Bulletin of Earth Sciences of Thailand

Sweet spot Identification of shale gas from 2D modeling at Sinphuhorm field, onshore Thailand

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Abstract

This research aimed to enhance the understanding and assessment of the shale gas potential of the Huai Hin Lat Formation in the Sinphuhorm Field, located in the Khorat Basin, northeastern onshore Thailand. The Huai Hin Lat Formation is recognized as a significant source rock in this region deposited in the rifted basin during Triassic. To achieve the research objectives, geological, geophysical, and geochemical characteristic interpretations were integrated using published reports, well data, and seismic data. The results of one- and two-dimensional petroleum system models can identify the shale gas sweet spot areas and estimate the potential gas-in-place resources of the Huai Hin Lat Formation. The geological analysis was derived from existing well data, including the final well report, mudlogging data, and wireline logging data. These data facilitated a comprehensive understanding of the lithological characteristics and depositional environment in terms of both vertical and lateral dimensions. A composite seismic line was selected for geophysical analysis and two-dimensional (2D) petroleum system modeling. This seismic line was extracted from the crest structure of the Sinphuhorm field, extending from the production wells in the east to the basin center in the western part of the field. Seismic facies analysis was applied to identify lithological variations in the seismic profile. Results from the 2D petroleum system modeling indicated that the Huai Hin Lat Formation in the study area is in the late stage of the dry gas generation window at the present-day temperature model giving a high hydrocarbon transformation ratio. However, despite favorable rock properties suitable for shale gas production through hydraulic fracturing, the Formation exhibited lower potential for unconventional resources due to less promising hydrocarbon generation, poor hydrocarbon qualification, a high degree of maturation, and restricted hydrocarbon migration.

Keywords: Petroleum System Modeling, Seismic Interpretation, Source Rock Evaluation, Huai Hin Lat Formation, Khorat Plateau

1. Introduction

Shale gas refers to natural gas that is trapped within shale rock formations. Shale formations are sedimentary rocks with low permeability, which means that the gas is not easily able to flow through the rock. Extracting shale gas requires the utilization of advanced drilling and extraction techniques, most notably hydraulic fracturing (Adibhatla and McWhorter., 2011). It presents a promising opportunity for future exploration and development, supplementing conventional resources. Consequently, comprehending the petroleum system and assessing the potential of shale gas through an integrated analysis encompassing geological, geophysical, and geochemical aspects assumes paramount importance in this study.

The Khorat Basin in the Khorat Plateau is the largest onshore sedimentary basin in Thailand spanning approximately 90,650 square kilometers and holds significant shale gas potential (Wichan et al., 2019). Among the petroleum basins in onshore Thailand, the Khorat Plateau stands out, and despite several unsuccessful drilling attempts, the gas discovery in the Sinphuhorm Field validates the effectiveness of the petroleum system in this area (Kositgittiwong et al., 2018). The Triassic Huai Hin Lat fluvial-lacustrine shale emerges as a prominent proven source rock within the Khorat Plateau, as depicted in the stratigraphic chart (Chidthaisong et al., 2021).

Exploration wells that penetrate the Huai Hin Lat shales are limited in the Khorat Plateau due to the presence of the thick overburdened rocks (Racey, 2009). Consequently, the sedimentary basin development and geochemical characteristics of different lithofacies within the Huai Hin Lat shale have not been systematically elucidated (Chenrai et al., 2022). The understanding of the shale gas potential of the Huai Hin Lat Formation in the Sinphuhorm Field remains incomplete due to data limitations. Nonetheless, various techniques and information, such as geochemical, report, well log, and seismic data, have been employed in this study to determine optimal input parameters for Petroleum System Modeling and to identify reasonable shale gas potential (Jirapongpaisal et al., 2017).

The study area is regarded as a potential basin located in the western part of the Sinphuhorm field, spanning an extensive area of 2,500 km^2, with the inclusion of an existing well within its boundaries. Despite the data obtained from the Sinphuhorm wells revealing a relatively low total organic carbon (TOC) value (PTTEP, 2021), it is plausible to consider that this observation may be attributed to the well's positioning, potentially failing to penetrate the central region of the basin.

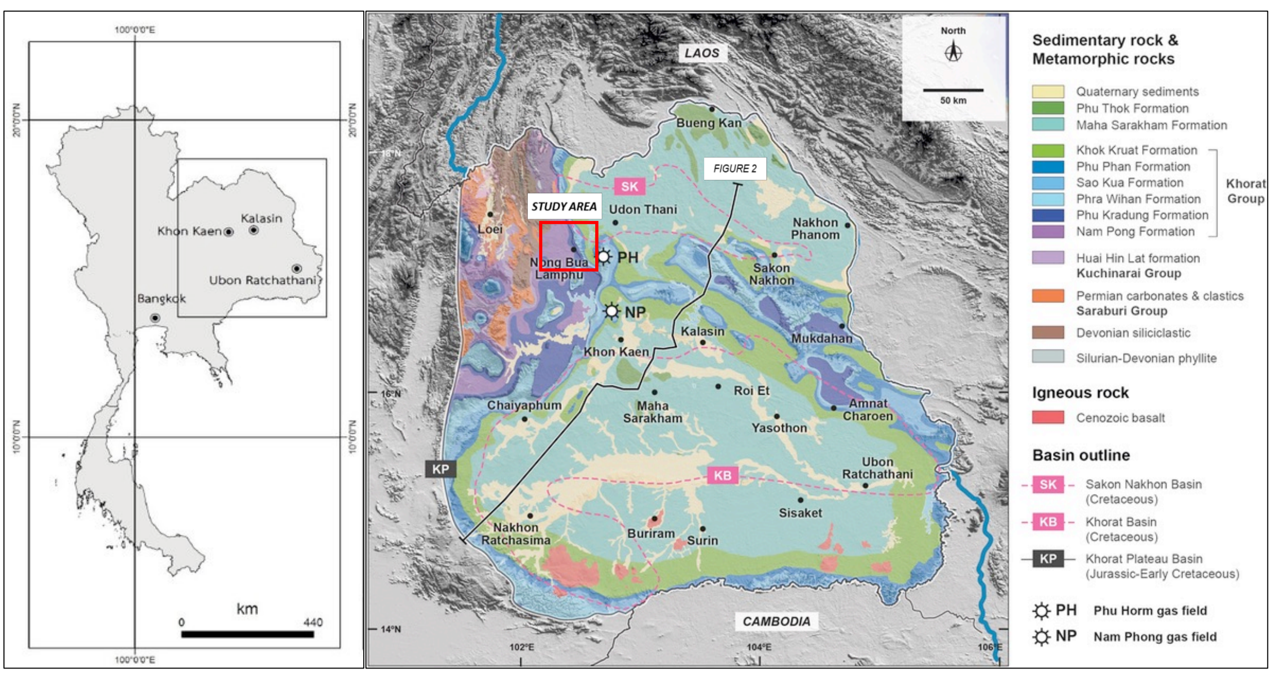


Figure 1 Simplified geological map of the Khorat Plateau, with the main producing gas fields. The study area is displayed in the red rectangle (modified after Chenrai et al., 2022).

2. Geological Overview

The Khorat Plateau is a large and flat region located in northeastern Thailand, covering an area of approximately 155,000 km² (Figure 1). The plateau is bounded to the west by the Phetchabun Mountains and to the east by the Mekong River. The geology of the Khorat Plateau is complex and various with several different rock types and Formations presented in the region. The Khorat Plateau is a gently undulating plateau elevated about 150-500m above mean sea level that slopes gently towards the Mekong River to the east. The dominant landforms are broad fold and low hills. The plateau was formed in the central part of the Indochina Terrane. This terrane underlies most of Vietnam, Cambodia, Laos, and eastern Thailand (Sone and Metcalfe, 2008; Burrett et al., 2014). The structure of the study area reflects different phases of tectonic events. (Figure 2)

The Khorat Plateau, characterized by sedimentary rock Formations, was deposited during the Mesozoic Era, specifically spanning the Late Triassic to Late Cretaceous periods (Košťák et al., 2018). These sedimentary rocks were laid down in diverse environments, encompassing alluvial fans, fluvial systems, lacustrine systems, and shallow marine environment. The lithological composition of the Khorat Plateau varies depending on the depositional environment but generally consists of sandstone, siltstone, shale, limestone, and conglomerate (Soares et al., 2012).

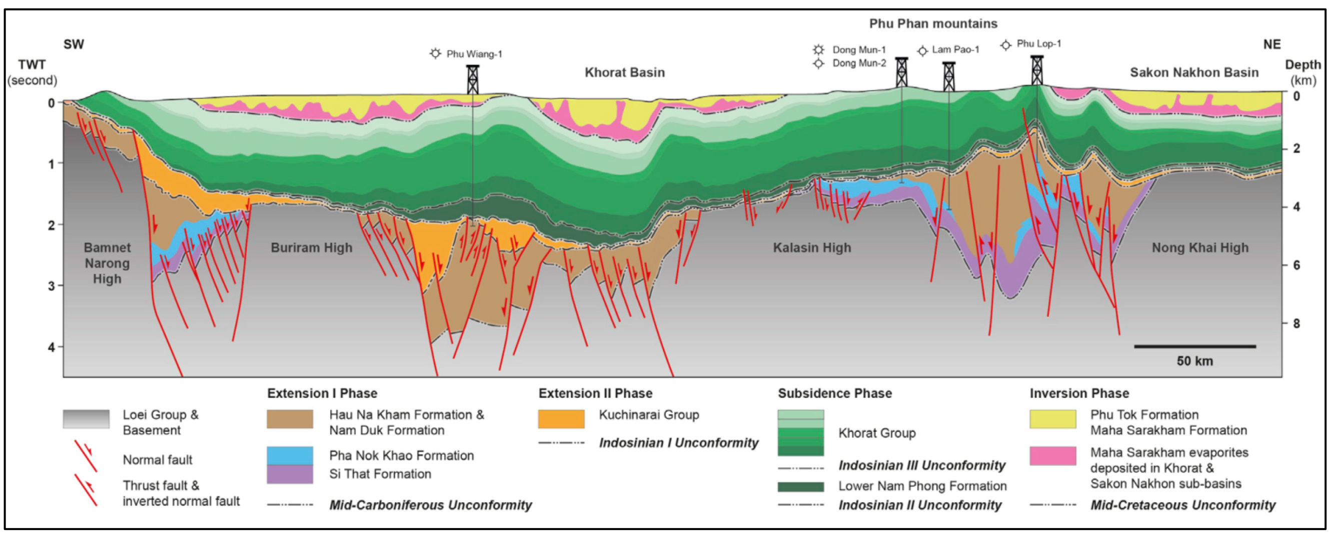


Figure 2 Stratigraphic cross sections across the Khorat Plateau, showing the major lithological and tectonic units in the subsurface (modified from Booth and Sattayarak, 2011; Minezaki et al., 2019). The distribution of the Khorat and Sakon Nakhon basins is also shown in this section.

