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The Milestone of Cambodian First Oil Production in the Khmer Basin, Gulf of Thailand

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Abstract

As an ASEAN member country, Cambodia is the eighth country to produce oil from its maritime water in late 2020. The first oil was produced from Cambodian Block A (CBA) which covers most of the Khmer basin, located in the east and in the north of producing oil and gas Pattani and Malay basin respectively, in the Gulf of Thailand (GoT). Before being an oil-producing country, Cambodia has been involved in a long history of exploration activities since the 1970s with international companies including Elf-Erap, Marine Associate, Enterprise, Campex, Premier, etc. The first phase of petroleum development was initiated by Chevron Texaco in 2010 when this US company submitted the Petroleum Permit Application (PPA) to the government of Cambodia. The company failed to reach an agreement with the government on revenue sharing, then KrisEnergy bought out the working interest in 2014 and became the only operator of CBA. A justified Mini Phase 1A was operated by KrisEnergy to flow the oil from six production wells in the Apsara area where there is still a high risk of geological information and time constrain. Apsara area which covers the most prospective petroleum exploration geological trend in Cambodian water was built a minimal facility platform and used the production barge, Ingenium II, to separate the reservoir fluids. As long as the accumulative oil production reached about 300,000 bbl for about five months, the operator of CBA went into the liquidation. In the primary plan, this initial phase was expected to produce 7500 bopd at the peak, however it actually produced the oil less than double in the end. This situation indicated the underperformance of Mini Phase 1A, which resulted in a huge declination of each well capacity. This underperformance of Mini Phase 1A seemed express clearly the results of the uncertainties of petroleum formation, the complexities of the particular reservoir properties in the CBA and the inappropriate method of Mini Phase 1A. This paper synthesizes the existing literature, and the technical reports to reassess the geology, basin evolution, and reservoir characteristics of the CBA, especially the Apsara oil field. This review could be a help to disseminate of the update the CBA for the petroleum business companies and for academic in the purpose of researches.

Keywords

Khmer Basin, Khmer Ridge, Apsara Oil Field, Petroleum, Cambodia

1. Introduction

Cambodia has just achieved its first oil production stage since twice attempts failed. On December 28, 2020, the Prime Minister announced officially the first drop of Cambodian crude oil was pumped successfully from its exclusive seawater by KrisEnergy [1] [2]. It is about fifty years to become an oil-producing country since many international companies have explored hydrocarbon resources through different political regimes.

The first oil was produced from Cambodia Block A (CBA) which covers most of the Khmer basin, in the Gulf of Thailand (GoT). KrisEnergy, the operator of CBA, planned to develop first the most advanced exploration trend, namely the Apsara area, which is situated in the northeastern section of the CBA concession. This Apsara oil trend is one of the seven geological trends where there are potential for oil and gas to be trapped in CBA [3] and has been formally declared the commercial quantities of oil in 2010 by Chevron Texaco [4].

The original Petroleum Permit Application (PPA) of Chevron Texaco was designed in 2010 for a phase field development plan in which the initial phase 1A comprised one production mini platform with twenty-two production wells and was estimated to produce the oil at the peak 7500 bopd out of the recoverable oil of 8.6 mmbbl from this Area [2] [4]. In subsequent circumstances, KrisEnergy became the operator of CBA in 2014 and adjusted the original PPA for dealing with the government in order to move forward to the production stage. Mini Phase 1A was finally adopted for the flow of Cambodian first drop as soon as the new PPA of KrisEnergy was approved in 2017 by the government of Cambodia. The Mini Phase 1A in the current PPA was simplified to an unman mini platform that accommodated the mini facilities with a maximum of six production wells [1].

The expectations of both Chevron Texaco and KrisEnergy were to commence the first Phase to evaluate whether the reservoir performance would be appropriate with the exploratory estimation in the Apsara oil field. According to the reassessing drilling wells by Chevron Texaco in 2007, it was concluded that the oil accumulation in CBA was much less than the previous estimation lead to initiate a lower risk method of three phases (1A, 1B, and 1C) for oil field development in CBA [4]. In addition, KrisEnergy which was a marginal field development company deployed the lowest risk Mini Phase 1A due to the awareness of high-level uncertainty surrounding the oil reserves and did not expect to produce economically within this phase on its own [2] [4].

Since the beginning of the offshore activity in the 1970s, it took forty years to identify the Khmer Basin within seven prospective trends and about another ten years to discover the first economical petroleum reservoir, the Apsara area. In the early 1970s, a French oil company, Elf-Erap, shot the first seismic survey and achieved the study drill of three wells in the early acreages [5] [6] (**Figure 1(a)**). After the collapse of Khmer Rouge regime, the Cambodian government divided the offshore licenses into seven blocks (block I-VII) [5] [7] where 2D, 3D seismic, and nine explorational drills were conducted by Enterprise, Campex, and Premiere in their block licenses (**Figure 1(b)**). These companies decided to give up at the end when world oil price slumped down and left these block licenses to be free. In 2002 Chevron Texaco came and signed the production sharing agreement with the government to explore and extract the hydrocarbon resources in CBA.

The geological formation of the Khmer Basin, consisting of the CBA, in the GoT is reported many similarities to other Thai, Malaysian and Vietnamese Basins which lie to the west, south and east respectively [8]. However, the degree of success of first oil involved many challenges of operatorship and the diverse geological factors that affect the petroleum formation and hydrocarbon accumulation. By knowing the complexities and uncertainties of the particular geological characteristics including age and type of source rock, age and type of

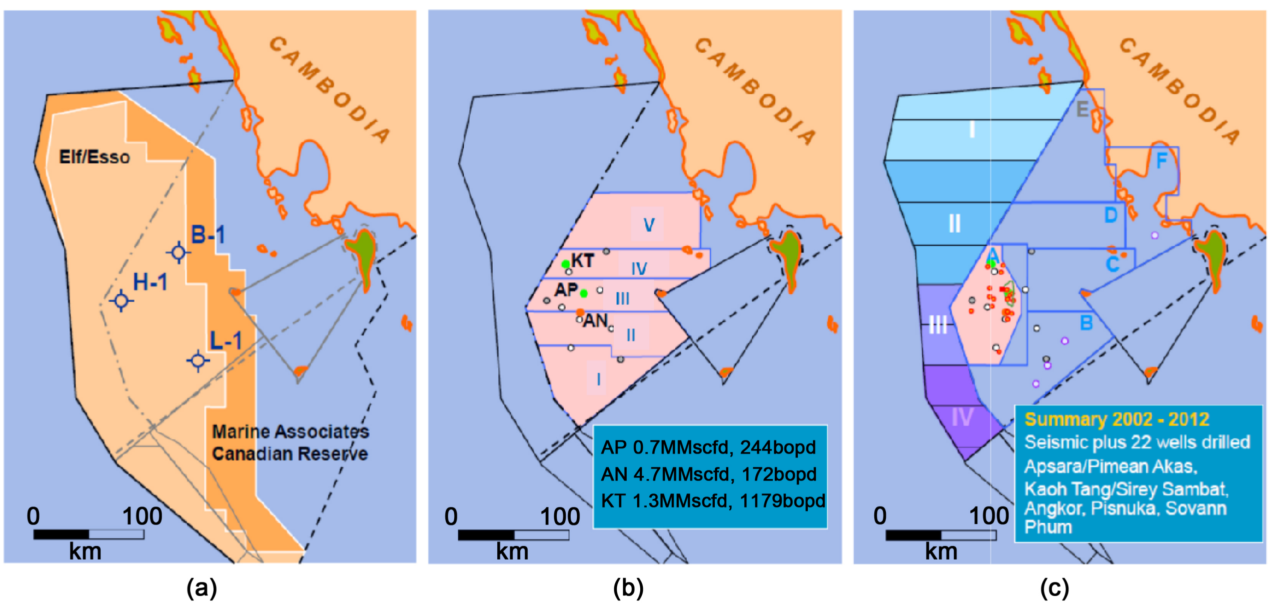


Figure 1. Block license modifications based on the continental shelf claims, geological discoveries, and hydrocarbon potential during 1972-2002. (a) Cambodia-Cambodian Shelf Concessions in 1975; (b) The seven offshore blocks after Cambodia-Russia geologists studied the geological and geophysical information to identify the basins entire the country in 1987 and (c) The offshore blocks were revised and divided into 6 blocks in 2002.

reservoir rocks, structural trapping styles and the hydrocarbon reservoirs in the offshore Cambodia through exploration programs, time and huge budget were necessarily needed in order to reduce risks and conclude the oil more confident [9] [10] [11].

