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Hydrocarbon Generation History of Tertiary Source Rocks in Phu Khanh Basin, Offshore Vietnam

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Abstract

The source rock maturity and the hydrocarbon generation history are evaluated in the deepwater Phu Khanh Basin. The average values of heat flow, paleo water depth, and surface-water interface temperatures range from 50.80–61.69 mW/m^2, 150-3,500 m, and 2.3^0-25^{0}C, respectively. The Oligocene and Lower–Middle Miocene source rocks are presented. The Oligocene source rock is derived from the lacustrine environment; it is mature to overmature in the Southwest part of the Phu Yen Depression. The main oil phase started in the Early Miocene, and the amount of wet gas occurred only at the bottom part. The Lower-Middle Miocene source rock has been immature in both the Southwest and Northeast part of the Phu Yen Depression. Based on the geochemical analysis, these source rocks were predominantly a mixture of type II and type III kerogens. The total organic carbon and the hydrogen index values range from 1.8-2.5 % and 250-320 mg/g, respectively. The results can help define reservoir locations for future field development planning in the Phu Khanh Basin.

INTRODUCTION

The Phu Khanh Basin is off the eastern coast of Central Vietnam, stretching 250 km length in north-south and 50–75 km in east-west directions. It is a narrow, elongated basin extending from 11°N to 14°N latitude and from 109°20'E to 111°E longitude (Bojesen-Koefoed et al., 2005; H. T. Nguyen et al., 2012). The shallow marine region of the western section of the basin is less than 300 m in depth. The depth increases gradually from 300 m to 4,000 m below sea level toward the east. The basin is surrounded by N–S (meridian fault 110°) and NW–SE fault systems (along the spreading axis of the South China Sea), which are separated by different structural segments (Savva et al., 2013). The tectonic structures classified into five units: Da Nang Shear Zone, Phan Rang Shelf, Phu Yen Depression, Tuy Hoa Shear Zone, and Khanh Hoa Swell (H. Nguyen, 2009; Tran et al., 2019) (See Figure 1).

Based on previous explorations, including the 1972 gravity survey and the 2008 seismic survey (Maingarm et al., 2011), three exploration wells (HT-1X, CMT-1X in 2009, and TH-1X in 2011) were drilled the uplift blocks in shallow water. However, only the CMT-1X showed oil and gas in the Miocene carbonate reservoir (H. T. Nguyen et al., 2012), as evidenced by the Phu Khanh Basin's petroleum potential. Source rock properties are described on wells data in shallow water as a reference to the Deepwater area.

This study aims at providing recent progress on a comprehensive history of hydrocarbon generation in both SW and NE of the deepwater Phu Khanh Basin. The hydrocarbon generation process will be reconstructed along in the SW-NE geological cross-section from shallow water to deep water. The source rock properties in the Deepwater area were described using existing wells in adjacent regions. Paleo heat flow, paleo-water depth (PWD), and paleo sediment-water interface temperature (SWIT) are reconstructed as ancient climatic conditions to facilitate hydrocarbon production. It reveals an initial picture of basin

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evolution, the maturity of source rock, hydrocarbon generation in SW, and NE of Vietnam's deepwater basin.

