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A QUICK COMPARISON OF PLIOCENE AND UPPER MIOCENE SHALE RESOURCES IN NORTHERN, CENTRAL AND SOUTHERN PARTS OF SONG HONG BASIN WITH REFERENCE TO THEIR GAS POTENTIAL

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Summary

This research is a follow-up of a more comprehensive PhD study on assessment of shale gas resources in the northern Song Hong basin that was conducted at the Asian Institute of Technology (AIT). The Song Hong basin, a typical pull-apart Cenozoic basin, had experienced a post-extensional stage accompanied by seafloor spreading from Upper Oligocene to Lower Miocene with its stratigraphy characterised by a fault-controlled syn-rift continental sequence followed by a post-rift marine sequence. In recent years, a number of gas fields have been discovered in the Song Hong basin with the Oligocene-Eocene and the Lower-Middle Miocene shales as the major and minor source rocks, respectively. On the other hand, the Pliocene and Upper Miocene shales, present in the stratigraphy from the north to the south of the Song Hong basin, have generally been considered as the seals, but not the source rocks in some previous studies. In July 2020, an exploration well (Ken Bau-2X) was drilled in Block 114 by ENI, reaching a total depth of 3,658 m and encountering a pay of about 110 m in several intervals of Upper Miocene sandstones interbedded with shales, confirming a considerable gas accumulations discovered in Vietnam so far. The interesting thing is that this well only encounter the Pliocene and Upper Miocene shales, the Oligocene-Eocene or Middle-Lower Miocene sediments underlying is absent or very thin. Therefore, potential source rock of these shales should be considered in the area, in particular with reference to petroleum system of the central Song Hong basin.

In this study, a preliminary comparison of the Pliocene and Upper Miocene shale resources in the northern, central and southern blocks in the Song Hong basin was conducted based on the analysis results of XRD, Rock-Eval pyrolysis, vitrinite reflectance, respectively. While the Pliocene and Upper Miocene shales in many areas of Song Hong basin, show a very low or no hydrocarbon generation potential, the very deep and thick Pliocene and Upper Miocene shales in the center and adjacent areas, deposited in a marine environment under the special conditions of abnormal pressure and high geothermal gradient, can be potential source rocks that have possibly generated and released a large amount of hydrocarbons. Further geochemical analyses and petroleum system modelling of the Pliocene and Upper Miocene shales in particular and for the whole central Song Hong basin are recommended.

Key words: Song Hong basin, shale gas, Ken Bau discovery, Rock-Eval pyrolysis, vitrinite reflectance, XRD.

1. Introduction

In July 2019, ENI has confirmed a considerable hydrocarbon accumulation in the Ken Bau discovery, further expanding its potential in the Song Hong basin, offshore Vietnam [1] with the announcement that the first exploration KB-1X well, drilled in Block 114 in the Song Hong basin to a total depth of 3,606 m, discovered gas and condensate in several intervals of Miocene sandstones interbedded with shales. The water depth is 95 m deep at the well site. The well, however, was subsequently plugged and abandoned before reaching deeper levels as planned due to some technical problems. One year later, in July 2020 according to ENI [1] the second exploration well, KB-2X, drilled 2 km apart from the first discovery well of KB-1X to a total depth of 3,658 m, encountered a pay of about 110 m in several intervals of Miocene sandstones

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interbedded with shales. The second well was considered a success, confirming a considerable hydrocarbon accumulation. The news on Ken Bau discovery has been covered extensively in all Vietnamese mass media, e.g. [2]. It is hoped that this big gas discovery would have an impact on the national energy development strategy to 2030 and outlook to 2045.

2. Overview of geology and petroleum systems in the northern, central and southern parts of Song Hong basin

A number of studies were conducted to understand to a certain extent the geology in general and the petroleum system in the Song Hong basin [3 - 11]. During the Upper Cretaceous to Upper Oligocene, the crust of the East Sea's continental margin had been stretched and thinned, forming a series of rift basins in Southeast Asia, including the Song Hong basin, a typical Cenozoic pull-apart basin that is stratigraphically characterised by a fault-controlled syn-rift continental sequence and a post-rift marine sequence. From the Upper Oligocene to Lower Miocene, the basin was in a post-extensional stage accompanied by seafloor spreading. Thus, a number of gas fields from the north to the south of the Song Hong basin have been discovered, proving the prospects and opportunities for offshore gas exploration and production in this basin.