Few sources of technical report can be accessed through the purposes of academic research and knowledge sharing to review for this paper. The General Department of Petroleum (GDP) of the Ministry of Mines and Energy (MME) is a primary channel for knowledge sharing and the informative references. In addition, the technical reports of operators, consultants, and academic researchers are also resourceful for the reviews even if some critical information is partially disclosed regarding to the restrictions of subsurface geology of Cambodia, especially the results of oil and gas exploration [12].

This paper reviews comprehensively the relevant research articles related to oil and gas in the GoT, and the exploration activities in Cambodian water from the 1970s to 2022s through many exploration programs including seismic surveys, drilling wells, and the interpretation in the paucity of both published information and exploration data availability. There have been reports of the formation of the Khmer Basin with the earlier assumptions, then, followed by reassessments and detailed studies to figure out a more certain geological formation, petroleum system, chemical and physical properties of the rock, and the circumstance of choosing the method to flow the first oil. The review also aims to provide the concrete information of Cambodian oil industry which will be the dissemination to the international oil industry the frontier nature of oil and gas and provide a basis for further study.

2. History of the Offshore Cambodia Exploration

2.1. The Period of 1970-1987

Based on Blanche & Blanche, the early exploration activities in Cambodia offshore were commenced significantly in the early 1970s when the government granted the rights (under the Mining Law of 1968) to 80,000 km^2 of Cambodian shelf area (**Figure 1(a)**) to Elf du Cambodge [6]. At the initial exploration period of 5 years, Elf acquired 2880 km of seismic line and accomplished a wildcat well in 1971, called H-1 where reached a total depth of 2437 m and encountered oil and gas in the upper unit. However, other reports expressed the absence of oil and gas within this well [13] [14] [15].

In 1973 Marine Associate (Hong Kong) Ltd. acquired a 17,000 km^2 concession in the Cambodian territorial sea (**Figure 1(a)**), a portion of which covered the original acreage of Elf and finished the 1992 km of seismic in its concession. In 1973 Elf and Esso also conducted a joint marine seismic survey of a total of 2159 km and decided to drill two more wells in 1974, called L-1 (TD 1714 m) and the B-1-1 (TD 1983 m). Both wells were completed as tight holes but were found to be dry. Vysotsky *et al.* (1994) reported that Well H-1 was drilled to a depth of

2665 m in 1972, Well L-1 reached 1875 m and Well B-1 reached 2169 m in 1974 (**Figure 1(a)**) [16]. In 1973 Marine Associate farmed out 75%, within which Canadian Reserve Oil and Gas Ltd. held 51.5% and completed a 1994 km seismic survey in 1974.

During 1970-1974, a number of US and Canadian companies, together with the French Elf-Erap shot approximately 7000 km of seismic surveys on the Cambodian Shelf, and three nonproducing wells were drilled, totaling 6709 m. The following year in 1975, the fall of Phnom Penh to the Khmer Rouge regime made both onshore and offshore exploration be very difficult. Thus, there have been no reported exploration activities for about 12 years [6].

2.2. The Period of 1987-2002

Until 1987 Russian and Cambodian geologists conducted geological and geophysical investigations (a regional grid of seismic lines) and illustrated the mapping of sedimentary basins in the country [14]. After this reconnaissance study, the Cambodian government announced a bidding round for the interested companies. The offshore blocks were awarded to international companies such as Enterprise (blocks I & II), Campex (block III), Premier (block IV) [15] and Nawa (Block V) [5], as shown in **Figure 1(b)**.

From 1992 to 1998, 2D and 3D seismic surveys were acquired over all four Blocks and a number of wells were drilled as a result. Of these, Angkor-1 (by Enterprise 1994), Apsara-1 (by Campex 1993), Da-1 (by Enterprise 1996), Devada-1 (by Campex 1994), Kaoh Tang-1 (by Premier 1994), Poulo Wai-1 (by Campex 1996), and Preah Khan-1 (by Enterprise 1996), Bayon-1 (by Enterprise 1996), Kaoh Pring-1 (by Idemistsu 1998) were included as study wells [5] [13] [14] [15] [17]. All four companies encountered varying degrees of success in their exploration programs. In 1997 Woodside was awarded 2 offshore Blocks (Block V and Block VI) and exploration activity commenced seismic 5000 km^2 in mid late 1998 [15]. In the circumstance of world oil prices slumped, all license holders relinquished their blocks by the end of 1998.

Woodside entered into a Study Agreement with the Cambodian National Petroleum Authority (CNPA) in 1999 covering Block I-IV and VII. The purpose of the study is to determine the prospectively of those Blocks and the feasibility of the developing the discovered reserves [15]. The result of the Study had shown that there was some potential for gas to be present in the area and model has been developed to assess the reserve potential of the area based on analogue from elsewhere in the GoT [13].

During 1990-1997, about 13,675 kmof 2D seismic lines and 1050 km^2 of 3D seismic surveys were acquired and processed in these offshore blocks by Enterprise Oil, Premiere Oil, Campex, Idemitsu and Woodside [13]. As the result, the area A was demarcated on the western part of Block I, II, III, and IV, and covers most of the body of Khmer basin, bounded an area of 6278 km^2 (**Figure 1(c)**) [5].

2.3. The Period of 2002-2014

In 2002, CNPA, a representative of the government of Cambodia revised the offshore Blocks, divided into 6 alphabet names from A to F, and signed the production sharing contract (PSC) with Chevron Texaco and Moeco to explore the area A (recently called Block A) [17].

In 2003 Chevron and its partners shot 2650 km^2 of 3D seismic, and decided to drill 18 exploratory and appraisal wells in 3 campaigns to establish in 5 oil fields in this CBA. The discovery was confirmed the presences of hydrocarbons with light oil (42 ˚API) and sweet (low Sulphur) crude oil, but it is a waxy and specifically high CO_2 gas in Mealdey-1 well [5].

In 2007, the area of Block A was relinquished 25% and become 4709 km^2 in the block license. Three years later, in 2010, PPA was submitted to the government of Cambodia for the phase approach to develop the resources, but the approval was not reached due to failing an agreement on revenue sharing and going down the crude oil price. This finally resulted in the US oil giant abandoning the project and selling its interest in 2014 to KrisEnergy [4].