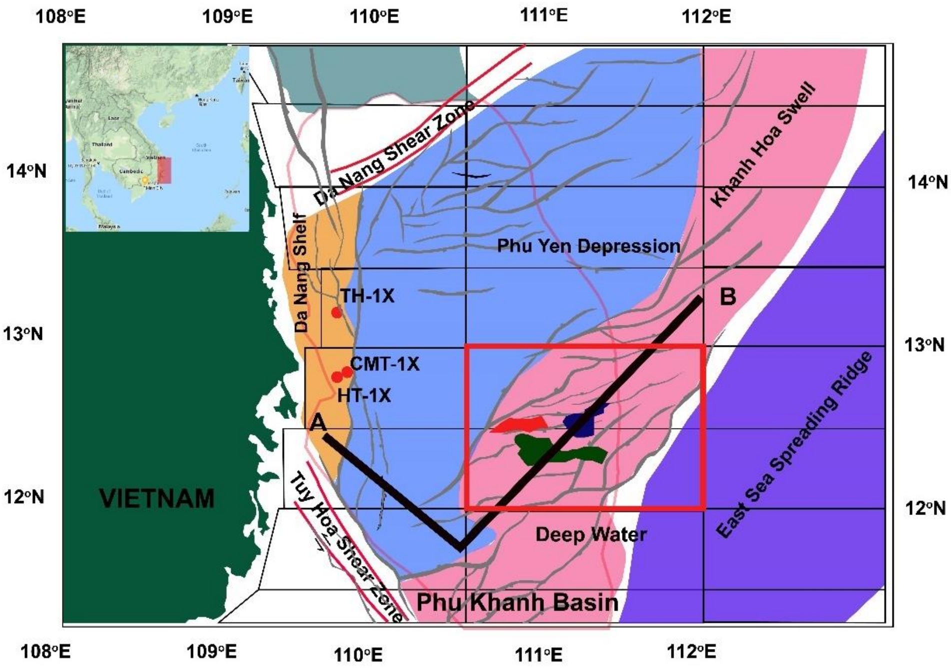

Figure 1. Location of the study area and major tectonic structures of the Phu Khanh Basin

METHODOLOGY

Source Rock Parameter

There are no well data in the deepwater area. A similar approach matches the kerogen type based on the Cenozoic sedimentary basins and adjacent regions, where the formation mechanisms of the Cuu Long, Nam Con Son, and Phu Khanh Basins are similar. Therefore, source rock properties have the same origin. The TOC and HI values of Oligocene source rock in the Nam Con Son basin correspond to 1.8%, 320 mg/g, which can be taken as the input parameters.

According to Neogene sedimentary rocks' statistics in Borneo (Indonesia) and Malaysia's deep-sea have a considerably high TOC/ HI value (Weimer et al., 2006). Combined with the hydrocarbon findings in Miocene sediments from TH-1X and CMT-1X wells, the average values of TOC / HI of Lower – Middle Miocene source rock was selected at a minimum of 2/250.

Geological Properties

Each dataset of well was used to establish a relationship between the seismic facies and lithofacies. The correlation between the lithological components of the TH-1X, CMT-1X, and HT-1X wells and the interpreted seismic sections were divided into six facies: Siltstone, Claystone, Volcanic Sandstone, Limestone, Sandstone, and Granite (Table 1).

Table 1. Interpreted horizons, geological age, and lithology

Interpreted horizon	Layer	Age (Ma)	Lithology (Facies)
Near Top Pliocene	Plio-Pleistocene	2.58	75-95% Claystone; 5-25% Sandstone
Near Top Upper Miocene	Upper Miocene	5.33	Claystone/shale with occasional thinly interbedded sandstone and siltstone
Near Top Middle Miocene	Middle Miocene	11.63	90-100% Claystone; 0-10% Sandstone; 5% Siltstone
Near Top Lower Miocene	Lower Miocene	21	Predominantly limestone with dolomitic zones and thin shale interbeds
Near Top Oligocene	Eocene–Oligocene	23.03	75% Shale, 25% Sand
Near Top Basement	Basement	56	Basement

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Boundary Conditions

The initial boundary conditions of heat flow, paleo-water depth, and sediment-water interface temperature play a significant role in building an evolutionary history of the basin and significantly affect the source rock's thermal maturity generating petroleum.