The Khorat Plateau experienced two significant rift episodes and three main phases of compressional events (PTTEP, 2021), resulting from the subduction and collision of tectonic plates from the Carboniferous to Tertiary periods. These geological processes have shaped the complex tectono-stratigraphic history of the region. During the first rift event (Late Carboniferous-Permian), the deposition of primary source rocks and carbonate reservoirs followed the horsts and grabens/half-grabens pattern in a shallow marine setting. The Early-

Mid Triassic orogeny, known as the Indosinian I Unconformity event, led to intense deformation and erosion of underlying Formations, resulting in the Formation of NW-SE and E-W structural trends and fractures. Fluvio-lacustrine shales, deposited during the second rift phase in the Late Triassic, represent another potential source rock. Geochemical analysis of these rocks indicates the generation of hydrocarbons from a mixture of terrestrial and marine organic matter, currently reaching a state of maturity or over maturity. Fluvio-lacustrine sandstones were also deposited during this period. Subsequent to the Indosinian II unconformity event, thick Late Triassic fluvial floodplain sediments were extensively deposited, serving as an effective regional seal for both reservoirs. Tectonic reactivation in the Paleogene period enhanced porosity and created new open fractures, predominantly oriented NE-SW and N-S, in the Permian carbonates in the region. Hydrocarbons, primarily gas, were migrated from paleo-structures and/or the kitchens through carrier beds or faults during this period.

The Huai Hin Lat Formation has been divided into two major sequences, namely the lower and upper sequences, each comprising five members (Wongwanich et al., 2010). The lower sequence is composed of the Pho Hai Member and the Sam Khaen Conglomerate Member, while the upper sequence consists of the Dat Fa Member, the Phu Hi Member, and the I Mo Member (Wongwanich et al., 2010).

The Pho Hai Member primarily consists of volcanic rocks, including tuff, agglomerate, rhyolite, andesite, along with interlayers of sandstone and conglomerate (Wongwanich et al., 2010). On the other hand, the Sam Khaen Conglomerate Member, which is considered a lateral equivalent of the Pho Hai Member, is predominantly composed of conglomerate with intermittent limestone beds. It is commonly associated with intermingled sandstone and shale (Wongwanich et al., 2010).

The Dat Fa Member overlays either the Sam Khaen Conglomerate Member or the Pho Hai Member. It is characterized by calcareous, carbonaceous shale, and argillaceous limestone containing fossils (Wongwanich et al., 2010). Similarly, the Phu Hi Member is identified by the presence of sandstone, shale, and argillaceous limestone, along with some conglomerate (Wongwanich et al., 2010). In certain areas, the I Mo Member is present, consisting of volcanic rocks interbedded with shale, sandstone, and limestone (Wongwanich et al., 2010). Based on previous studies, the shale found in the Huai Hin Lat Formation is rich in organic matter, characterized by a total organic carbon (TOC) content ranging from 0.5 to 15 wt.% with an average of approximately 3-4 wt.% (Sriaporn et al., 2020; Ihsan et al., 2019). The kerogen presented in the shale mainly comprises type II and III kerogens indicating a combination of marine and terrestrial organic sources (Sriaporn et al., 2020; Ihsan et al., 2019). Due to its elevated organic content and thermal maturity, the Huai Hin Lat Formation has become an appealing target for shale gas exploration. Petrophysical analysis reveals that the shale exhibits low porosity and permeability (Sriaporn et al., 2020; Ihsan et al., 2019). However, the mineral composition of the shale is favorable for hydrocarbon generation and storage. Clay minerals, particularly illite, smectite, and chlorite, dominate the mineralogy of the shale, with minor constituents such as quartz, feldspar, and calcite (Sriaporn et al., 2020; Ihsan et al., 2019). The presence of abundant organic matter and pyrite within the shale can act as natural fracture agents and facilitate gas adsorption (Sriaporn et al., 2020; Ihsan et al., 2019).

3. Materials and methods

The research study was analyzed through geological analysis using mudlogging data, wireline data, and the final well report. Additionally, geophysical analysis was conducted using a seismic composite line for seismic unit analysis. Furthermore, geochemical analysis was performed using existing data and newly acquired XRD data, along with the application of a petroleum systematic model.

For the geological analysis, 10 specific wells were carefully selected to provide log characteristics and facilitate well-to-well correlation across the study area. Petrel Software (Version 2021) was utilized for this purpose. In addition, the lithostratigraphic correlation and cutting description analysis were conducted based on the mudlog data. These analyses were essential in defining the lithology, depositional environment, and facies variations within the Huai Hin Lat Formation.

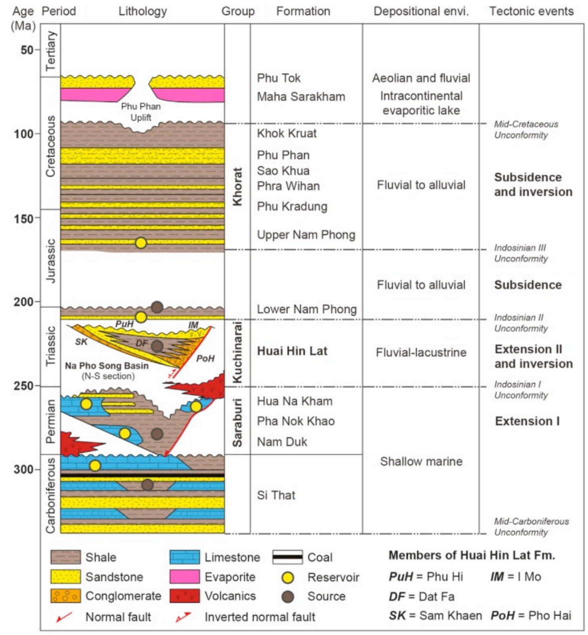


Figure 3 Stratigraphy of Khorat Plateau including petroleum system elements and key events (modified after Chenrai et al., 2022).

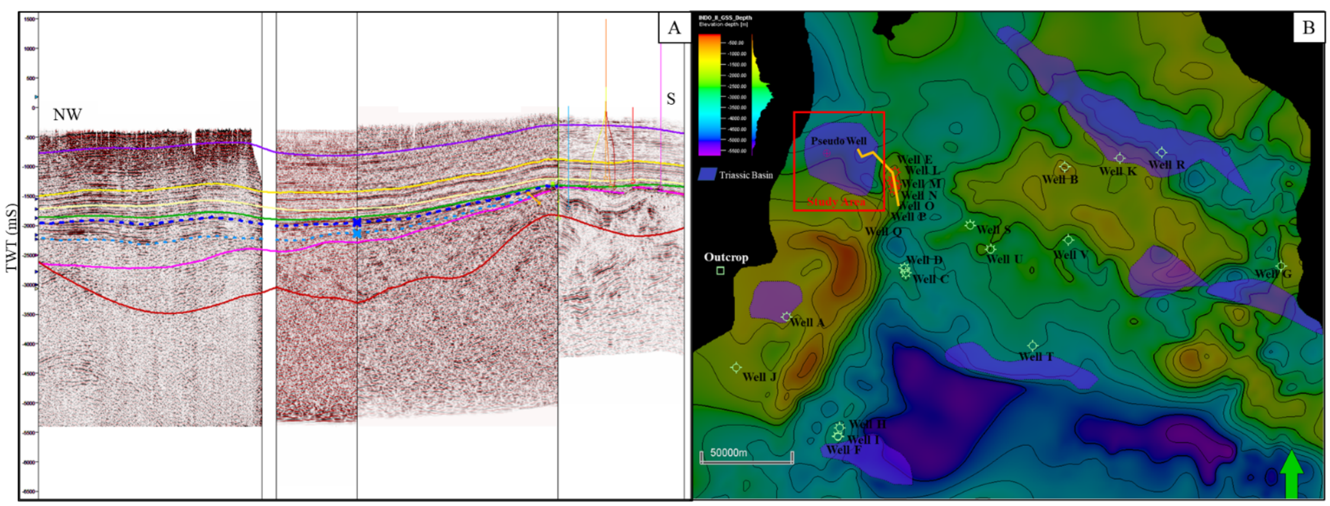


Figure 4 A) Selected seismic cross sections across the area showing crest at the south to the basin center at northwest. B) The depth-structural map of Khorat Plateau with existing well locations and the location of the selected seismic section line (combined of 3D and 2D seismic data) in yellow line and overlays with the location of Triassic basin from PTTEP internal study, 2021.

A carefully selected single composite seismic line was utilized for geophysical analysis, effectively capturing the structural high of the Sinphuhorm field in the south and extending towards the basin center in the northwest (Figure 4). To address the absence of wells drilled through the basin center in the study area, a seismic unit analysis technique from Vail et al. (1987) was employed to identify both vertical and lateral facies changes. This involved integrating the geological model derived from geological interpretation with the seismic data. The main objectives of this analysis were to determine the distribution of different lithological facies, delineate their boundaries, and classify them into distinct sub-units.

In this study, the geochemical evaluation primarily relied on existing data, supplemented with newly acquired X-ray diffraction (XRD) data. The total organic carbon content was analyzed through various types of cross-plots using data from 13 wells. A vitrinite reflectance analysis was conducted using data obtained from 12 wells and 2 outcrop locations to identify the geochemical characteristics and assess the source rock potential, existing data from nine wells and two outcrop locations were utilized for various types of plot analysis. Additionally, the mineral composition of well-cutting samples from 26 cutting samples obtained from 4 wells in Huai Hin Lat was determined using X-ray diffraction (XRD) analysis. The purpose of this analysis was to assess the brittleness of the Huai Hin Lat (HHL) Formation in the study area.

To classify the sedimentary facies, a comprehensive approach was employed, integrating wireline log characteristics, well-cutting lithology, seismic character sedimentary structures, facies interpretation from geochemical analysis, and existing internal reports.