In 2014, the Singaporean-based company KrisEnergy bought the right of oil exploration from Chevron Texaco and became the operator in CBA. The potential for offshore oil extraction became more visible when the government and KrisEnergy reached an agreement on production details and finances, allowing KrisEnergy to prepare for extracting oil from the area of 3140 km^2 over CBA [4] [18] [19].

2.4. The Period of 2014-2023

In August 2017 the government signed a production-sharing agreement with Singapore-listed KrisEnergy, which held 95% of working interest over production area 3083 km^2 [11] [20], became the major operator to develop the early phase in Apsara area and the remaining 5% belongs to Ministry of Economic and Finance to be a representative of Cambodian government.

After there had been delayed for few times, until 28 December 2020 Prime Minister of Cambodia announced the producing Cambodia's first oil in the Apsara oil field, the current area of CBA. The oil flowing was primarily from a single production well and expected to reach the peak production rate of around 7500 bopd once the drilling program of four additional wells would been achieved for three months afterward [2].

The production plan of phase 1A was changed to a designated Mini Phase 1A that constructed a minimum facilities wellhead support structure capable of housing up to six development wells, brought in the Ingenium II production barge for oil, gas, and water processing, and added a storage vessel on the field for storage of the processed crude oil before offloading [1] [2].

The operator decided to produce Cambodia's firs drop of oil within risks and time constrain. Kris Energy was reported a loss after tax of nearly \$169 M in 2019, and its total debt was more than \$503 M, according to its 2019 annual reports [4] [21]. The individual oil accumulations in CBA were small in size and spread over a large geological area, not seem replicated on the border reservoir on the Thai side, requiring significant funds and time to fully develop [22]. Additionally, the reservoir production performance in the Khmer Basin has yet to be proven. At the same time, the government of Cambodia had raised a serious consequence of concession termination if the company would not produce the first drops of oil from Block A and secure funding to achieve steady production.

Unfortunately, the firm went into liquidation in June 2021 after production failed to meet 7500 bopd, producing oil remain less than haft of its initial estimation, approximately in the end 1000 bopd, and leaving it unable to repay its debts [23]. The cumulative production volume was reported about 300,000 bbl of oil for a period of five months and stored in a contractor storage vessel, MT Strovolos.

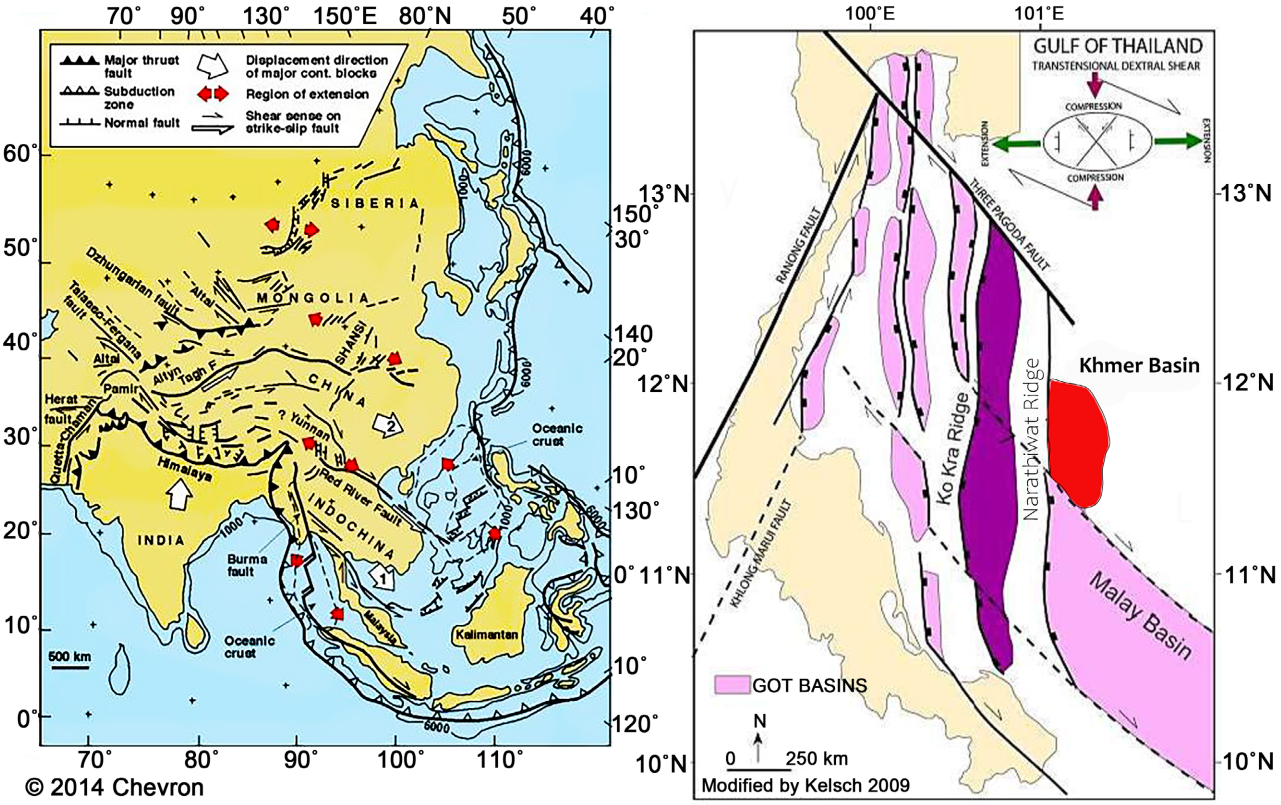
The escape of the extracted oil storage tanker was likely influenced by the bankruptcy status of its CBA operator. This TM Strovolos departed from the Cambodian water and headed to Thai territorial sea before proceeding to Batam, Indonesia islands. The government of Cambodia had been collaborating with its representative legal team to reclaim the crude oil belonged to Cambodia. Finally, in 2022, the parties agreed to share the benefit of selling crude oil 70%, 24% and 6% to the government of Cambodia, MT Strovolos, and operator respectively [24].

By 2023, Canadian-owned company Ener Cam Resources Co Ltd (Ener Cam) is studying the possibility of investing in oil extraction from Cambodia's offshore Block A after the government terminated an agreement with the bankruptcy KrisEnergy Ltd. in 2021 [25].

3. Geology of the Khmer Basin

3.1. Regional Tectonic

The tectonic setting of the Asia and SE Asia lead to the origin of the GoT [7] [15] [19] [26] [27] [28] [29]. The period from Late Cretaceous to Eocene time, the Indo-Australian plate separated from Gondwanaland moving northward to collide with the Eurasian plate (**Figure 2(a)**). As the Indian subcontinent continued pushing north, SE Asia was slowly rotated clockwise, changing the angle of subduction from perpendicular orientation to increasingly oblique. This new angle formed a major thrust fault in the region which is responsible for the development of N-S extensional zones and formed the numerous N-S trending basins currently. In addition to the lateral right extension, the plate collision causes either the Indo-Australian oceanic crust subducts under the Sundaland. This subduction opened the Gulf of Thailand 50 Ma with back-arc extension transpression/transtension associated with right-lateral strike-slip faulting. Looking closer at the formation of the GoT, all basins are N-S extensional faults formation in the Cenozoic, which link up with the NNW trending Three Pagoda Transfer Fault, as shown in the **Figure 2(b)**.



(a) (b)

Figure 2. Plate tectonic movements reform the continental and oceanic crust structures in the Cenozoic era in South East Asia: (a) The movement of Indo-Australia plate to hit with Eurasian plate causing major local thrust slip faults and uplifts which influence gradually the changes in geological distribution, and (b) The eleven N-S elongate pull-apart basins in the GoT associated with Eocene/Oligocene oblique slip. Modified from Fyhn *et al*., (2010) and Pakdeesirote *et al*., (1997) [8] [28].