1. Heat Flow

The 110° meridian fault reactivated during Middle to Late Miocene due to the South China Sea spreading seafloor, leading to sub-basins' formation filled up the Oligocene-Lower Miocene sediments. Besides, the heat plume moved upward into the seabed, leading to the appearance of volcanic activities during the Pleistocene. The heat flow value dropped rapidly since the Middle Miocene times and remained the lowest value up to the present day. This is due to a quick crustal cooling and a rapid shrinkage accompanied by the thermal subsidence stage. Using a trial-and-error approach, the average values of heat flow in deepwater could have been in the range of 50.80–61.69 mW/m^2. (Figure 2)

2. Paleo Water Depth

Paleo-water depth (PWD) fluctuated within the range of 50 m and 200 m in the Oligocene-Early Miocene (Miller et al., 2004) with lacustrine-derived sediment accumulating in the sub-basins. The 110° meridian fault strike-slip movement and stretching reactivated during Middle-Late Miocene, causing a sea level to fall deeper than 2,000 m. Volcanic activities and thermal subsidence have continued during Pliocene-Pleistocene, resulting in a sea-level reduction of more than 3,500 m (Figure 3).

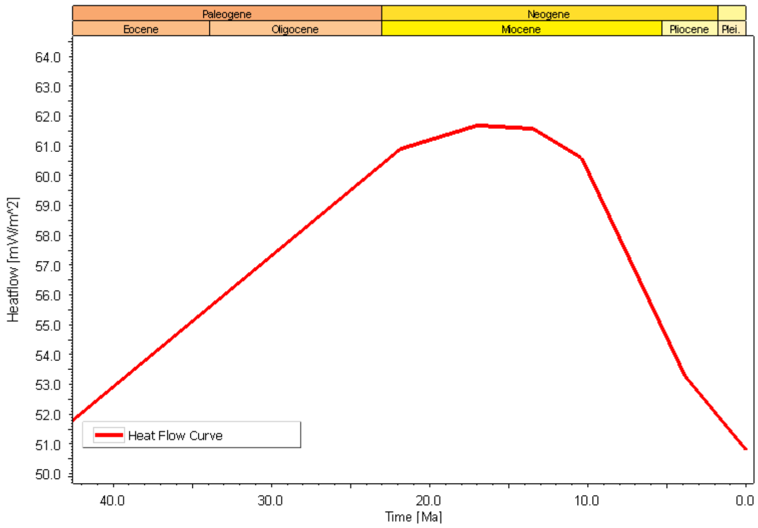

Figure 2. Heat flow diagram of the Phu Khanh Basin

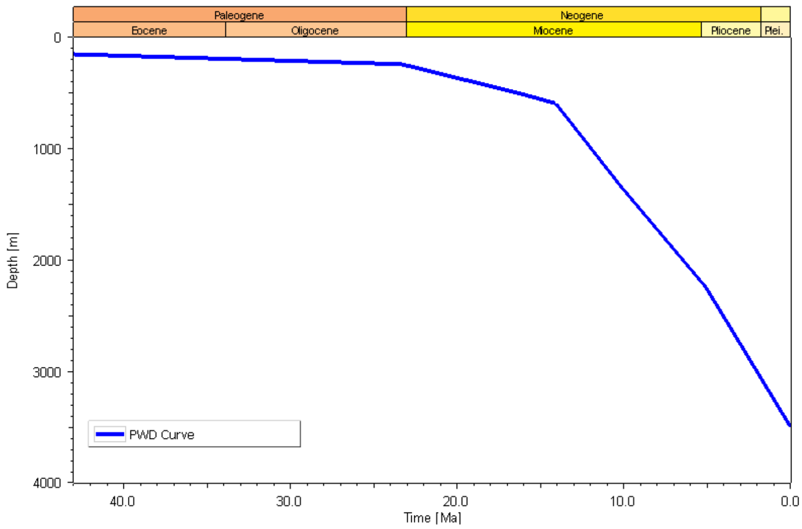

Figure 3. Paleo-water depth diagram of the Phu Khanh Basin

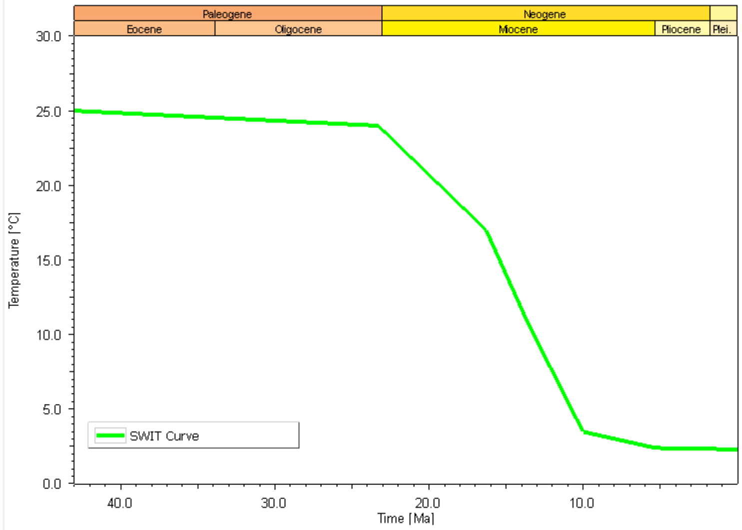

Figure 4. Sediment water interface temperature diagram of the Phu Khanh Basin

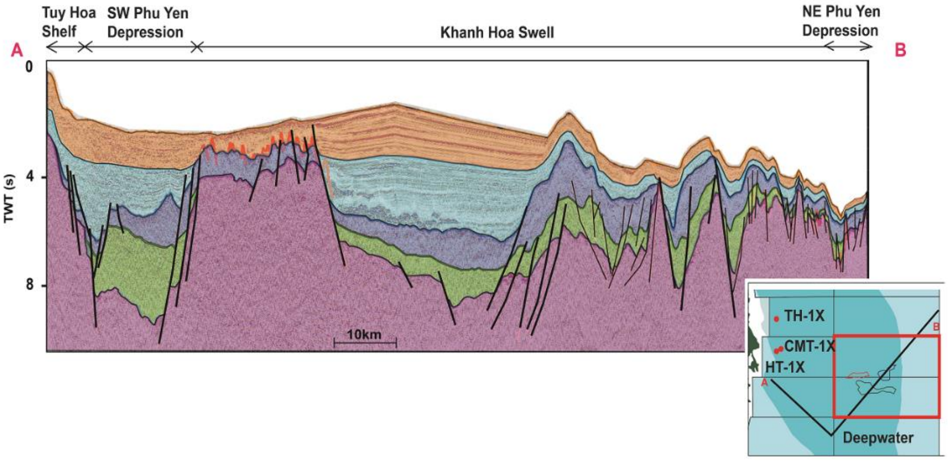

Figure 5. Seismic section surveyed along the AB route

3. Sediment Water Interface Temperature