Once the three components of the study were processed and all the required data were collected, the 2D Basin modeling approach was employed to achieve the study's objectives. The PetroMod software, provided by Schlumberger, was utilized to develop a petroleum system modeling of the study area. The input parameters for the model generation were based on the analysis of geological, geophysical, and geochemical data, reflecting the potentiality of the source rock. The seismic section selected for the study was digitized in the depth domain, and subsequent age and layer assignments were made based on PTTEP internal study findings. The facies variations, both vertically and laterally, were defined by integrating the results of geological, geophysical, and geochemical analyses. The TOC values in the model were assigned within a range of 1-4 wt. % (original TOC), while the HI values were set between 200-400 mgHC/gTOC. The kinetic model referenced for fluid type and HI values from pyrolysis was Burnham (1989) type III kinetic model. For the boundary conditions, the paleo water depth was determined based on the depositional settings of each Formation, and a lateral variation number was assigned from landward to basinward sections. The heat flow was assigned based on tectonic events, considering the absence of significant faults, salt deposits, or heat plumes that could affect lateral heat flow in the small basin. The model was calibrated using vitrinite reflectance and temperature to ensure the accurate determination of hydrocarbon generation, maturation qualification, and migration.

The final step of the study involves the utilization of specific criteria to identify the shale gas sweet spot area, supplementing the petroleum system model. These criteria comprise of 1) shale oil/gas production optimum cut-off range of 1000-5000 mTVDSS, which is relevant to fracking conditions, 2) a minimum thickness requirement of 15 m to address drilling operational considerations, 3) total organic carbon, 4) vitrinite reflectance within the range of 1.2-2.0 %Ro, representing the maturation window for shale gas development and 5) utilization of XRD analysis to create a brittleness map, enabling the identification of areas suitable for hydraulic fracturing. By incorporating these criteria, the study aims to delineate the shale gas sweet spot area, representing an optimal zone for potential shale gas extraction and development.

4. Results and interpretations

4.1 Geological Interpretation

The geological model was established by integrating the understanding of tectonic evolutions and stratigraphic successions derived from a comprehensive literature review.

Wireline log interpretation

The log character analysis of the Huai Hin Lat Formation (Figure 5) revealed its distribution throughout the Khorat Basin, exhibiting variations in lithology corresponding to the diverse gamma ray trends observed in different well locations. The wells that penetrated the basin center exhibited high gamma ray values, ranging from 100 to 150 API, as indicated by the thickness map of the Huai Hin Lat Formation (Figure 4). This distribution pattern can be attributed to the deposition of the Formation in a fluvio-lacustrine environment, with the thickest portions representing the basin center.

In the remaining wells, a combination of high gamma ray (shale) and low gamma ray (50-110 API) values was observed. However, the trend of high gamma ray values still aligned with the thickness map.

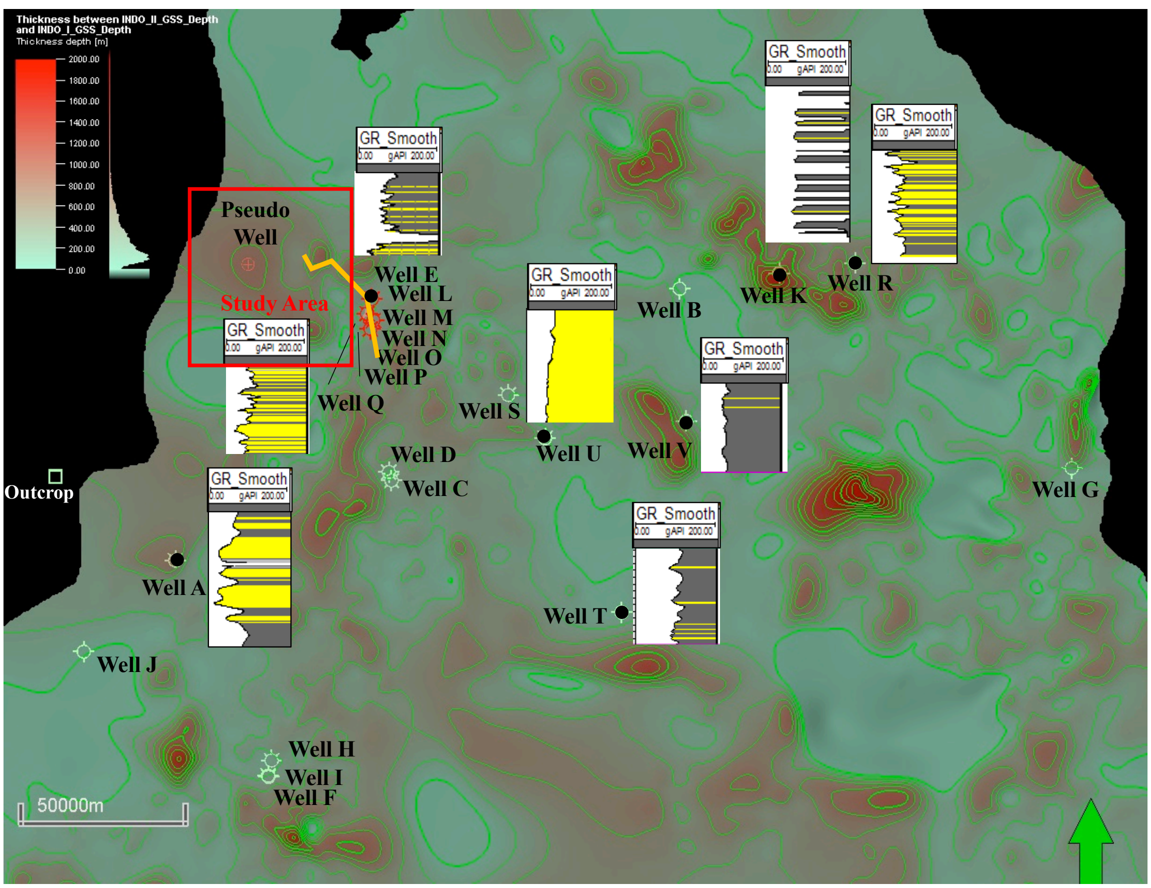


Figure 5 Huai Hin Lat thickness map over the Khorat Plateau overlays with well location and GR log character to demonstrate a variation of source rock lithology..

Mudlog and cutting description analysis.

The lithology descriptions based on cutting samples from mudlog data, in conjunction with the thickness map, provide insights into the variations within the Huai Hin Lat Formation. An increase in shale content is observed towards the basin center, where the color of the shale changes from red-brown, indicating a more oxidizing environment, to grey-dark grey and eventually black, suggesting potential anoxic conditions and higher TOC content (Figure 6).

Although the Huai Hin Lat Formation is deposited in a fluvio-lacustrine environment throughout the Khorat Basin, there are notable lithological variations dependent on the changing depositional settings. Proximal (landward) areas are dominated by sand, while distal areas in the basin center exhibit different lithologies due to lateral facies changes. These variations can result in differences in TOC content. It is important to note that the well in the Sinphuhorm area only penetrated a thin part of the Huai Hin Lat Formation and may not fully represent the entire member. This limitation could be attributed to the effects of uplift and erosion. The presence of calcareous content in the cutting samples suggests a potential source of sediment supply, likely derived from the erosion of carbonate structural highs.

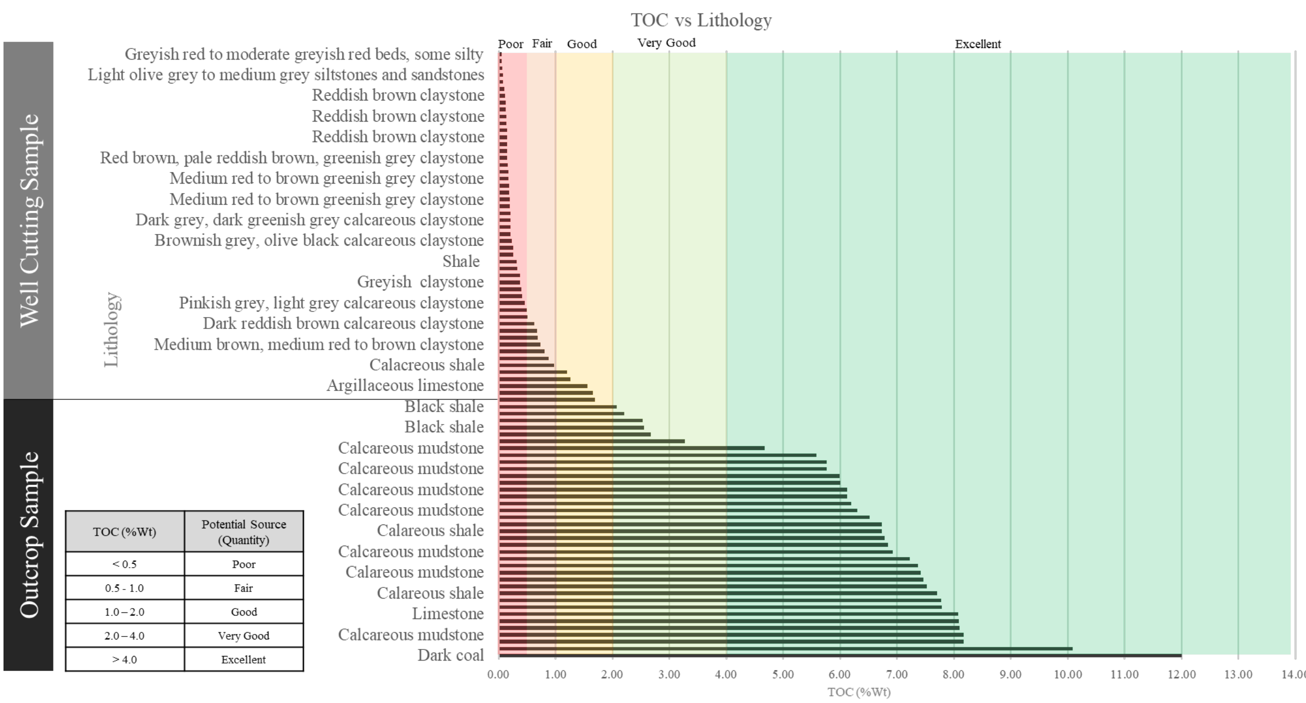


Figure 6 Various lithology types which can define as fine-grained sediments with sufficient amount of organic matter (>0.5% TOC) and can generate hydrocarbon.