The Khmer Basin is one of eleven N-S elongate pull-apart basins in the GoT associated with Eocene/Oligocene oblique slip. The Western and Eastern Gulf of Thailand sub-segments are separated from one another by the Ko Kra Ridge with nine basins in the west and three basins in the east: the Pattani and Malay Basins and the smaller Khmer Basin [8] [29].

3.2. Structural Features

The Khmer Basin is located in the offshore Cambodia, in the central Gulf of Thailand, an elongate N-S trending rift basin and has a length and width of 150 km and 60 km respectively, as shown in the **Figure 3(a)** [7]. The basin bounds in the west by the Narathiwat Ridge, which separates it from the Pattani Basin, in the south by the Kim Qui High which separates it from the north Malay Basin and in the east by the Khmer High. The northern edge of the Khmer Basin is influenced by the three Pagoda faults, a right-lateral strike-slip.

The offshore Cambodia area occupies a position of moderate structural complexity. Its location is on the relations of major plate boundaries which the region is situated on the southern part of the large Eurasian plate and away from

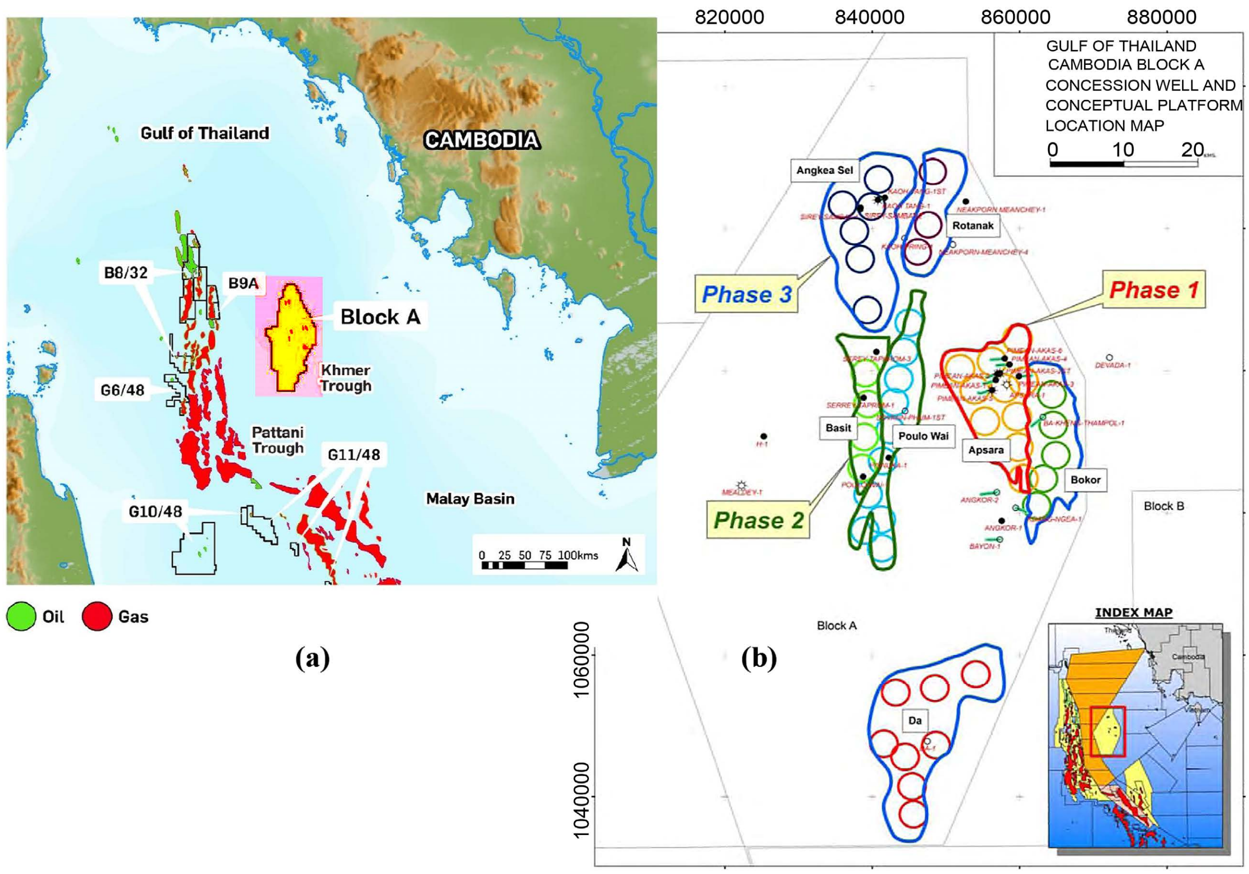


Figure 3. (a) The major N-S elongate basins in the GoT associated with Eocene/Oligocene oblique slip. The red rectangular border covers Khmer Bain in the Cambodian territorial sea and a yellow area is an acreage after applying the second relinquishment for the purpose of surface rental of production area in the CBA, and (b) the seven geological trends within the Khmer Basin in which a Mini Phase 1A was producing the first oil in Phase 1 KrisEnergy. Adopted from Pang, T. (2017), Nguon, P. (2018), and Sokunthea *et al*., (2022) [11] [18] [30].

active centres of crustal subduction and/or seafloor spreading [15]. The Tertiary tectonic history reveals the heavy influences of the collision with the adjoining Indian plate.

The initiation of basin formation probably commenced as early as the Eocene, coinciding with the collision of the Indian Plate with the Eurasian Plate. The compression from the northerly movement of the Indian Plate resulted in the south-easterly movements of the Southeast Asian Sundaland and the South China Plate. These tectonic movements caused a series of strike-slip faults to form through the GoT, including the Three Pagodas Fault Zone, the Kho Samui Fault, and their conjugates the Khlong Marui Fault and the Ranong Fault [8] [13] [27]. The extension relating to the strike-slip faults and the potential inherent extension due to crustal thinning under the GoT led to the initiation and formation of the Khmer Basin in a similar way as the Pattani, Malay and other Tertiary Basins in the GoT. These basins were separated by basement highs until the middle Miocene and fluvial and lacustrine sediments were deposited (**Figure 4**). After the middle Miocene the entire Gulf of Thailand was subject to marine