The central part of the Song Hong basin consists of very thick sediments, deeply deposited up to approximately 15 km deep with a significant amount of organic matters that is the reason why the drilled wells in the central part are deeper in comparison with those wells in the northern and southern parts. Practically, the central wells only penetrated to Pliocene to Upper Miocene, having not reached Middle Miocene yet. It is commonly accepted that the Oligocene-Eocene shales are the main source rocks in the Song Hong basin, while the Lower Miocene and Middle Miocene shales are the minor ones. On the other hand, the Pliocene and Upper Miocene shales are generally considered as seals, not source rocks, in most previous studies. This study presents a new outlook for shale gas potential of

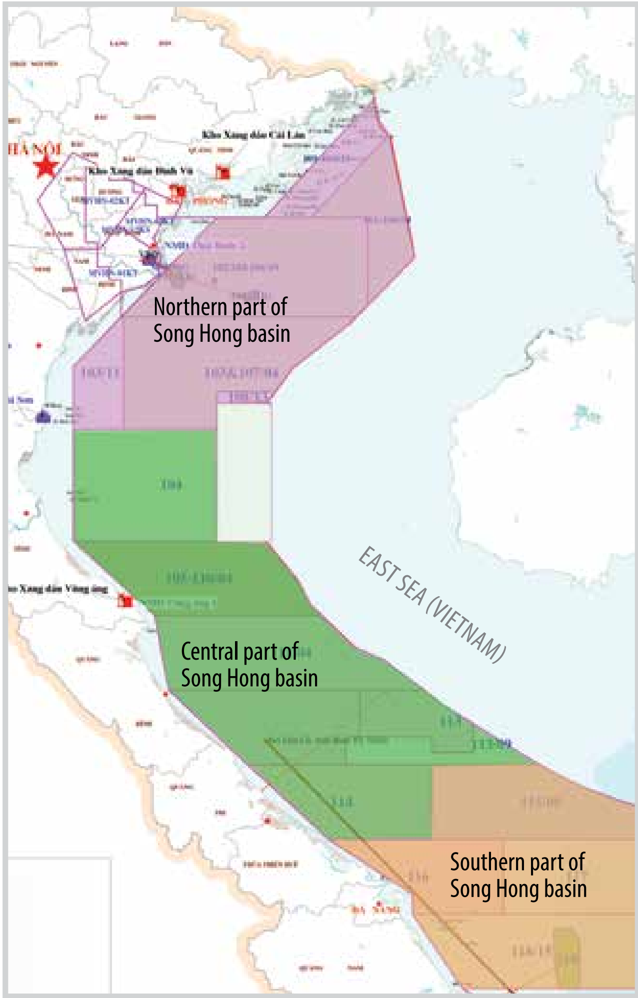

Figure 1. *Schematic distribution of the northern, central and southern parts of Song Hong basin based on [4].*

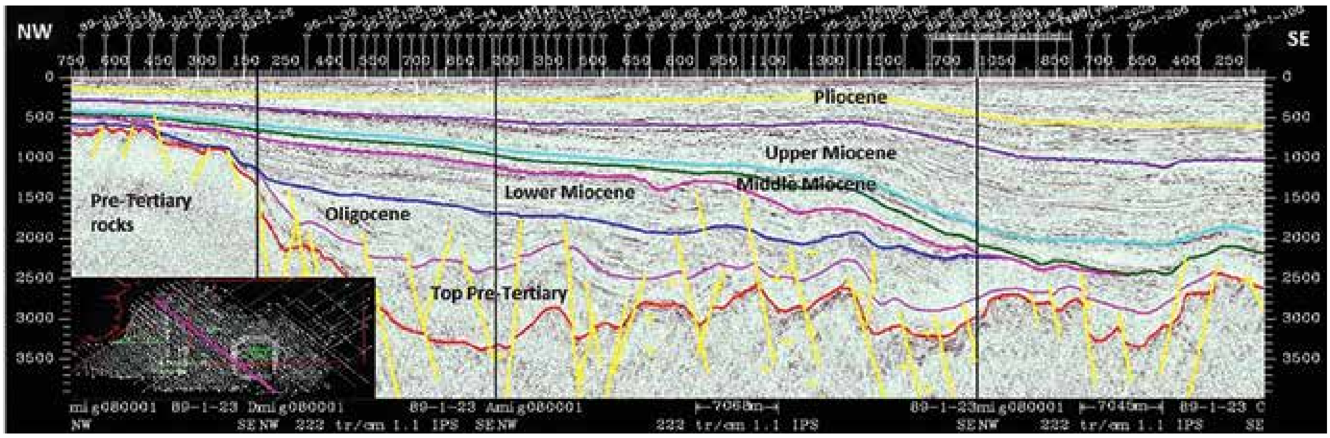

Figure 2. *Pliocene formation deposited above the base Pliocene unconformity, northern Song Hong basin after [11].*

the Pliocene and Upper Miocene shales in these parts of Song Hong basin. Three wells from the northern, central and southern Song Hong parts were selected for a preliminary geochemical assessment of their gas generation potential (Figures 1 and 2).

3. Samples and analytical methods

Three representative wells in the northern, central and southern parts of the Song Hong basin were selected for assessment and comparison between Pliocene and Upper Miocene shales based on the analytical results of Rock-Eval pyrolysis, vitrinite reflectance measurements and XRD tests. They are named as northern, central and southern wells in this research article.