4.2 Geophysical Interpretation

To overcome the lack of well data in the study area covering the basin center, a seismic unit analysis technique was utilized to identify variations in both vertical and lateral facies.

Seismic Unit Analysis

Based on the seismic characters observed within the Huai Hin Lat Formation, the seismic units can be classified into three distinct units. Firstly, Unit A represents the lowest unit and is characterized by a reflection package with variable amplitude, ranging from low to high amplitude reflections with medium continuity and medium frequency. The thickness varies from 0.1 to 0.5 second (S) TWT. This unit tends to thicken towards the northwest (in projection) and is distinguished by sub-parallel, wavy, and hummocky reflectors.

Moving upwards, Unit B constitutes the middle part of the seismic interval of interest, which displays a reflection package with variable amplitude ranging from low to high amplitude reflection. The reflection shows medium to high continuity and medium frequency, with a thickness ranging from 0.1 S to 0.5 S. Similar to Unit A, it thickens towards the northwest (in projection and analog from the primary section). This unit is characterized by parallel to sub-parallel reflectors, with occasional wavy and contorted reflectors. Lastly, Unit C represents the uppermost unit, which exhibits a reflection package with low to medium amplitude reflection. It demonstrates medium continuity and medium frequency, with a thickness ranging from 0.05 to 0.10 S. Like the previous units, it thickens towards the northwest (in projection and analog from primary section) and is characterized by sub-parallel and wavy reflectors. Regarding lateral facies changes, the seismic clinoform character, primarily present in mud or shale due to their compaction properties, can be observed in both Unit B and Unit C. This clinoform pattern indicates lateral facies change from landward to basin ward (Figure 7).

Seismic Facies Interpretation

The seismic unit analysis of Unit A reveals characteristics of low-high amplitude reflection, low-medium continuity, and medium frequency, with sub-parallel, wavy, and hummocky reflectors. These features suggest a deposition of gravity mass flow or talus, with the expected lithology being conglomerate, interspersed with limestone beds that may be equivalent to the Sam Khaen member. This unit is relatively low in potential as a source rock.

Unit B exhibits characteristics of low-high amplitude reflections, medium-high continuity, and medium frequency, with parallel-sub parallel reflectors, along with some wavy and hummocky reflectors. These attributes indicate a deposit in a lacustrine-fluviolacustrine with a low-energy environment, possibly under anoxic conditions. The fine-grained sediment is expected to increase towards the northwest (basin center), with the possibility of dark-colored shale in the basin center. This unit could be equivalent to the Dat Fa member, and the total organic carbon (TOC) content may range from 0.5 wt.% to 1 wt.%, increasing towards the basin center.

Unit C displays characteristics of sub-parallel or contorted low-medium amplitude reflection, low-medium continuity, and medium frequency, with sub-parallel and wavy reflectors. This suggests a deposit in a fluvio-lacustrine, higher-energy environment, under suboxic conditions. The lithology of this unit is expected to comprise medium-fine grain sandstone with shale, possibly equivalent to the Phu Hi Member. The TOC content in this unit may range from 0.5 wt.% to 1 wt.%, increasing towards the basin center.

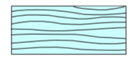
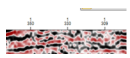
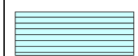
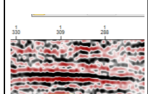
Unit	Description	Example	Facies Description	Reflection Geometry/Amplitude Characteristic	Interpretation	Depositional Environment	Expected Lithology	Expected TOC
C	Is a reflection package of variable amplitude ranging from low-medium amplitude reflection, low- medium continuity and medium frequency, unit C has relatively constant thickness 0.125 S and characterized by sub parallel, wavy reflectors		Sub-parallel/Contorted	low-medium amplitude reflection, low- medium continuity and medium frequency, sub parallel, wavy		Deposit of fluvio-lacustrine, higher-energy environment, Suboxic condition	Medium-fine grain sandstone with shale (Phu Hi Member)	Higher to basin center, original TOC can be 0.5-1 (%wt)
B	Is a reflection package of variable amplitude variable amplitude from low-high amplitude reflection, medium-high continuity and medium frequency, this unit has variable of thickness ranging from 0.125 S to 0.4 S (thicker toward NW) and characterized by parallel-sub parallel reflectors with some wavy and hummocky reflector		Bedded	low-high amplitude reflection, medium-high continuity and medium frequency, parallel-sub parallel reflectors with some wavy and hummocky reflector		Deposit of lacustrine-fluviolacustrine, low-energy environment, Anoxic condition	Increasing of fine grains sediment toward NW (basin center) Expected black shale in basin center (Dat Fa member)	Higher to basin center, original TOC can be 3-4 (%wt)
A	Is a reflection package of variable amplitude from low-medium amplitude reflection, low continuity and medium frequency along the section, this unit has variable thickness ranging from 0.1-0.5 S, thickening toward NW and characterized by wavy, hummocky , contorted and chaotic reflectors.		Chaotic	low-medium amplitude reflection, low continuity and medium frequency, wavy, hummocky , contorted and chaotic reflectors		Deposit of gravity mass flow/Talus	conglomerate with some intercalations of limestone beds (Sam Khaen member)	Relatively low and expect to non-potential for Source rock

Figure 7 The summary of the seismic unit analysis of the Huai Hin Lat Formation which can be divided into 3 unit based on seismic reflector characteristics.

4.3 Geochemical Evaluation

It is important to note that there are uncertainties associated with the geochemical data used in this study, as they were obtained from different laboratories and at different times. Therefore, caution should be exercised when interpreting and selecting geochemical data as input parameters for the petroleum system modeling.

Total Organic Carbon

The results revealed present-day TOC values ranging from 0.01 wt.% to 2.08 wt.% indicating a range from poor to good source rock potential while outcrop samples of black shales and organic shales from the Huai Hin Lat Formation exhibited mainly good to excellent TOC content (1.20–12.00 wt.%). However, it is noteworthy that 85% of the samples exhibited poor TOC content (Figure 8). Upon applying a conversion to estimate the original TOC values, a broader range of 0.1 wt.% to 5.20 wt.% was obtained, suggesting the presence of poor to excellent source rock. The relationship between TOC values, Huai Hin Lat thickness map, and TOC distribution map demonstrated that higher TOC content is typically observed in wells that penetrate the basin center or locations with the greatest thickness of the Huai Hin Lat Formation (Figure 9). Overall, the samples showed very low TOC content, suggesting a low generation potential, while very high TOC values were likely attributed to carbonaceous shales or coals.

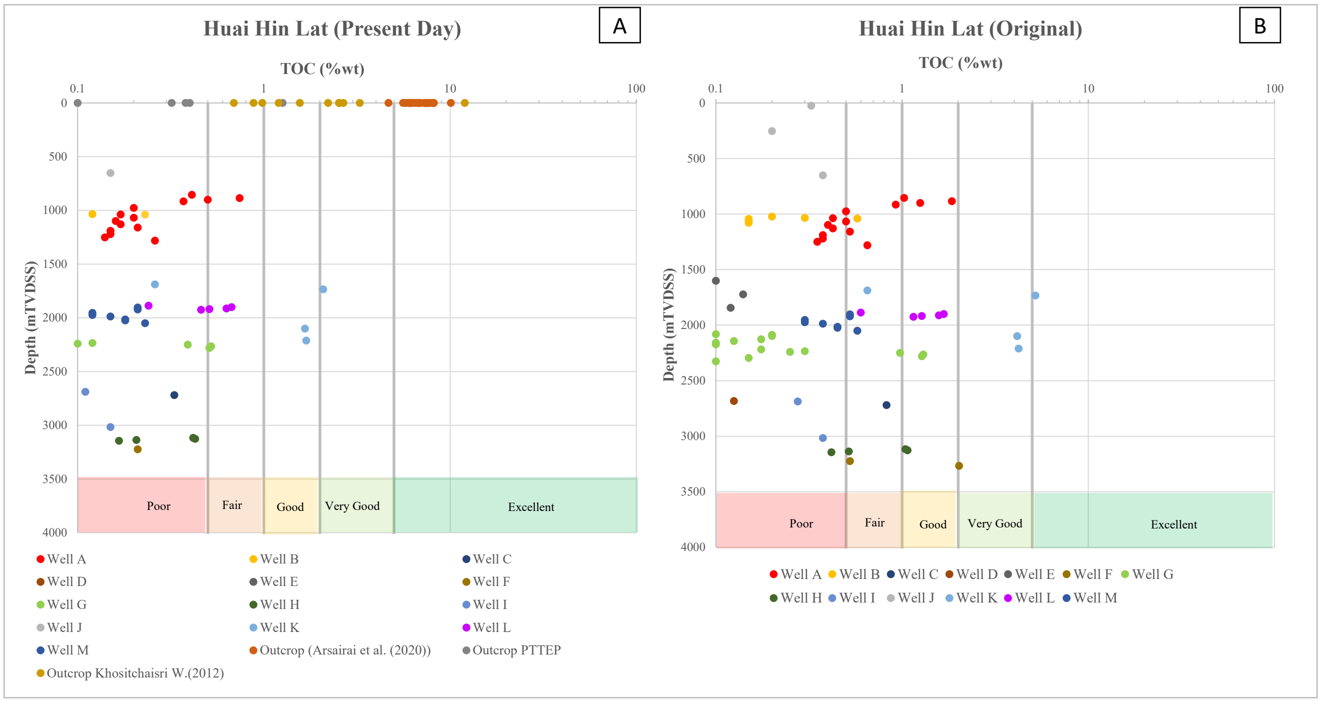


Figure 8 The plot of TOC (%wt) versus depth: A Present-day TOC value plot. B) Original TOC value after applying conversion formular.

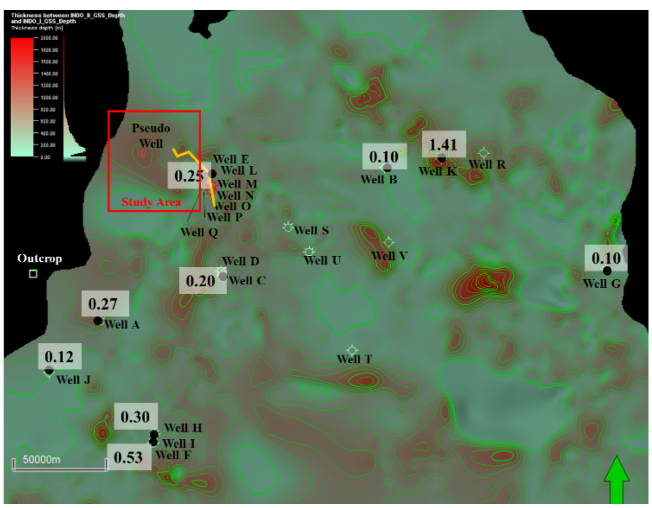


Figure 9 The thickness map of the Huai Hin Lat Formation modified from PTTEP (2021) overlying with TOC value (wt.%) along the well locations. The study area is in red rectangle.