Sediment water interface temperature (SWIT) depends on the change of sea level depth. However, the temperature decreases rapidly with sea-level increases in depth. Because of the complex changes in the paleo-sea level depth during the Middle Miocene–Pleistocene, the SWIT value changed accordingly. When the seawater depth dropped below 3,500 m, the SWIT was reduced to less than 2.5 °C (Figure 4).

Seismic Parameters

The 2D seismic sections were interpreted to have six main horizons: Seabed, Near Top Pliocene, Near Top Upper Miocene, Mid Miocene Unconformity, Near Top Oligocene, and Near Top Basement. A geological section of the AB route was crossed for particular structural elements that include structural uplift/anticline, wings, the Phu Yen Depression epicentre, and Khanh Hoa swell. Structural/stratigraphic traps formed in a four-way-closure trap for oil and gas accumulation and prospect structures (Figure 5).

RESULT AND DISCUSSION

The burial history was reconstructed based on the pseudo-wells located on the epicentre of the Phu Yen Depression. A total of subsidence depth was calculated about 2,600 m in depth during Paleocene - Oligocene. The subsidence rate increased gradually since Late Oligocene - Early Miocene because of the beginning spreading seafloor in the South China Sea. The geological record indicated that uplifts, grabens, and erosions had existed during that time. Since the Middle Miocene, the basin has experienced the highest subsidence rates to its present-day burial depth of about 10,000 m. However, the fast subsidence rates since the Late Miocene prevented sufficient sediment accumulation from filling the subsidence gap.