The Rock-Eval (RE) pyrolysis is applied for source rock characterisation. The instrument is a completely automated device consisting of two micro-ovens which can be heated up to 850°C controlled by a thermocouple located in contact with the rock sample. Basically, the steps to operate the RE analysis are as follows: measuring the weight of a rock sample, typically about 50 - 100 mg, placed it into a crucible, which will be put into the pyrolytic oven. The rock samples are heated in inert gas helium (He) atmosphere at 300°C and the isothermal condition is kept

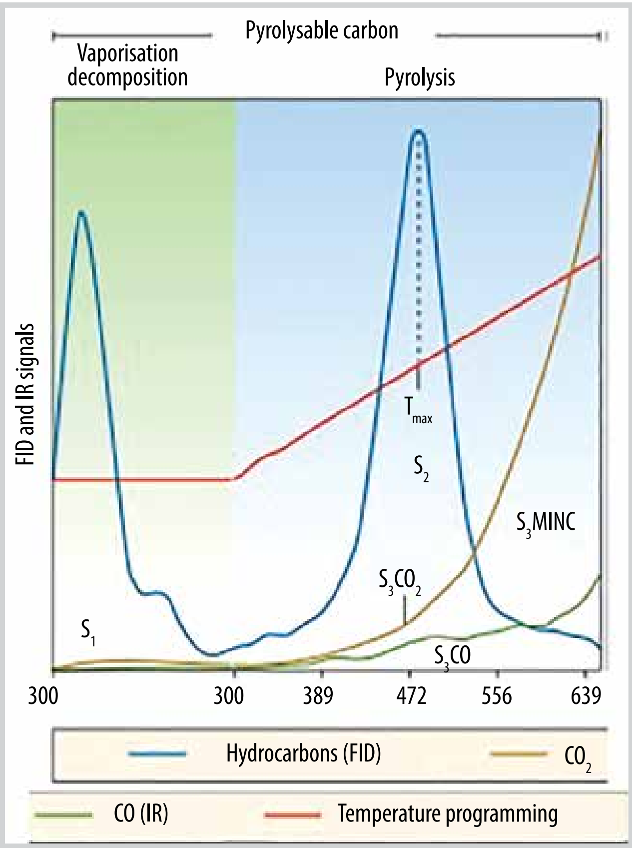

Figure 3. *Programmed pyrolysis results by Rock-Eval 6 [12].*

for up to 5 minutes, during which the evaporative organic materials are recorded by a flame ionisation detector (FID) and named as S_1 peak. Continuing the step of isothermal heating, rock samples are still kept in the linear thermal condition from 300°C to 650°C with step of 25°C/1 min, and the S_2 peak is recorded. The temperature T_{max} (°C) is defined at the maximum peak of S_2 and is also used as a thermal maturity parameter. An infrared cell (IR) detects amount of CO_2 (mg CO_2/g original rock) named as S_3 peak. This CO_2 content is generated during the progress of isothermal heating steps and setting up to 400°C. CO_2 released between 400°C and 650°C is measured by the decomposition of carbonate minerals through heating [12] as shown in Figure 3.

4. Results and discussion

The lab test results of Pliocene and Upper Miocene shales of three study wells are presented in Tables 1 and 2, respectively, that display the main data for the interpretation together with Figures 4 - 9. The details are presented as follows:

4.1. Pliocene shales of some wells in the northern and central blocks

For the Pliocene shales, there are no geochemical and XRD data for the southern well, and no XRD data for the central well either. Therefore, comparison of this formation is done based on Rock-Eval pyrolysis and vitrinite reflectance data of the northern and central wells only. Sediments in the northern well mainly comprise thick sands/silts interbedded with thin layers of shale (100 - 250 m), while those in the central well are very thick shales (~1,000 m) interbedded with thin sands/silts. The organic-richness and pyrolysis yields of these shales are generally of poor potential source rocks (TOC < 0.5%, S_2 < 2 mg HC/g rock). The organic matter are predominantly type III kerogen (HI < 200 mg HC/g TOC) of thermogenic gas-prone and deposited in deltaic to shallow marine environments. The organic matters in the northern well are in the immature stage, while the organic matters in the central well are in low mature to mature stages with R_o ranging from 0.45% to 0.65%, T_{max} ranging from 407°C to 435°C, and falling into mesodiagenesis phase. Therefore, an amount of gas probably was generated and released from the mature organic matters, causing original TOC and S_2 parameters decrease in these shales. The XRD data of the samples in the northern well show a dominance of authigenic quartz of more than 40% together with carbonate and clay minerals (illite-type). High quartz contents are thought to be a favorable condition for the brittleness of shales that can affect the performance of hydraulic fracturing operations and the production rate (Table 1 and Figures 4 - 5, 7 - 9).