Rock Eval Pyrolysis

Cross-plots of various parameters were conducted to enhance visualization and interpretation. The kerogen types present in the source rocks of the study area were identified using a modified Van Krevelen diagram (Figure 10). The HI values of the Huai Hin Lat Formation ranged from 2 to 14 mg HC/g TOC, with an oxygen index (OI) of 2-56 mg CO_2/g TOC. However, due to very low S2, S3, and TOC values, as well as the presence of highly mature samples, it was challenging to accurately determine the original kerogen type using HI and OI plots. The thermal degradation of these Formations has obscured the details of the original kerogen, making it difficult to differentiate between different macerals (kerogen types). Based on stratigraphic correlation and depositional environment, the Huai Hin Lat shales are considered to consist of kerogen types I and III of lacustrine origin.

Overall, the relationship between petroleum generation (S2) and genetic petroleum potential yield (PY; S1 + S2), and TOC of the studied units in the surrounding area confirmed that most of the Late Triassic Huai Hin Lat samples fall within the zone of gas-prone potential and exhibit poor to very good hydrocarbon generation (Figures 11 and 12). However, these data represent present-day conditions, and the hydrocarbons have already been generated through thermal maturity processes, influenced by several tectonic events in the study area, resulting in low S1 and S2 values.

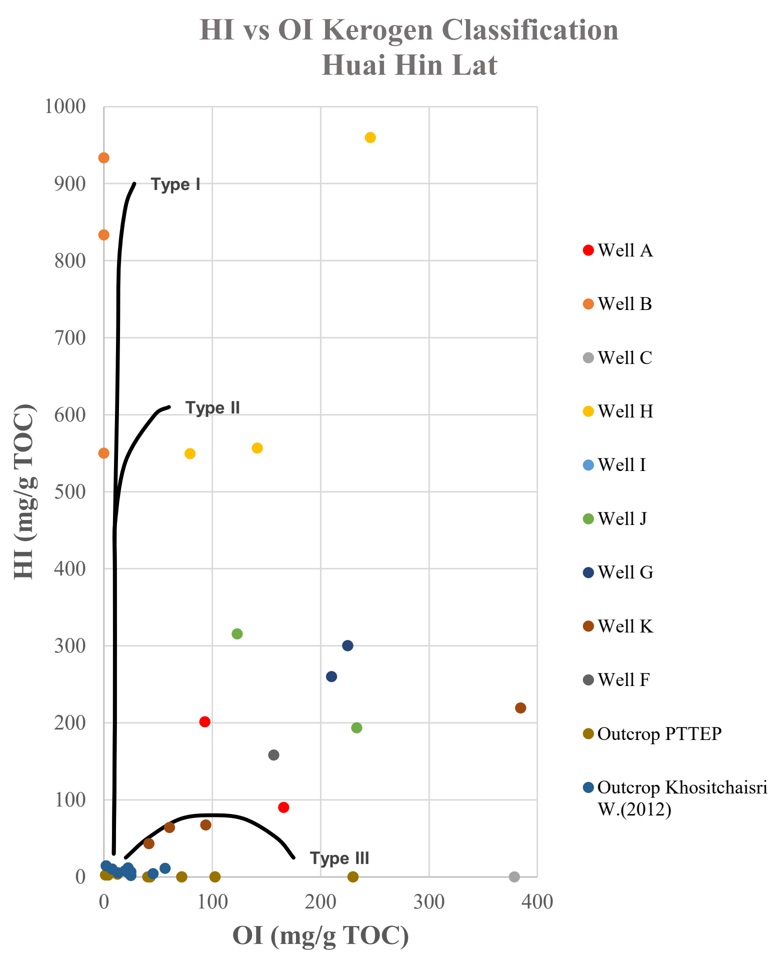


Figure 10 Plots of hydrogen index (HI) versus oxygen index (OI) showing kerogen quality of the Late Triassic samples, Huai Hin Lat Formation from nearby study area. See the well location in Figure 9.

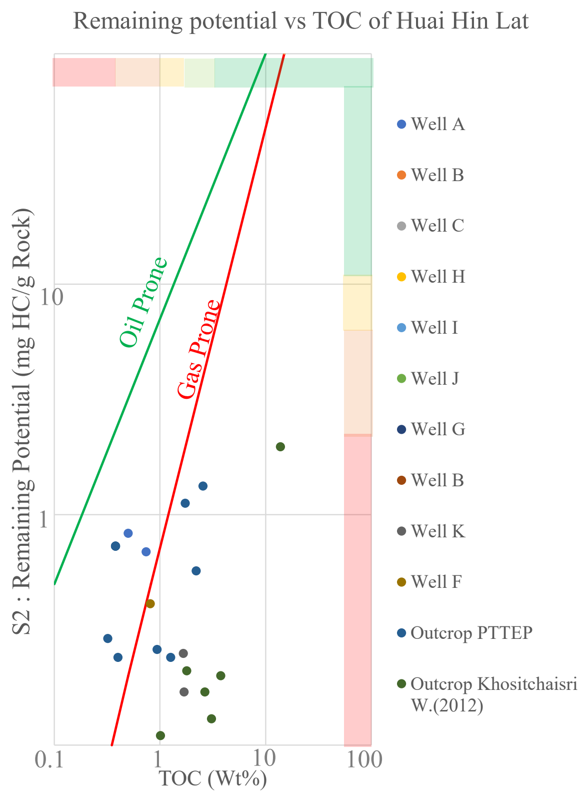


Figure 11 The plot of remaining hydrocarbon (S2) and TOC indicates that the studied samples have gas-prone potential and range from poor to good as potential source rocks. However, the low S2 values are a consequence of hydrocarbon generation through thermal maturity and the impact of various tectonic events in the study area. See well location in Figure 8.

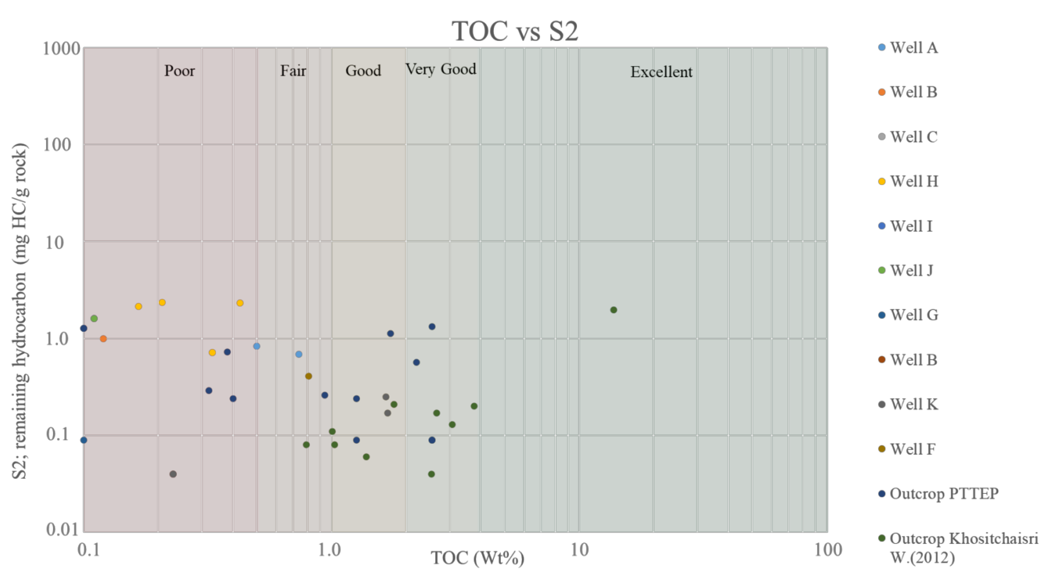


Figure 12 The plot of remaining hydrocarbon (S2, mgHC/g rock) versus TOC showing hydrocarbon generation potential of the source rock samples from the Huai Hin Lat Formation in the nearby study area. See well location in Figure 9.

The relationship between Tmax (Co) and depth for the studied samples in the study area (Figure 13) reveals values ranging from 330 to 450 °C indicating that the Huai Hin Lat Formation has reached a mature stage. However, it is important to note that the Tmax values may not accurately reflect the true maturity of the samples due to the low S2 values observed.

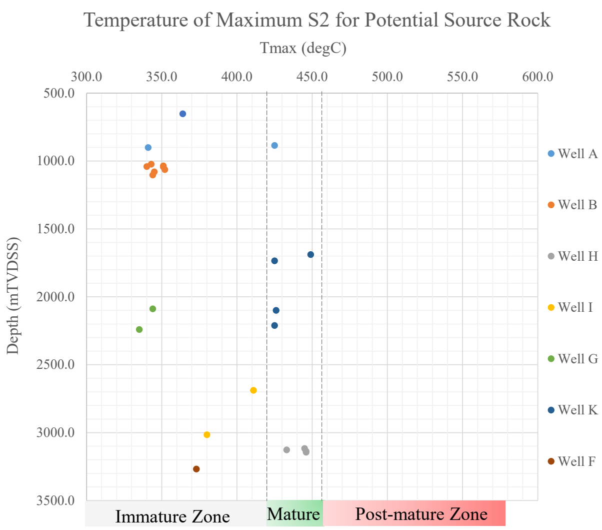


Figure 13 Plot of Tmax (Co) versus depths showing overall source rock samples in the study area are generally mature to over-mature. See well location in Figure 9.