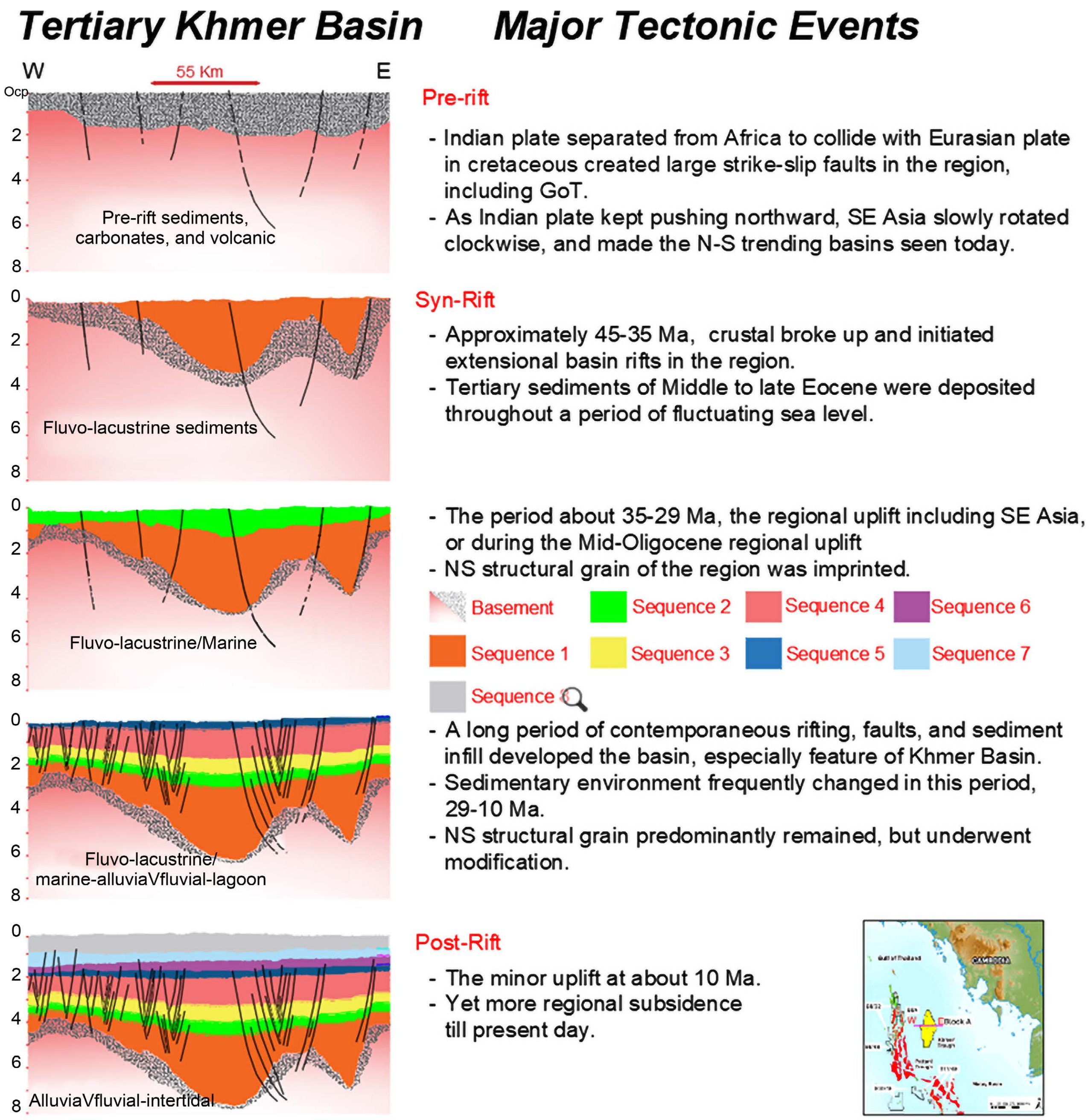


Figure 4. Khmer Basin evolution from the late Cretaceous to the Present day in the effects of global plate movements and local sedimentation.

conditions due to post-rift thermal subsidence [8]. The thickness of Tertiary sediments reaches 8000 m in the central Khmer Trough in which wells were drilled and three of them were discovered oil and gas since the 1990s [7].

3.3. Lithostratigraphy

The basement of the Khmer Basin consists mainly of pre-Tertiary rocks, metamorphic, and igneous sediments [7] [8]. The basin was stratigraphically divided into two main phases, syn-rift (Early Oligocene alluvial fan clastic and lacustrine shale) and post-rift (Late Oligocene to Recent fluvial sediments with minor lacustrine and marine episodes) [17].

As shown in **Figure 4**, the section is West to East across the Khmer Basin from the age of the late Cretaceous to the present day, which developed in a very similar history to other producing oil and gas basins in the GoT. Prior to 39 Ma, the Sinoburma and Indochina/East Malaysia plates adjoined in the late Triassic-early Cretaceous forming the Sundaland. The Indian plate separated from Gonwanaland, and moved past this Sundaland to collide with Eurasian plate in the Eocene. As the result of this collision, the uplifts occurrence created the erosion environment, particular Pre-Tertiary Unconformity. In Late Eocene to Late Oligocene, the Himalayan Orogeny began to appear in the India and the propagation of Mae-Ping, Three Pagoda shear system, and early basement faults created the N-S rift sub-basins in Indochina

Sequence 1 and 2 of the Khmer Basin is Rift-fill sediment in the early Syn-rift phase which burry the clastic fragment of sandstone to conglomerate, clay, silt and shale predominate in lacustrine to fluvial/alluvial deposits. In the middle of Oligocene wrenching along the Mae-Ping and Three Pagoda Faults causes uplift and creates the Mid Oligocene regional uplift.

During the Lower Miocene continued clockwise rotation creates renewed extension and basin downdropping along major N-S rifting which accommodates the graben systems in response to basin subsidence. Sequence 3, 4 and 5 compose of mainly mixed sediment infill organic rich shale with sand, limestone, coal, and claystone interbeds in the depositional environment from fluvial/lacustrine at the bottom to the fluvial at the top.

In the very late middle Miocene to early upper Miocene, an eustatic sea level dropped and caused widespread erosion. It is Middle Miocene Unconformity which marks in Sequence 6.

The continuation of compression along Indian-Eurasian sutures causes the rotation of the Indochina block clockwise and creates more extension in the GoT, including the accommodation of faulting as the basin subside and deepen. The sediment depositions are sandstone with particularly coal, shale and lignite in the transgressive environment, fluvial/lagoon to marine in sequence 7, and 8 respectively.

4. Petroleum Formation

4.1. Depositional Sequences

Among seven geological trends in the CBA, the Apsara trend (or Apsara area) is the most advanced exploration activity since Chevron Texaco confirmed the economical oil discovery. The depositional environment of the Khmer basin, including the Apsara area, is classified into eight sequential sedimentology as seen in **Figure 4** and **Figure 5**.

Upper Eocene to Plio-Pleistocene clastic sediments is widely distributed in the Khmer Basin as well as other basins in the GoT. As much as 8 km of Tertiary