4.2. Upper Miocene shales of some wells in the northern, central and southern blocks

The thickness of shales gradually increases from the northern and southern to the central basin. Sediments in the northern well comprise sands/silts interbedded with thin shales, while deposits in the southern and central wells comprise thick shales interbedded with thin sands/silts. These shales all reveal similar properties, i.e. containing poor to fair organic-richness (TOC<1 %) and poor pyrolysis yields (S_2 < 2.5 mg HC/g rock), mainly originating from type III and a minor type II kerogen, have been deposited in coastal plain to shallow marine environments. The Upper Miocene shales comprise authigenic quartz (>40%) and clay minerals (illite-type), which is a favorable condition for brittleness of shales. The available geochemical analysis results show that the organic matters of the northern and southern wells are in the immature to marginal mature of mesodiagenesis stage with R_o ranging from 0.32% to 0.55%, whereas the organic matters in the central well vary with depth and reached peak of hydrocarbon generation in late diagenesis to catagenesis stage with R_o up to 0.93%, i.e., TOC contents are low in the upper part (2,705 - 2,942 m), ranging from 0.19% to 0.24%, which are typically poor source rock potential for hydrocarbon generation; TOC contents vary from 0.56% to 0.79% in the lower part (3,007.5 - 3,599 m), indicating fair potential source rocks for hydrocarbon genration (Table 2 and Figures 6 - 7). All the evidences are thought to be the available Upper Miocene shale samples in the northern and southern wells are poor potential source rocks, giving very low or no hydrocarbon generation potential (Table 3), whereas a large amount of gas could possibly be generated and released from the Upper Miocene shales in the central block and the reservoirs could possibly be in Pliocene sands and/or it self-source and self-reservoir. Moreover, the central block shows favorable conditions for shale gas sections, i.e., shales are deposited more widely and thicker in a marine environment under the abnormal pressure and high geothermal gradient conditions that were possibly caused by: (i) a rapid sedimentation rate; (ii) a continuous loading and incomplete gravitational compaction of sediments; (iii) faulting; (iv) phase changes in minerals during compaction; (v) shale diapirism; and (vi) tectonic compression.

Table 1. *Comparison of Pliocene shales in the northern, central and southern wells*

Items	Northern well	Central well	Southern well
Number of samples	RE: 2 R_o: 2 XRD: 61	RE: 19 R_o: 19 XRD: 0	-
Depth (m)	945 - 1,365	1,520 - 2,645	700 - 1,000
Lithology	Sands, silts interbedded with very thin shales	Thick shales interbedded with thin sands and silts	Very thick shales interbedded with thin sands, silts
Minerals	Quartz + Feldspar, carbonate and clay minerals (Illite-type)	-	-
Shale diagenesis	Mesodiagenesis (60 - 70°C)	-	-
Depositional environment	Deltaic to shallow marine	Coastal plain, shallow marine	Shallow marine
Estimated thickness of shale (m)	100 - 200	~1000	~250
Organic richness (TOC, %)	0.14 - 0.24	0.15 - 0.21	-
Quality of OM, S_2 (mg HC/g rock)	0.09 - 0.24	0.17 - 0.32	-
HI (mgHC/g TOC)	60 - 100	103 - 196	
Type of kerogen	III	III	
Genetic OM	Higher plant	Higher plant	
R_o (%)	0.38	0.45 - 0.65	
T_{max} (°C)	419 - 421	407 - 435	
HC generation potential	No source potential	Poor to fair source potential	-
Origin of gas	-	Thermogenic gas	-
Remarks	No hydrocarbon generation potential	Poor to fair potential SRs, favorable conditions for generating gas	-

Note: RE = Rock-Eval pyrolysis, R_o = Vitrinite reflectance, XRD = X-Ray diffraction

Table 2. Comparison of Upper Miocene shales in the northern, central and southern wells

Items	Northern well	Central well	Southern well
Number of samples	RE: 6 R_o: 6 XRD: 12	RE: 16 R_o: 16 XRD: 20	RE: 32 R_o: 17 XRD: 0
Depth (m)	1,495 - 2,637	2,705 - 3,599	1,000 - 1,930
Lithology	Sands, silts. interbedded with thin shales, coal	Thick shales interbedded with thin sands, silts, limestones	Thick shales interbedded with thin sands, silts., limestone
Minerals	Quartz and clay minerals (Illite-type), some carbonate	Quartz and clay minerals (Illite-type), some carbonates	-
Shale diagenesis	High mesodiagenesis (70 - 80°C)	Intermediate to late diagenesis (70 - 90°C)	-
Depositional environment	Delta plain to shallow marine	Coastal plain, inner shelf	Coastal plain, shallow marine
Estimated thickness of shale (m)	100 - 200	800 - 900	600 - 700
Organic richness (TOC, %)	0.21 - 0.54	0.21 - 0.79	0.25 - 0.80
Quality of OM, S_2 (mg HC/g rock)	0.22 - 2.70	0.37 - 2.05	0.17 - 1.07
HI (mg HC/g TOC)	100 - 500	109 - 296	9 - 181
Type of kerogen	Type III/II	III and minor II	Mainly type III
Genetic of organic matter	Higher plant and little amount of marine algae	Higher plant and little amount of marine algae	Higher plant
R_o (%)	0.42 - 0.55	0.70 - 0.93	0.32 - 0.42
T_{max} (°C)	423 - 435	377 - 433	407 - 431
HC generation potential	Poor source rock potential	Poor to fair source rock potential, reached peak of HC generation	Poor to fair source rock potential
Origin of gas	Thermogeneic	Thermogenic	Thermogenic
Remarks	Poor potential SRs, possibly for gas/oil	Low to fair potential SRs, favourable conditions for gas generation	Low potential SRs, possibly for gas generation at higher maturity