Vitrinite Reflectance

The analysis revealed a wide range of Ro values for the well samples, ranging from 0.4 to 2.19, while the outcrop samples exhibited Ro values ranging from 0.6 to 2.0. Plotting the Ro values against depth demonstrated the presence of several trends that may be associated with uplift and erosion events (Figure 14). However, an overall increasing trend of Ro with depth was observed. The vitrinite reflectance analysis indicated that the study area exhibits high thermal maturity, with the samples already in the oil and gas windows. The vitrinite reflectance profiles for well samples indicated the occurrence of significant uplift and erosion processes (Figure 13). The data suggest that the study area has experienced considerable geological activity, resulting in the exposure of deeper rock Formations. Present-day estimates indicate that the samples failed within oil window extends to the surface, while the gas window is estimated to be at a depth of approximately 2000 m TVD (true vertical depth).

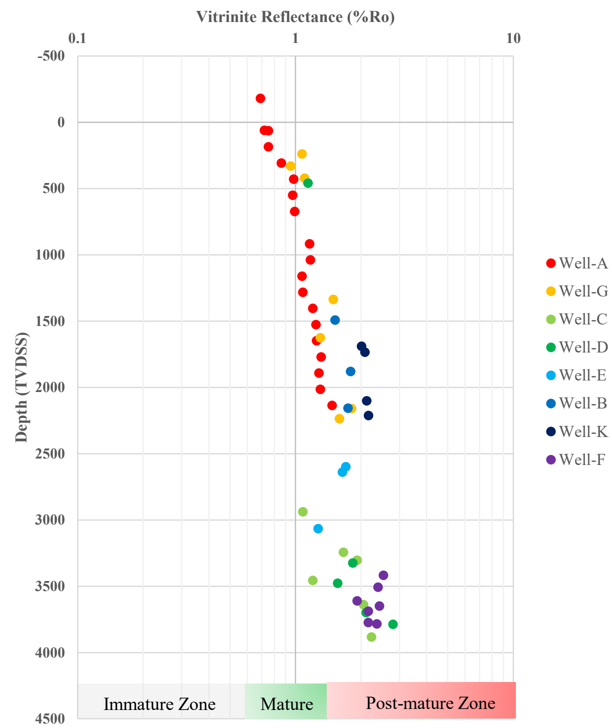


Figure 14 Plot of vitrinite reflectance data (Ro) versus depths showing thermal maturity stages of the source rock samples in the study area. See well location in Figure 9.

These findings suggest that the study area has undergone substantial geological transformations, including uplift and erosion, leading to increased thermal maturity. The presence of samples within the oil and gas windows indicates the potential for hydrocarbon generation and accumulation. Further analysis and modeling will be necessary to better understand the extent and distribution of hydrocarbon resources in the study area.

Biomarker

The Information presented in this study was derived from the plotting of Pr/n-C17 versus Ph/n-C17. The Pr/Ph ratios of the potential source units exhibited a range of 0.50 to 5.07 indicating a mixture of kerogen types II and III (Figure 15). Specifically, the Huai Hin Lat Formation demonstrated Pr/Ph ratios varying between 0.50 and 1.84, suggesting the preservation of organic matter under oxic to anoxic conditions in a transitional environment. This observation is supported by the elevated values of Pr/nC17 and lower Ph/n-C18. Furthermore, steranes (C27, C28, and C29) were employed to identify the depositional environment of the source rocks (Figure 16). The plotting results indicated that the Huai Hin Lat Formation is primarily associated with a shallow lacustrine environment.

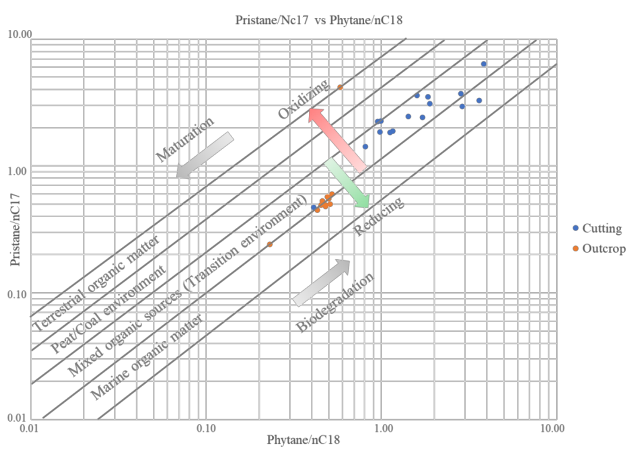


Figure 15 Phytane to n-C18 alkane (Ph/n-C18) vs pristane to n-C17 alkane (Pr/n-C17) ratios for source rock extracts.

Brittleness

The results revealed that the majority of the samples exhibited a significant presence of quartz-feldspar-mica (QFM) minerals, ranging from 12% to 76%. Carbonate minerals were also detected in the samples, with concentrations ranging from 5% to 70%. Additionally, clay minerals were identified in the samples, constituting 9% to 29% of the composition (Figure 17). This composition indicates a brittle deformation behavior, making the Formation suitable for hydraulic fracturing and shale gas production.

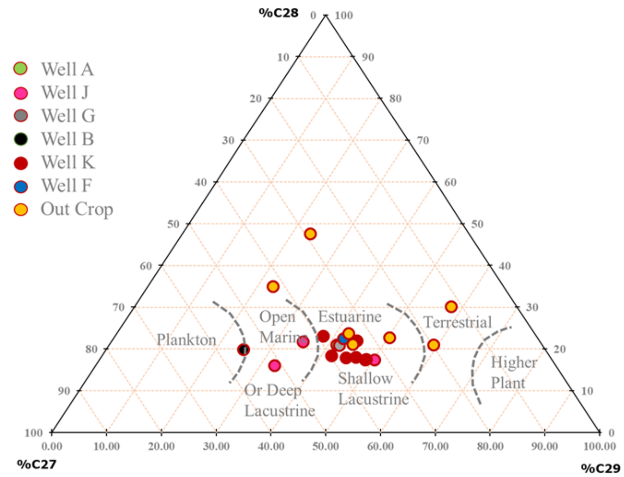


Figure 16 C27, C28, and C29 steranes plot showing the depositional environment of potential source rocks in Study area.

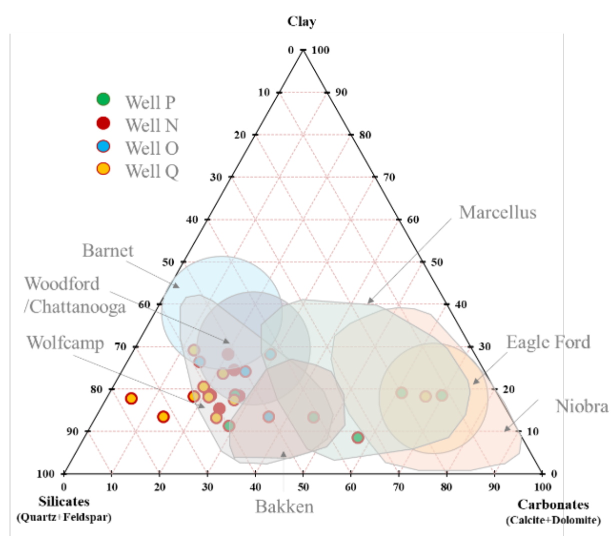


Figure 17 Mineral ternary plot comparing the Huai Hin Lat shale in study area with American analogues (modified after Brindle et al., 2015).

However, it is important to consider that the well locations and samples analyzed in this study may have been collected from a landward setting. Consequently, these samples might contain a lower proportion of clay minerals. It is expected that the Huai Hin Lat Formation in the basinward region may have a higher clay mineral content, which can significantly influence the rock's elastic properties and hydraulic fracturing potential.

4.4 Petroleum System Modeling

Through the integration of geological, geophysical, and geochemical analyses and the selection of appropriate input parameters, a comprehensive 2D petroleum system modeling was developed to assess the hydrocarbon generation and shale gas potential of the Huai Hin Lat Formation within the study area.

To calibrate and assign paleo-temperature and paleo-heat flow of the study area, vitrinite reflectance and bottom hole temperature data were used to assess the thermal maturity of the Huai Hin Lat rocks. One dimensional (1D) basin modeling was generated at pseudo-wells to represent burial history within the study area exhibiting the highest thickness of the Huai Hin Lat Formation and serving as representative basins (Figure 18). These pseudo-wells were instrumental in demonstrating the burial history, as well as the patterns of hydrocarbon generation and expulsion within the study area.

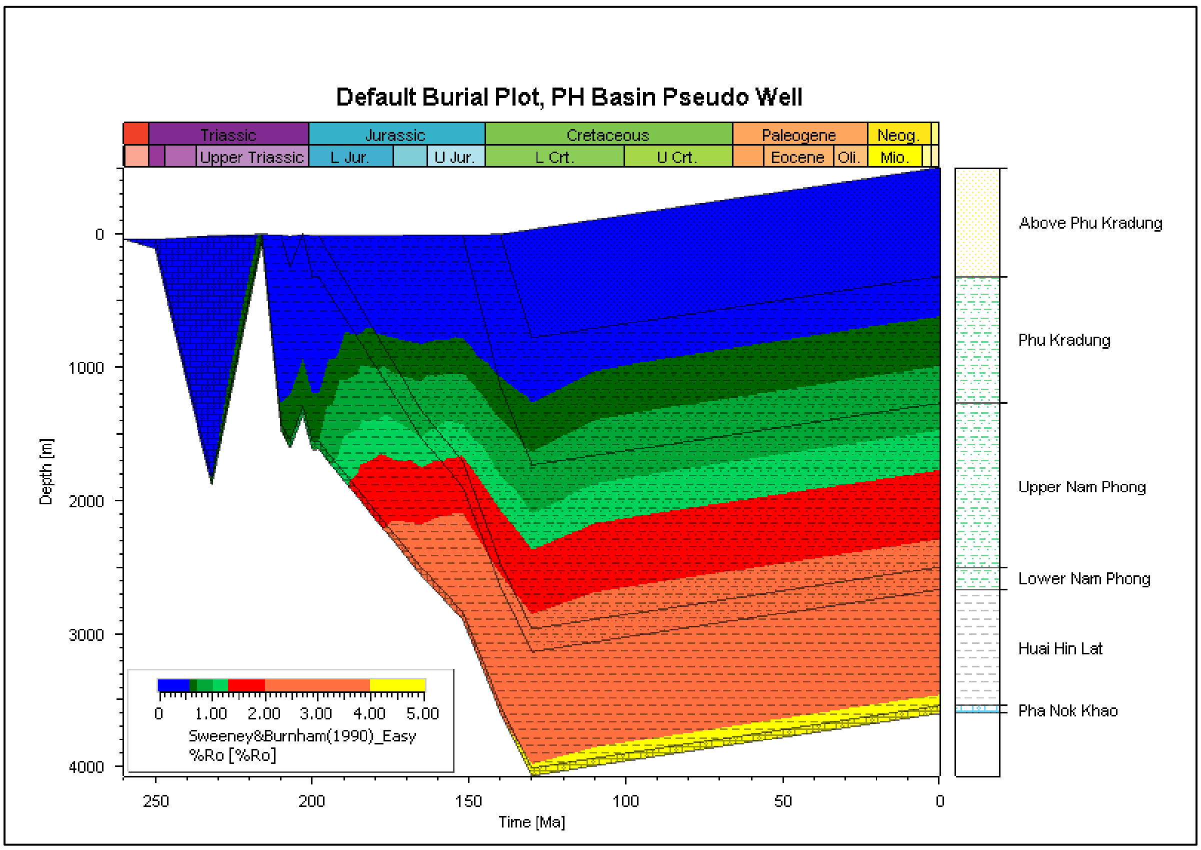


Figure 18 The 1D Petroleum system modeling from the pseudo well at basin center of the study area overlying with maturity.