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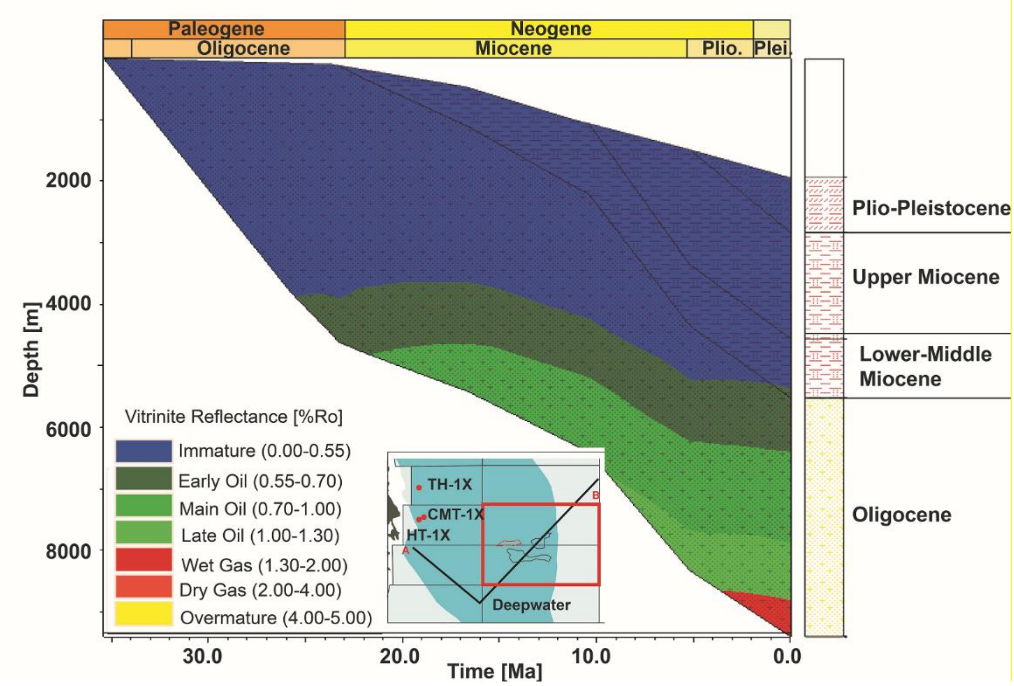

Figure 6. Burial curve with maturity overlays for pseudo-well in Phu Yen Depression

Table 2. Detailed results of hydrocarbon generation zones in the Phu Khanh Basin

Source Rock	Time (Ma)	Depth (m)	Zone
Oligocene	21.61 (Early Miocene) – present	4,817-8,823	Main Oil
	9.27 (Late Miocene) – present	6,811-8,823	
	3.6 (Pliocene) - present	8,637-9388	Wet Gas
Lower-Middle Miocene	Immature		
The upper part of Oligocene source rocks oil had been released out extremely			
The lower part of Oligocene source rocks generated wet gas.			

In the Southwestern part of Phu Yen depression, the Oligocene source rocks had produced hydrocarbon since Early Miocene (21.61 Ma) at a depth of 4,817m and have continued to this day. However, a peak hydrocarbon generation had occurred strongly since the Late Miocene (9.27 Ma) at a depth of 6,811 m. (Figure 6, Table 2). The upper part of the Oligocene source rock has been in the oil window to the present day, and the lower part has been generating wet gas at a depth of 8,637 m since Pliocene (3.6 Ma) (Figure 6, Table 2). Most of the uplifted areas and flanks at potential structures were still immature for hydrocarbon generation.

Due to different heat flow histories, source rock in NW was immature until Middle Miocene. These areas had been buried to depths more than 3500 m and were in the early oil generation phase at 11.2 Ma (Figure 7). Heat flow in these areas increased slowly because of the minor effect of the South China Sea floor spreading. The primary oil is continuing at present. The transformation rate of organic matter occurred gradually because of the low value of heat flow in the NW sub-basin part. The Lower-Middle Miocene source rock has been immature in both SW and NE part of the Phu Yen Depression.