Note: RE=Rock-Eval pyrolysis, R_o=Vitrinite reflectance, XRD=X-Ray diffraction

Table 3. Hydrocarbon generation potential and thermal maturity of source rock [13]

HC potential	TOC (%)	S_2 (mg HC/g rock)	
Poor	< 0.5	< 2.5	
Fair	0.5 - 1	2.5 - 5	
Good	1 - 2	5 - 10	
Very good	2 - 4	10 - 20	
Excellent	> 4	> 20	
Maturity	**R_o (%)**	**Tmax (°C)**	**PI**
Immature	< 0.55	< 435	< 0.10
Mature			
Early	0.55 - 0.65	435 - 445	0.10 - 0.15
Peak	0.65 - 0.90	445 - 450	0.25 - 0.40
Late	0.90 - 1.35	450 - 470	> 0.40
Post mature	> 1.35	> 470	

5. Conclusions and recommendations

Although sediments in the central Song Hong basin are younger than the others, the rapid sedimentation rate of the sediments deposited in this basin had caused them subjected to a quick increase of temperature with depth, which is the very reason why the organic matters

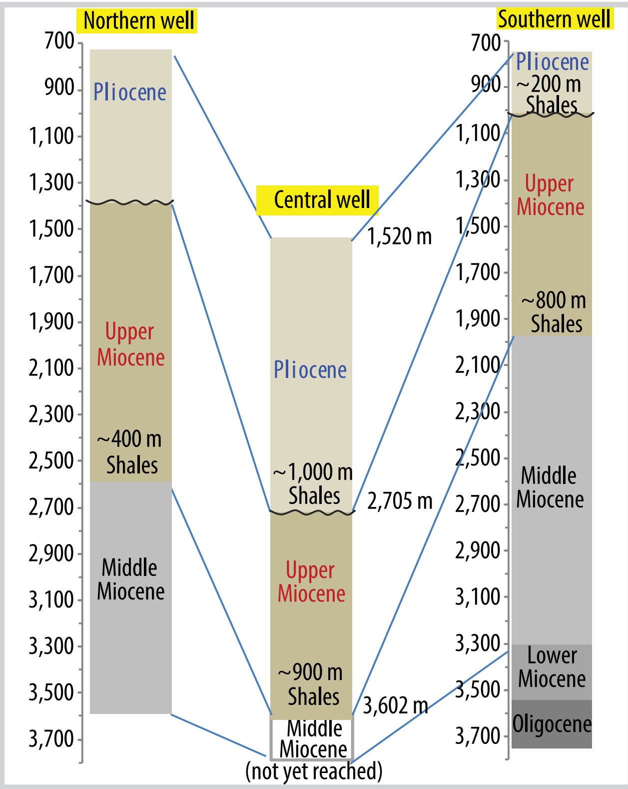

Figure 4. A scheme of three studied wells in the northern, central and southern parts of the Song Hong basin.