Interpreted Basin Evolution

The tectonic evolution of the region has exerted a significant influence on the uplift, erosion, burial, and thermal history of the study area. To accurately predict the timing of hydrocarbon generation and expulsion, it is crucial to understand the burial (subsidence) and thermal histories.

Subsidence curves were constructed based on well profiles, utilizing formation thicknesses (present-day thickness) and lithological assignments derived from mud logs and composite well logs. Initially, the subsidence curves were developed for the well of interest by decompacting the sedimentary sections. Figure 16 displays the subsidence curves and the basin history filling for the representative pseudo well. This figure illustrates that during Late Permian period, sediments deposited in the shallow marine section underwent a relatively short burial history. Subsequently, the entire section experienced uplift, and approximately 1,500-2,000 m of sediments were eroded during the Indosinian I Orogeny, which occurred in the Early to Middle Triassic period.

Following the Indosinian I event, a Late Triassic fluvio-lacustrine Huai Hin Lat deposition took place, characterized by an unconformity associated with the Indosinian II Orogeny. Subsequently, thick sedimentary sections (ranging from 2,000-3,000 m) were deposited during the Late Triassic to Tertiary period (Figure 18). During this time, significant burial and compaction processes occurred, facilitating the generation of oil and gas in the study area. Approximately 40 million years ago, the collision between the Eurasia plate and the India plate gave rise to the Himalayan Orogeny, resulting in extensive uplift and erosion that affected approximately 1,800-2,400 m of the Cretaceous Khorat Group section in the study area.

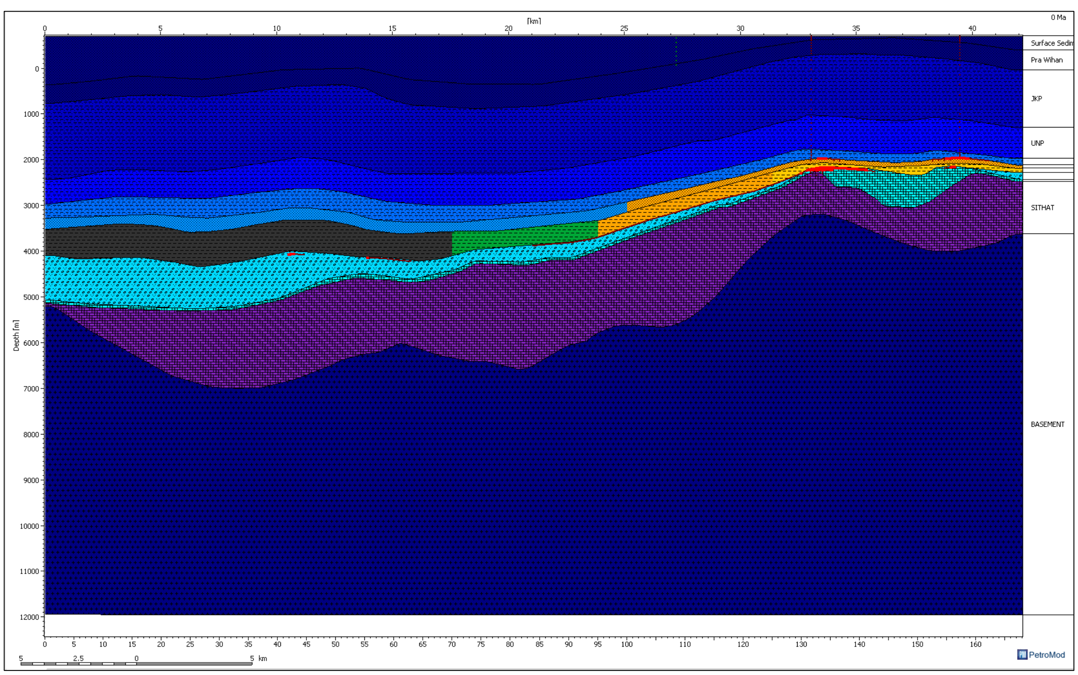


Figure 19 Present day simulation model of the selected seismic section illustrates gas accumulation locations in red areas.

Source Rock Maturity

The Huai Hin Lat Formation is characterized as being post-mature and overmature, reaching the dry gas and overmature window in the deepest parts of the basin at present day (Figure 19). The potential for oil generation is deemed unrealistic and not supported by the geochemical analysis data. The hydrocarbon maturation process, as indicated by present-day temperature, vitrinite reflectance (Sweeny & Burnham 1990), and transformation ratio models, increases with burial history, as observed in the depth profile (Figure 20). The hydrocarbon generation history of the source rocks within the model exhibits variations due to differences in thermal and burial history (Figure 20). Overall, the source rocks are assessed as being mature to overmature in terms of thermal maturity.

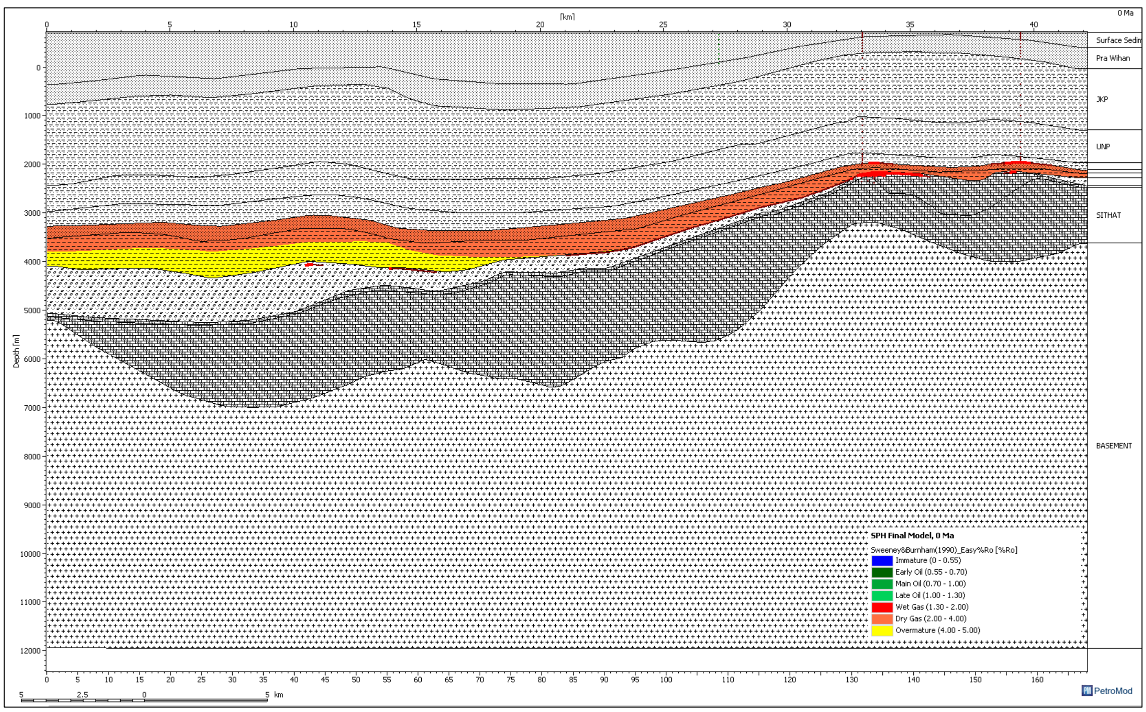


Figure 20 Present-day Huai Hin Lat source rock maturity from 2D petroleum system modeling in the study area, showing the source rock reaching dry gas and overmature window at the basin center.

Hydrocarbon Generation and Migration

The results of the modeled hydrocarbon generation and expulsion from the 2D petroleum system modeling indicate that the Late Triassic Huai Hin Lat source rock generates hydrocarbon during the Early Jurassic to Late Cretaceous period, approximately 200-80 million years ago. In this study area, hydrocarbon migration from the Huai Hin Lat source rock is primarily observed to occur vertically, both upward and downward, along the up-dip direction towards the Permian reservoirs. It is expected that the migration pathway follows permeable carrier beds in the up-dip direction. To determine the timing of petroleum generation and expulsion from Late Triassic source rocks, modeling was performed (Figure 22). The expulsion of hydrocarbons from this source rock occurred from the Early Jurassic to Late Cretaceous period, around 195-70 million years ago (Figure 22).