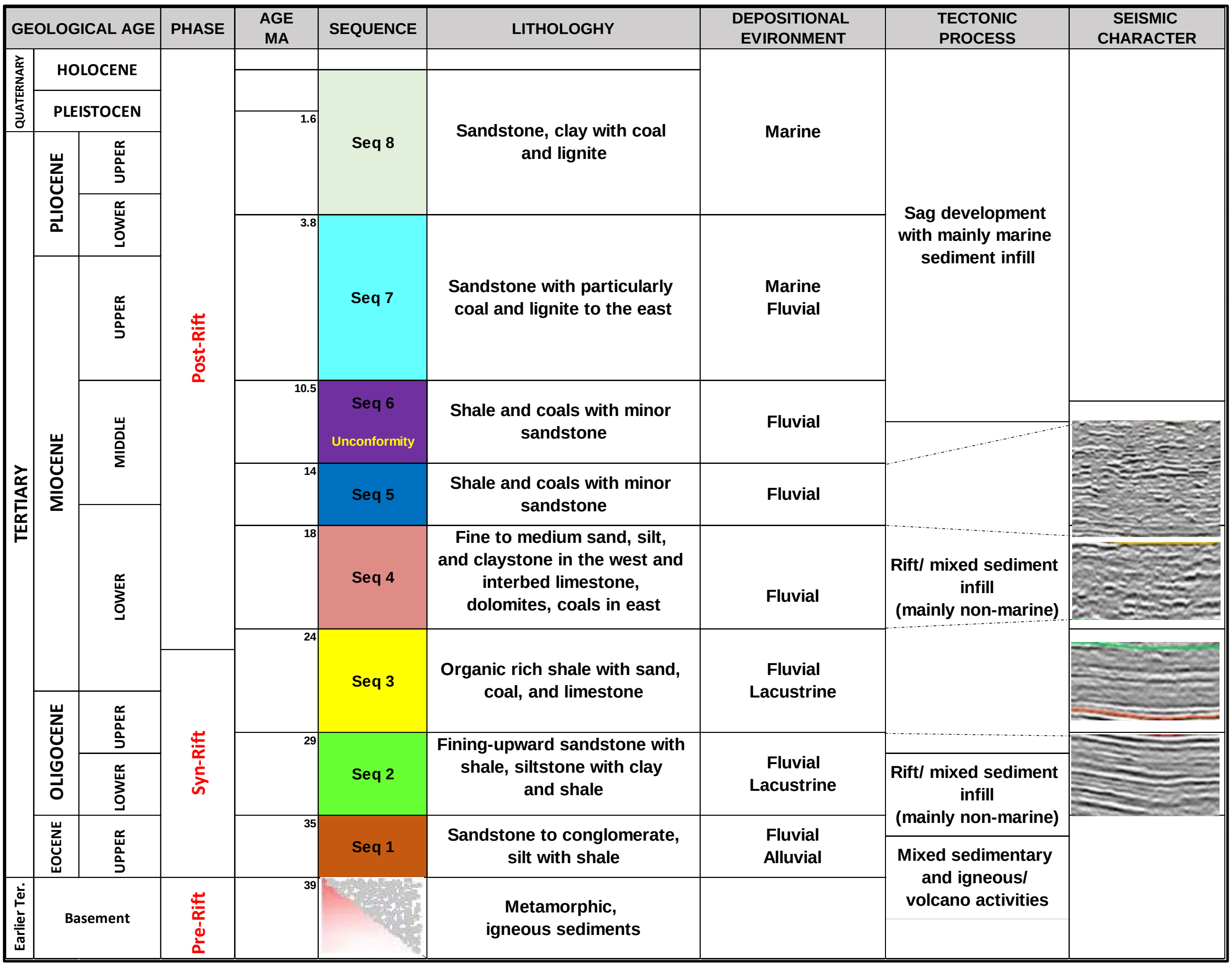


Figure 5. The Khmer Basin stratigraphy sequence correlations with tectonic processes and seismic characteristics [19] [26].

sediments were deposited in the central Khmer Basin which is subdivided into 8 sequential strata, sequence 1 is the oldest deposit at the bottom and sequence 8 is the youngest at the top. The environments of sedimentation and depositional hierarchies within the GoT rift basins are similar to those of rift basins worldwide. They typically progress from an initial phase of alluvial-fluvial deposition to a mid-phase fluvial-lacustrine environment and finish with a fluvial-dominated environment. Sequences 1 - 3 are syn-rift deposits comprised of alluvial, fluvial and lacustrine sediments. Lacustrine shales are present in these syn-rift sequences, some of which are sources for the oil and gas accumulations in the Khmer Basin. Most known hydrocarbon-bearing reservoirs within the Khmer Basin belong to the latest syn-rift to post-rift, lower Miocene fluvial-lacustrine and fluvial sandstones in Sequences 3 and 4. Sequences 5 and 6 are dominantly fluvial, which potentially can be additional hydrocarbon bearing reservoirs.

4.1.1. Sequence 1

Sequence 1 sands and shales were deposited from approximately 39 Ma to 35 Ma and are believed to be primarily fluvial-alluvial to lacustrine sediments. The sandstones may consist of relatively coarse-grained to conglomeratic material. Exploration well Devada-1 and H-1 were drilled to the depth of this sequence 1, though these wells are outside and on the flank of the Khmer Basin as seen in the Figure 6 and Figure 7. It is believed that any potential reservoirs in this sequence will have insufficient porosity, due to compaction and thermal diagenetic alteration, to make them suitable for producing hydrocarbons. The lacustrine shales in this sequence, similar to those in Sequences 2 and 3, can be source rocks for the oil and gas accumulations.

4.1.2. Sequence 2

Sequence 2 was deposited from approximately 35 Ma to 29 Ma in a predominately fluvial-lacustrine environment. The lacustrine facies probably increase in thickness towards the basin center. This sequence consists of very fine-grained sandstones, siltstones, and shales and is considered a source rock. The Apsara-1 was drilled in the Apsara area (Figure 6) where reach this sequence with no hydrocarbon pay encountered. Due to the depth of this sequence and subsequent compaction, encountering reservoir quality sands in this interval is unlikely.

4.1.3. Sequence 3

Sequence 3 was deposited from approximately 29 Ma to 24 Ma in a predominately fluvial-lacustrine environment and probably is dominated by lacustrine

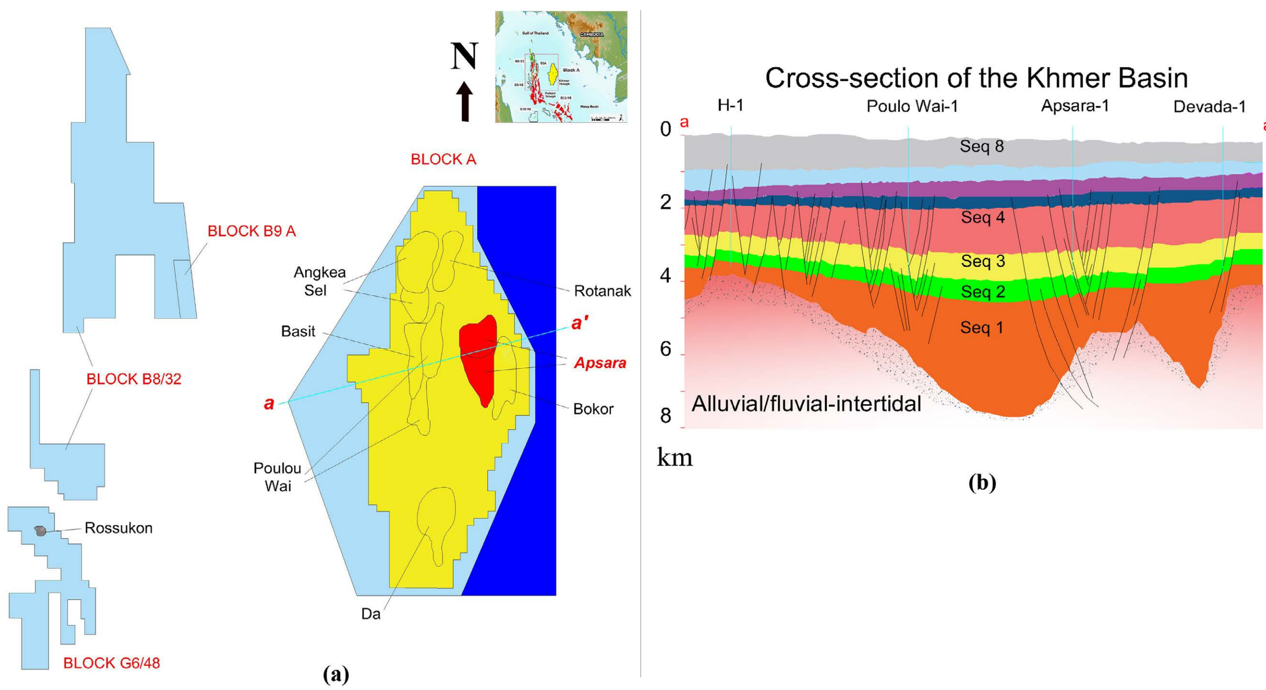


Figure 6. Structural trends were determined by integrated geological information of the Khmer Basin. (a) The seven geological trends in Cambodian water. The CBA was relinquishment three times until the pilot project of the first Cambodian oil production flowed from the Apsara trend, and (b) illustrates the cross-section E-W of the Khmer Basin from a regional high, well H-1 in the west, to the fault-bounded Khmer Ridge, well Devada-1 in the east, across Poulo Wai, well Poulo Wai-1 and Apsara, well Apsara-1 trend in the center.