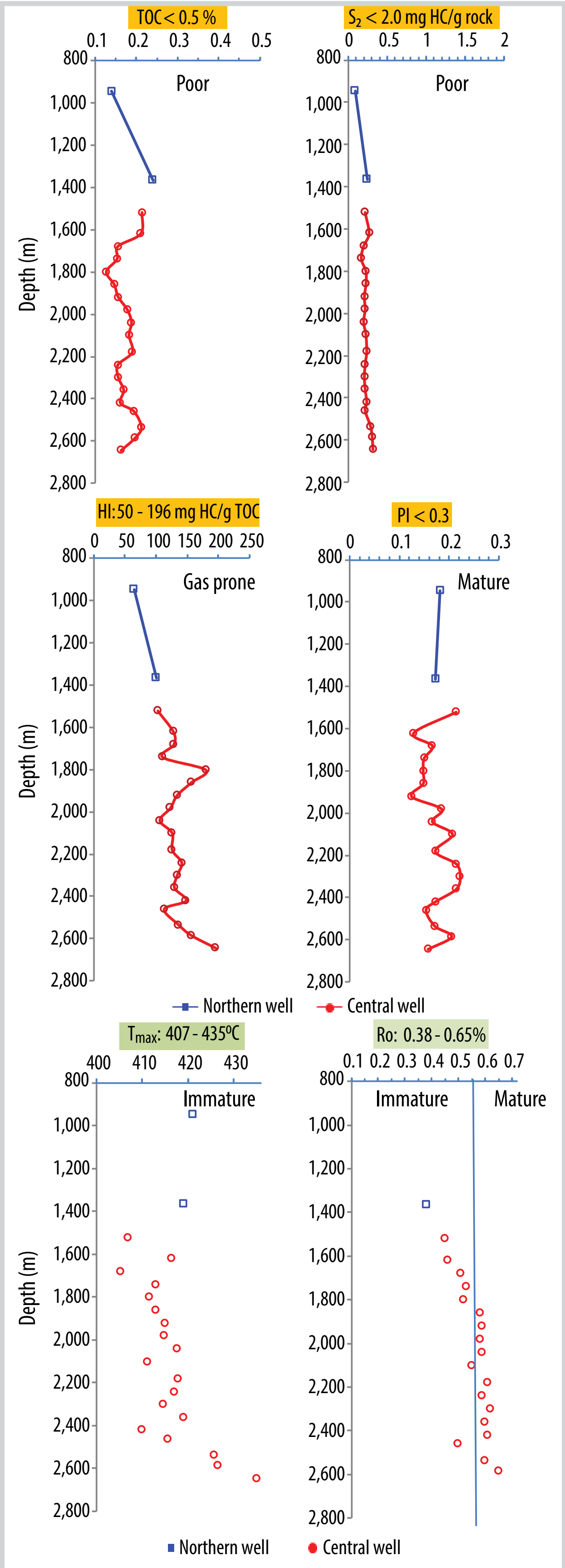

Figure 5. Comparison of Rock-Eval parameters of Pliocene shales in the northern, central and southern wells.

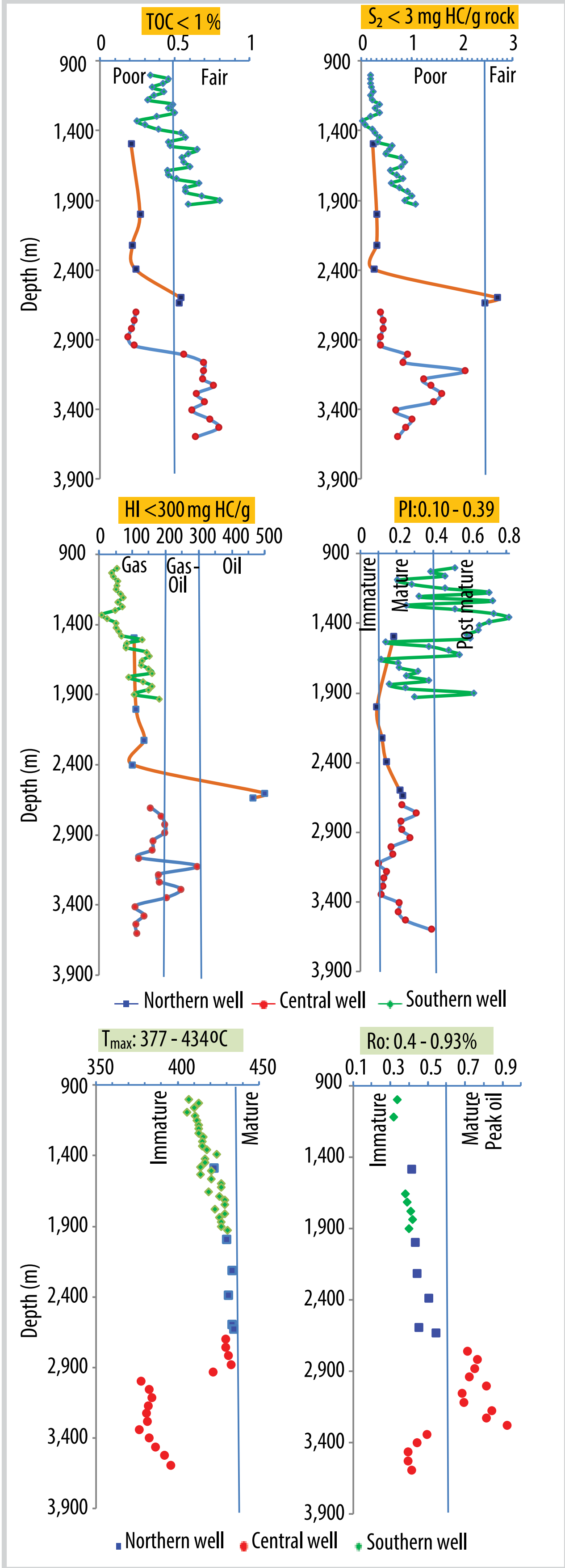

Figure 6. Comparison of Rock-Eval parameters of the Upper Miocene shales in the northern, central and southern wells.