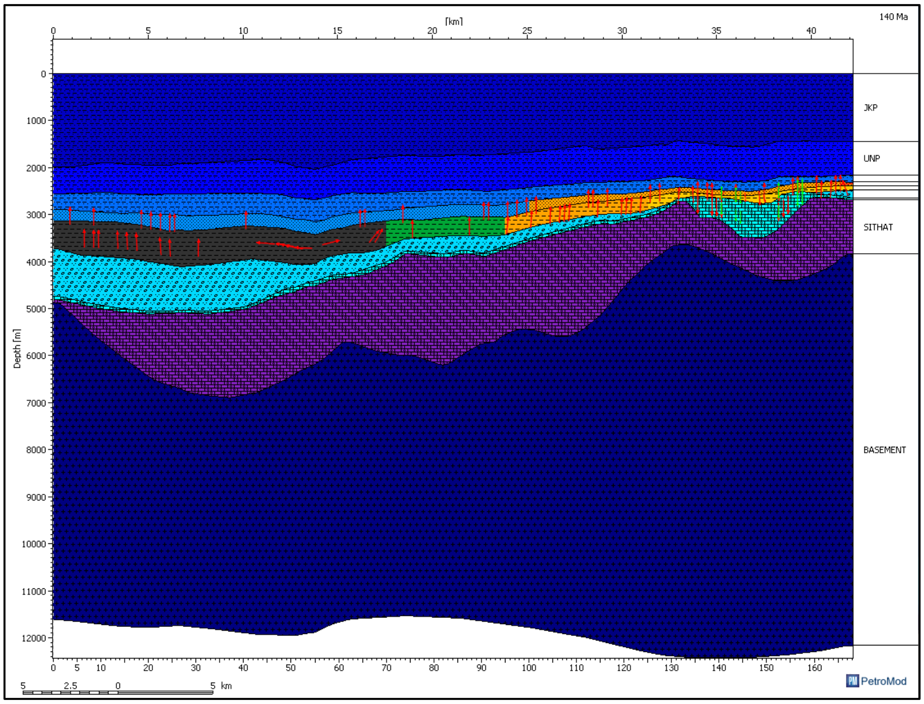


Figure 21 2D petroleum system modeling with migration vector during 140 Ma .

Shale gas potential and sweet spot area

According to the high maturation level and the current state of the Huai Hin Lat Formation entered the dry gas window since 175 Ma (Figure 22). The expulsion and transformation ratio models reveal that the Huai Hin Lat source rock has generated and expelled a significant volume of hydrocarbons. Consequently, there may not be a substantial remaining volume of hydrocarbons, particularly since the main generation unit in the Huai Hin Lat source rock is unit B, which is bounded by the lower unit (unit A) and upper unit (unit C) that exhibit higher inferred porosity. These surrounding units could potentially serve as carrier beds after the expulsion process. Therefore, the remaining volume available for shale gas in the Huai Hin Lat source rock is likely limited. Based on the thickness map of the Huai Hin Lat Formation, the sweet spot area can be identified as the region with the highest thickness within the study area.

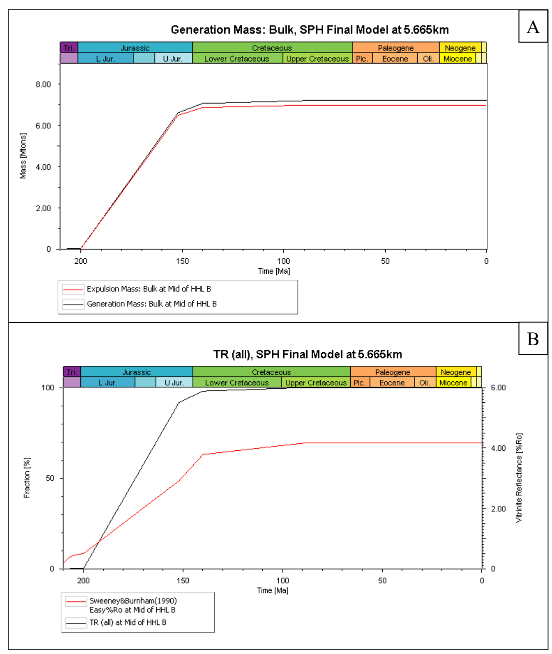


Figure 22 A) Generation mass from 2D petroleum system modeling of the Huai Hin Lat Formation at the basin center of the study area. B) Transformation ratio from 2D petroleum system modeling of the Huai Hin Lat Formation at the basin center of the study area.

In this area, the basin center, where the shale reaches its greatest thickness, is potentially reached the gas window and possibly in the overmature window due to its depth. According to the transformation model, this specific area exhibits a high level of hydrocarbon generation and expulsion (Figure 22).

Upon analyzing the anticipated lithology derived from the geological model and XRD outcomes, a conspicuous trend emerges, indicating an elevated shale proportion within the basin center as opposed to the higher structures.

Consequently, the basin center is anticipated to exhibit reduced suitability for hydraulic fracturing operations. Furthermore, incorporating factors such as the cut-off depth, thickness, total organic carbon (TOC), maturation level, and brittleness, it becomes feasible to identify the sweet spot region within the shale gas reservoir. The shale gas sweet spot is situated in the upper portions, away from basin center, delineating the area between the basin center and the Sinphuhorm Field (Figure 23).

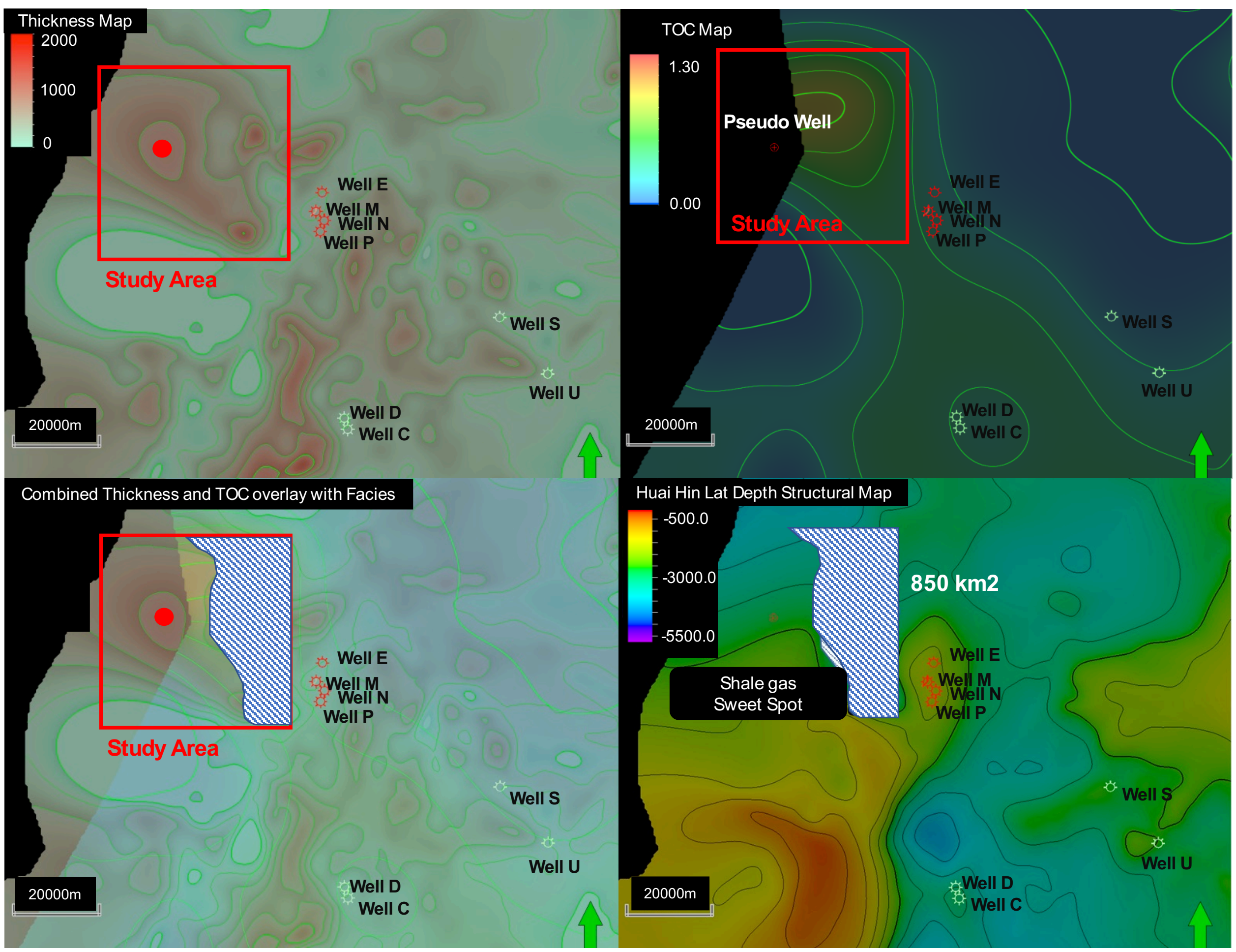


Figure 23 A) Thickness map of the Huai Hin Lat Formation with the study area in red rectangle. B) TOC Map of the Huai Hin Lat Formation with the study area in red rectangle C) Overlay of the Huai Hin Lat thickness map and TOC map for shale gas sweet spot identification D) the Huai Hin Lat depth structural map with sweet spot area.

5. Conclusions

The results obtained from the 2D petroleum system model provide valuable insights regarding the Late Triassic Huai Hin Lat Formation as a significant hydrocarbon source, owing to its substantial organic matter content in the form of organic shales and coals. These characteristics suggest a favorable generative potential ranging from good to excellent. The kerogen types present within these Formations have been identified as a mixture of types I and III, deposited in lacustrine environments under anoxic to suboxic conditions. Maturity data, including vitrinite reflectance and pyrolysis Tmax, indicate that the samples have reached a state of thermal maturity ranging from mature to over-mature for hydrocarbon generation. However, the utilization of HI and OI plots to identify the original kerogen type posed challenges due to the remarkably low S2, S3, and TOC values, as well as the presence of highly mature samples, which led to unreliable HI and OI estimations. Vitrinite reflectance values indicate a high level of thermal maturity within the study area, already situated within the oil and gas windows. Furthermore, the 2D basin model reveals that the source rocks in the study area have ceased the generation and expulsion of hydrocarbons due to thermal cooling events, such as uplift or erosion associated with the Himalayan Orogeny. Additionally, these source rocks have reached an overmature state, as indicated by the high vitrinite reflectance values, resulting in a diminished capacity for hydrocarbon generation and expulsion.

In the basin center, where an extremely high maturity level and a predominance of shale content are expected based on the lateral facies changes derived from the geological model and the X-ray diffraction (XRD) results, it is likely that this region may be less suitable for hydraulic fracturing. Considering these factors, the shale gas sweet spot is situated in the upper portions, distinctly removed from the basin center. Specifically, it encompasses the region delineated between the basin center and the Sinphuhorm Field.

Acknowledgment

I would like to extend my sincere appreciation and gratitude to PTT Exploration and Production Company Limited for their generous contribution to the database, which has greatly enriched the data analysis and findings of this research. Furthermore, I would like to acknowledge Schlumberger for providing access to the Petromod and Petrel Software. Additionally, I am deeply grateful to Monporn Mesdakom and Chayarus Centhonglang for their significant contributions to my research.

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