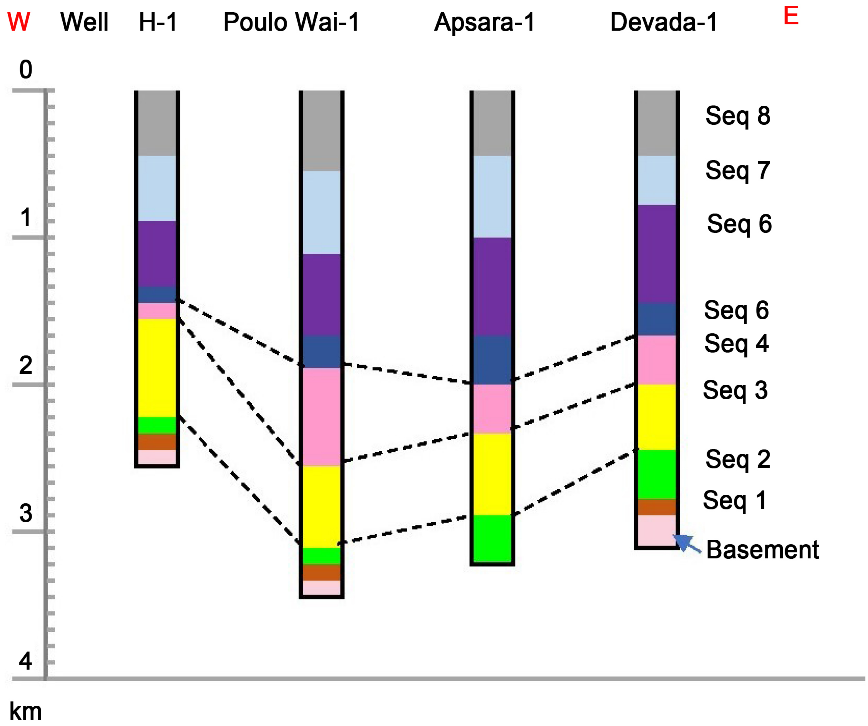


Figure 7. Well-sequence correlation through the cross-section E-W and cross-cut Apsara, Poulo Wai, and Basit geological trend. Devada-1 was drilled in the eastern flank of the main Khmer Basin. Apsara-1 and Poulo Wai-1 were drilled into the main Khmer Basin where the Apsara and Poulo Wai geological trend proved the presence of hydrocarbon (**Figure 5(a)**). H-1 was drilled in the Khmer ridge in west of the central Khmer Basin [13] [14] [15] [29].

sand and shale facies at and near the basin center. Apsara-1 shows the oil-bearing sand; however, the thick sand layers are at the lower sequence 3 (**Figure 7**). The Apsara-1 well has a total organic carbon (TOC) value of approximately 5% from a lacustrine shale sample within this sequence. Hydrocarbon pays are mostly observed in upper Sequence 3 to date. Its average reservoir thickness and quality are, overall, inferior compared to those of Sequence 4.

4.1.4. Sequence 4

Sequence 4 contains the main reservoir interval in Cambodia Block A. It consists of fluvial sediments deposited from about 22 Ma to 18 Ma. This clastic sequence includes fine to medium-grained sandstones, siltstone, and claystone. Hydrocarbon pay is found in the lower portion of Sequence 4 of the Apsara area (**Figures 5-7**), which has been conducted multiple tests at Lower and Middle Sequence 4 sands and proven them to be producible and potentially commercial.

4.1.5. Sequences 5 and 6

Sequence 5 and Sequence 6 were deposited from approximately 18 Ma to 14 Ma and from 14 Ma to 10.5 Ma, respectively. These sequences consist of sandstone, shale, and coal. Their depositional environments are generally fluvial. Top Sequence 6 is a regional erosional surface often referred to as the Mid Miocene

Unconformity (MMU) throughout the GoT. Both Sequences 5 and 6 contain reservoir quality sands. Drilling up to date has not discovered oil or gas pays in these sequences.

4.1.6. Sequences 7 and 8

Sequence 5 and Sequence 6 are fluvial to marine sediments. Shallow gas hydrocarbons have been found in the Sequence 7 sands of the Apsara area. The gas resources in Sequence 7 are too small to warrant a gas development project in this Apsara Field.

4.2. Potential Reservoir

Economical hydrocarbon accumulations were discovered in the reservoir sand in the lower Miocene [7] [26] which indicates that quality of reservoir sand in upper sequence 3 to lower sequence 4 controls the oil production in the Apsara trend (**Figure 6**).

The geothermal gradient of the Khmer Basin is generally around 5˚C/100 meters, which is slightly high compared to the geothermal gradient of regional SE Asia, but it is lower than the Pattani Basin in Thai water to the west, up to 5.8˚C/100 meters [29] [31]. Reservoir temperatures for the lower sequence 4 to the upper sequence 3 reach approximately 175˚C, Apsara-1 [15].

The Khmer basin hydrocarbon occurrences suggest local (in-situ) charges as the maturity of source rocks at the well bore locations is close to the maturity of the recovered oil. This suggests that the Sequence 3 reservoirs are not receiving deeply sourced oil and gas [15]. Oligocene lacustrine shales of Sequences 1 - 3 containing Type I algal organic matter are the source rocks that generated the oil accumulations in the Khmer Basin. At the Apsara-1 location, the hydrocarbon generations are approximately 1.3 - 1.8 bcf/km^2 for gas, and 8.7 - 12.8 mmbbl/km^2 for oil (data from GDP). These hydrocarbons probably migrate laterally across the faults through sand-on-sand juxtaposition and vertically through faults. The discovered oils in lower Sequence 4 to Sequence 3 were generated down dip in the kitchen area. The lack of hydrocarbon pays in the younger sands such as Sequences 5 and 6 was likely related to the lack of fault activities after the MMU time (10.5 Ma) [19].

Even though some previous studies indicated that Khmer Basin may consist of several types of play, four types have been identified to be more likely prospective. These types are synthetic, antithetic, inner terrace, and horst, of which the synthetic Angkor Prospect is the most viable for first gas and condensate development [13] [17].

In the Khmer basin, reservoir characters show a thick distribution channels and stacked channel sand stones in the Miocene and Oligocene, sequence 3 and 4 (**Figure 5** and **Figure 7**). The well Apsara-1 and Poulo Wai-1 are located in central body of the Khmer basin where accommodates thick potential hydrocarbon reservoir sequences between the upper Oligocene to the lower Miocene as seen in **Figure 7**.