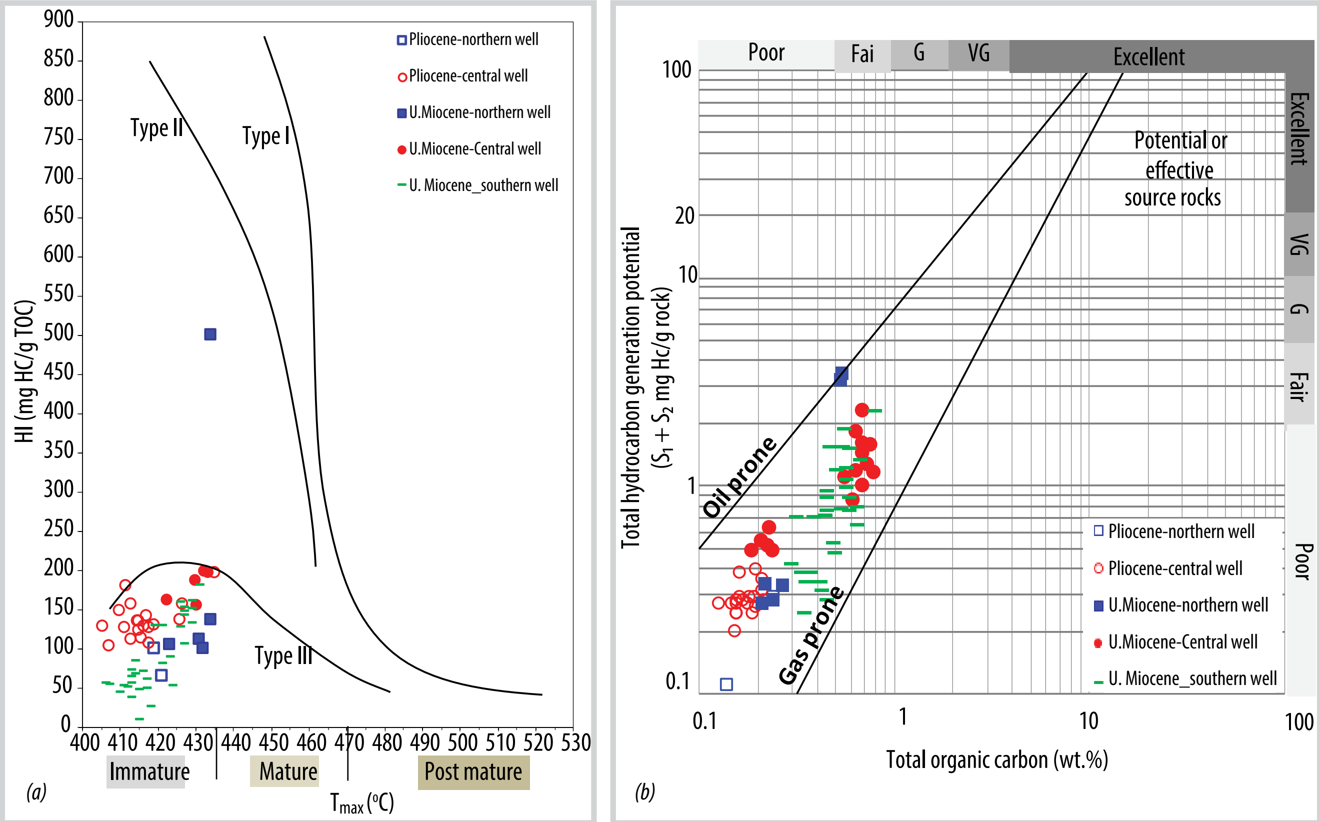

Figure 7. *Kerogen types of organic matter (a) and hydrocarbon generation potential of organic matter (b) in the northern, central and southern wells.*

