphic traps

Other kinds of undrilled stratigraphic trap are also identified in the study area using seismic data analysis. They are pinch-out and truncation traps located in the Southeastern margin of the Cuu Long basin. Although these traps have not been penetrated by drilling, their reservoir distribution and other characteristics are also predicted in order to support further exploration of these traps in the future.

Primary stratigraphic traps - pinch-out: The result of porosity prediction for the reservoir of this trap type



(a) *(b)*

Figure 13. *Reservoir porosity prediction for two stratigraphic traps in Block 09-2/09. Predicted porosity map of pinch-out trap. In the trap's area, the reservoir is predicted to have porosities from 9% to 16% (a); Predicted porosity map of truncation trap. In the trap's area, the reservoir is predicted to have porosities from 9% to 18% (b).*

shows that in the trap's area the predicted porosities are from 9% to 16%, 13% in average (Figure 13a). This reveals that the reservoir of the trap has medium quality.

Unconformity-related stratigraphic trap (truncation): As the above-mentioned forming mechanisms, these traps are predicted to distribute in the erosional areas close to Con Son swell. Stratigraphy in these areas are mostly sandy sediments deposited in the near-source areas. Therefore, the reservoir quality of these traps is predicted to be good. This is supported by porosity prediction for reservoir of the truncation trap in the study area (Figure 13b) ranging from 9% to 18%, 14% in average.

6. Conclusions

The presented study discussed the research methodology and practical issues associated with assessing different Oligocene trap types, trapping mechanisms and associated risks in exploration in the Cuu Long basin. Based on the results, several statements can be concluded as follows:

- Oil and gas in the Oligocene section were accumulated in both structural and stratigraphic traps with different forming mechanisms. The structural traps could develop widely in the Cuu Long basin. While the distribution of stratigraphic traps is evidenced in the Southeastern area of the basin. Some of which have been confirmed by drilling, thus making them important in oil and gas exploration.

- Structural traps were formed by post-depositional tectonic activities or draping over the existing topography highs with less risks in exploration except for fault seal and migration in some places. The key forming factor for stratigraphic traps is lithology changes, tapering off of sand layers or truncating of underlying strata. These stratigraphic traps have more risks in exploration than the structural ones, mostly are sealing capacity of both top and bottom ones. Although the stratigraphic traps' reservoir qualities are interpreted to be good, their distribution is one of the issues for prospecting these traps. Migration could also add more risks in exploring these traps in some places due to long distance to the source area.

- It could be said that the existence of Oligocene stratigraphic traps and their hydrocarbon bearing reservoirs confirm the importance of these traps and demand more attention to them in future exploration strategies and activities. However, further studies focusing on petroleum system, especially top and bottom seals, and the hydrocarbon potential of these stratigraphic traps need to be carried out in order to optimise the next-stage exploration strategy in the Cuu Long basin.

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