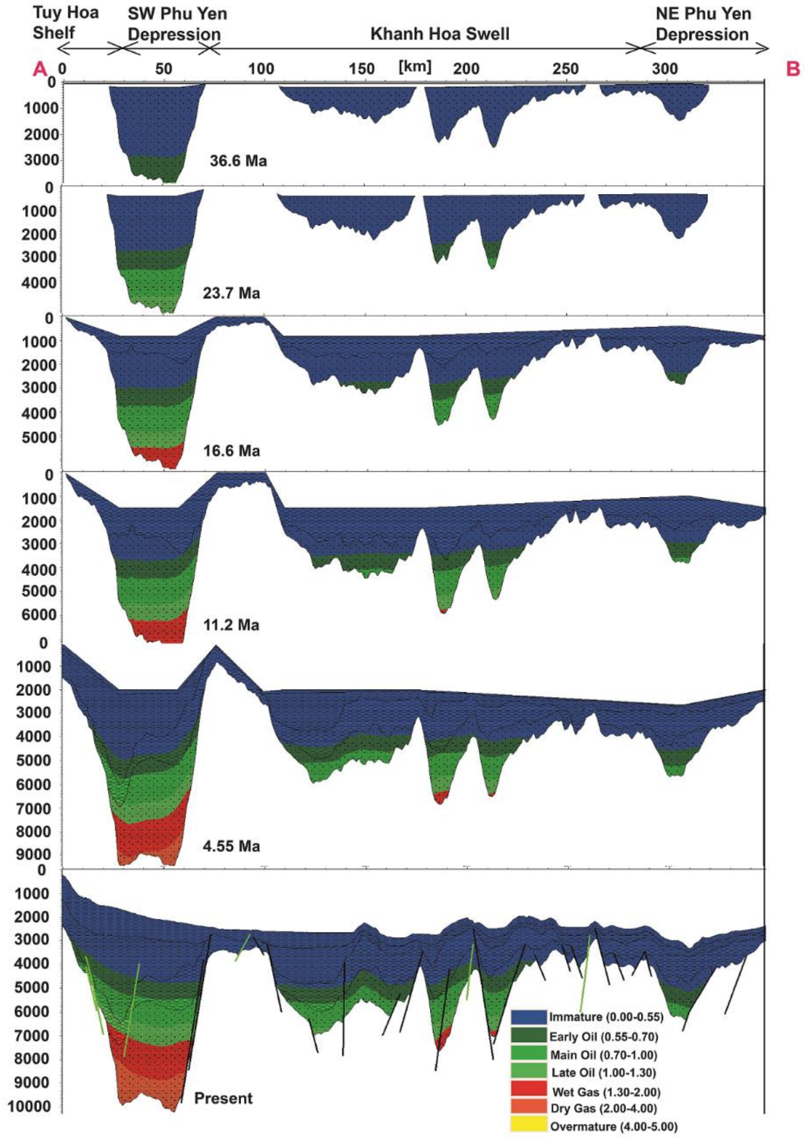

Figure 7. Hydrocarbon generation history along the AB route

CONCLUSION

This study analysed that the Phu Khanh Basin consists of two main source rock units: the Oligocene and Lower–Middle Miocene source rocks. The Oligocene source rocks were derived from clastic and lacustrine environments. The organic matter dominated a mixture of type II-III kerogen, which mostly produced oil and gas. The Oligocene source rock of the SW Phu Yen Depression had undergone from mature to overmature under varying paleo-heat flow. The primary oil-producing phase occurred from the Early Miocene (21.56 Ma) to the present-day, and rapid subsidence of Phu Khanh Basin could be attributed to seafloor spreading in the South China Sea. At present, these source rocks in SW Phu Yen Depression have still generating wet gas since Pliocene (3.6 Ma). The maturity of Oligocene source rock in NE Phu Yen Depression had occurred slower than those in the SW Phu Yen Depression. The main oil phase began in the Late Miocene in the NE Phu Yen Depression. The Lower-Middle Miocene source rock has been immature in both SW and NE part of the Phu Yen Depression.

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