Figure 8. *Minerals of shales in the northern, central and southern wells.*

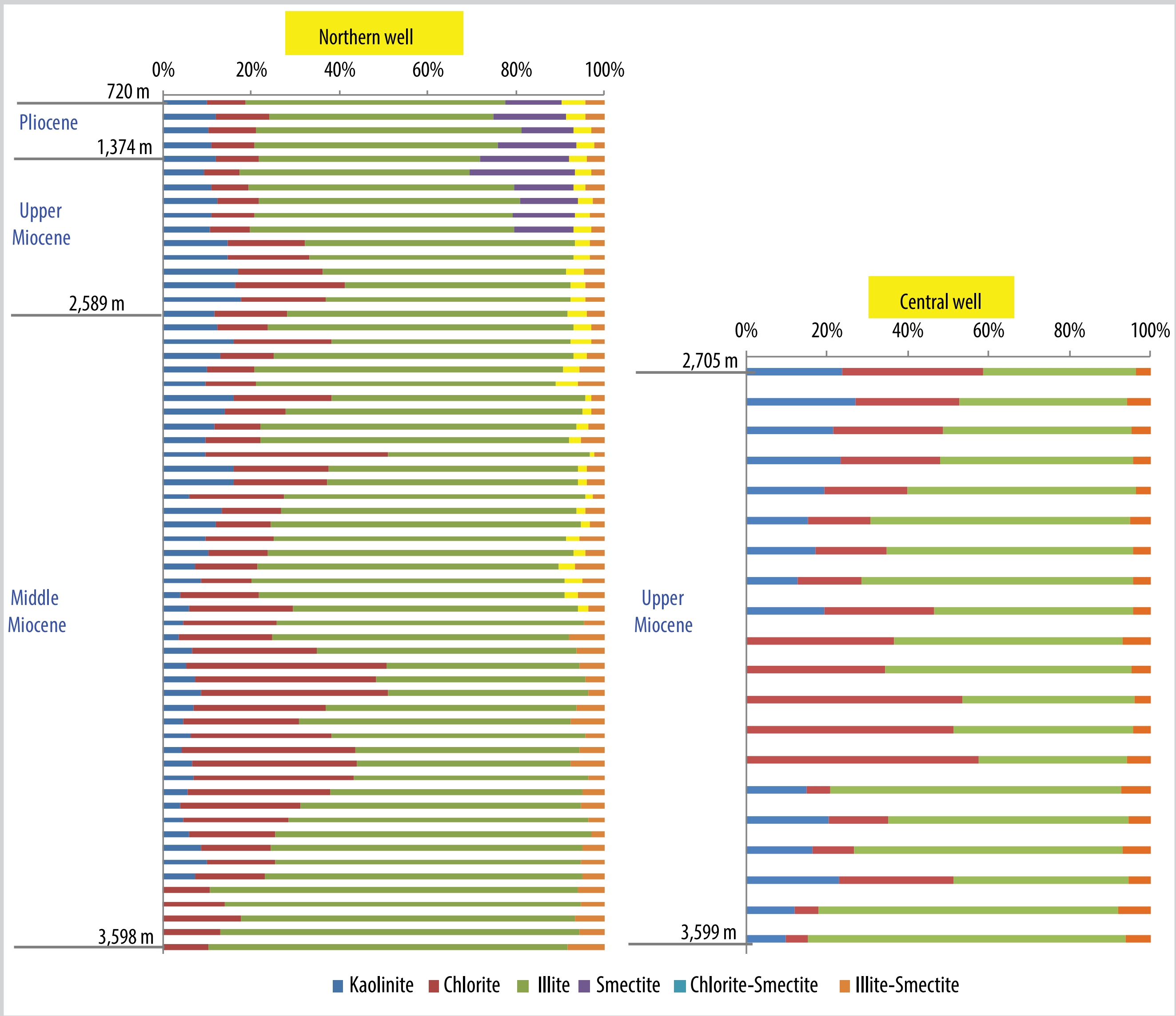

Figure 9. *Clay minerals of shales in the northern, central and southern wells.*

are in mature stage and could have been generating hydrocarbons in the Upper Miocene shales in this part. Some quick findings in this study can be outlined as follows:

- Pliocene and Upper Miocene shales in the northern and southern wells have their TOC, S_2, HI, T_{max} and R_o values of less than 0.5%, 2.5 mg HC/g rock, 200 mg HC/g rock, 435°C and 0.55%, respectively, which indicate poor potential source rocks for little gas generation possibly.

- The Upper Miocene shale samples in the central well comprise TOC varying in two parts of 2,705 - 2,942 m and 3,007 - 3,599 m, i.e., TOC contents are low in the upper part, ranging from 0.19% to 0.24% that indicate typical poor potential source rocks, whereas TOC values range from 0.56% to 0.79% in the lower part, which suggest fair potential source rocks. Moreover, shales in the central part of the Song Hong basin are possibly more favorable conditions for shale gas sections, i.e., these shales are deposited more widely and thicker in a marine environment under the abnormal pressure and high geothermal gradient conditions that are caused by rapid sedimentation rate, continuous loading and incomplete gravitational compaction of sediments, faulting, and phase changes in minerals during compaction, etc. Therefore a considerable amount of gas could possibly be generated from the Upper Miocene shales of the central part into the possible overlying reservoirs in Pliocene sands and/or the Upper Miocene sediments, which can play the double roles of self-source and self-reservoir.

- It is strongly recommended the Pliocene/Upper Miocene shales and sands be investigated further as potential source rocks and reservoirs. More geological and structural studies are recommended for a better characterisation of these three major blocks of the Song Hong basin, i.e., the northern, central and southern ones.

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