KrisEnergy reported the economical hydrocarbon accumulation of the Apsara oil field in the lower sequence 4 to particular sequence 3 where the depths ranging primarily from 1820 to 2900 m (**Figure 7**). The porosity trends studied decreases with the depth increases because of compaction. A general, reservoir sand in the range is coarsening upward in grain size. Overall reservoir sand quality tends to be low due to the burial depths. The porosity and permeability are reducing noticeably through compaction, quartz and carbonate cementation, and the additional diagenetic clays into the pore space. It goes from about 30% to 10% at the reservoir zones [13] [15] [17] [19].

The exploration wells which encountered the hydrocarbon shows that the hydrocarbons are waxy, high pour point, low sulfur oils and wet gas/condensate. The correlation analyses of these hydrocarbons are thought to have been expelled from Sequence 3 lacustrine source rock.

In general, GoT basins are characterized by series of elongate, narrow, north south or northwest-southeast trending tertiary basins and collapse grabens. The sedimentary sickening is in the central basin and thinner to the west and the east flanks. The reservoir section is potentially in sequence of sand and shale with a few coals, which deposited in a fluvial environment, with linear, discontinuous sands through laterally extensive amalgamated sand sequences. Most hydrocarbon accumulation reservoir sands are associated with three-way dip closure, which formed along normal faults [15] [19] [32].

5. Phases Development Approach

The fiscal and technical agreements for the Apsara field development were signed between KrisEnergy and the Government of Cambodia in August 2017, which was followed by a final investment decision (FID) for the initial Phase 1A in October 2017, and modified to Mini Phase 1A to commence the production in 2020 [33].

The Apsara Mini Phase 1A development commenced the production by the end of 2020 with the primary estimation cost approximately $87 m [34]. The field was expected to produce at a rate of 7500 bdp at the peak in the initial phase.

The CBA is spread over 3083 km^2 of which the Apsara field (Apsara Trend) occupies approximately 200 km^2 (**Figure 6(a)**). The water depth in the Apsara field area ranges from 50 m to 80 m.

Apsara field will be developed in multiple phases (**Figure 3(b)**) in order to reduce risk as it is the first development in the Khmer Basin. Phase 1 refers to development of Apsara field with potentially ten platforms and is sub-divided into three stages, namely phase 1A, phase 1B and phase 1C [4] [11] [33] [35] [36].

Phase 1A was designed as the first single producing and processing platform (Apsara Platform A) which includes twenty-four slots of wellhead and processing facilities. Phase 1B will be appraisal and potential development of the additional three platforms (Apsara Platform B, C, D, and so on) in the Apsara Core Development Area (ACDA). Phase 1C is the appraisal and potential development of the six remaining platforms in the Apsara Field.

Up to the successfully development of Phase 1 (comprising the stages, Phase 1A, 1B, 1C), the other two phases will be developed in accordance with previous geological data and production performances. The phase 2 is the extension development to oil accumulation in the Poulo Wai and Basit trends , while phase 3 is the final huge expansion to develop the extraction from Angkea Sel, Rotanak, Bokor and Da trends (**Figure 6(a)**) [19].

However, when the Mini phase 1A (a modified from phase 1A) was agreed to commenced the initial development in the ACDA, operator constructed a minimum facilities wellhead which is capable the housing up to six development wells, brough in the Ingenium II production barge for the fluid processing, and added a floating storage and offloading vessel (FSO) on the field for storage of the processed crude oil before offloading (**Figure 8**) [1] [2] [19] [33].

A success of commencing the Mini Phase 1A has involved various companies as listed in **Table 1**. Kepinvestment Singapore offered a loan of $87 m to the operator of CBA for its initial phase development and hold 40% equity interest. Seven other sub-contractors have awarded for the scope of responsibilities in the development. Profab, a subsidize of the National Oilwell Varco, was awarded to

Table 1. Shareholders and sub-contractors for the Mini Phase 1A development in Apsara Oil Field, CBA [32].

No.	Companies in charge	Agreement	Service
1	Kepinvestment Singapore (Keppel Corporation)	Apr-20	loan of $87 m to develop the first phase, and hold 40% interest
2	Profab (National Oilwell Varco)	2019	Facilities wellhead platform
3	Offshore Construction Specialist	2019	Structural Design the wellhead platform
4	Petrovietnam Drilling and Well Service Corporation (PV Drilling)	Aug-20	Drill five production wells
5	Keppel Shipyard (Keppel Offshore & Marine)	Nov-18	Contract $21 m to modify and upgrade Ingenium II production barge
6	Fugro	Jan-20	Geotechnical survey
7	Shearwater Geoservices	Jun-Jul-19	3D seismic 1200 km^2
8	PTSC Geos and Subsea Services (PetroVietnam Technical Services Corporation)	Nov-19	Geophysical survey at facilities wellhead platform

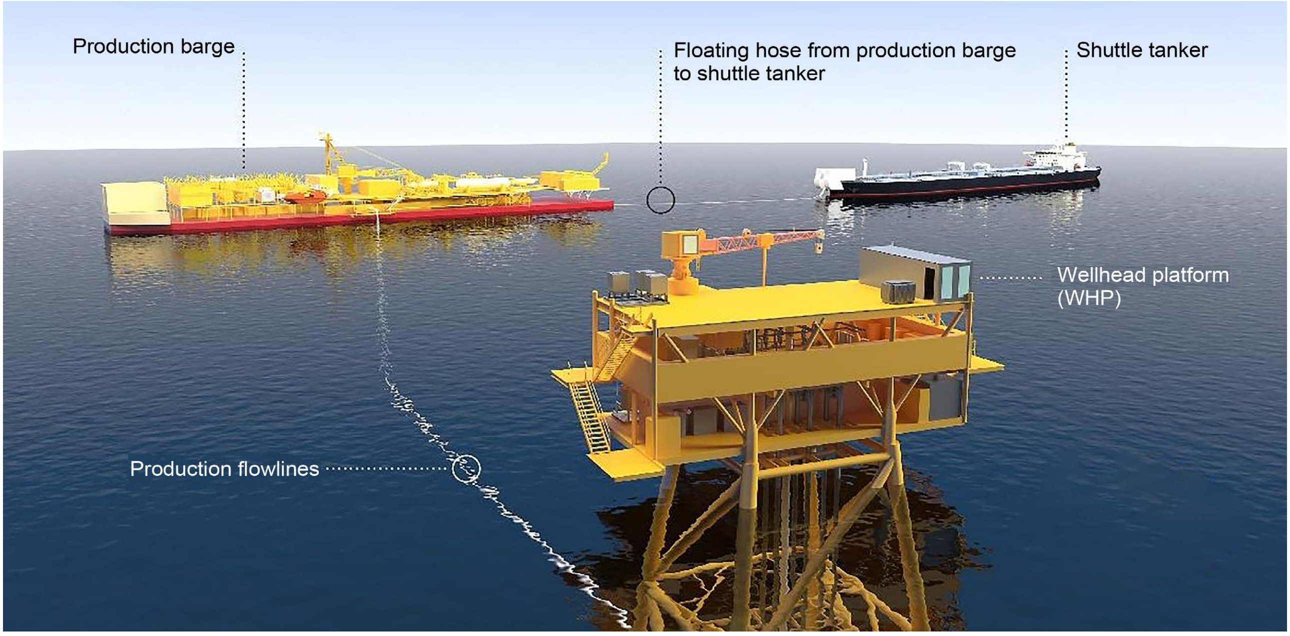


Figure 8. Conceptual mini phase 1A development in the Apsara oil field [1] [2] [34].

fabricate the minimum facility wellhead platform (Mini-Platform) as seen in the **Figure 8**, which comprises five initial development wells connected to the Ingenium II production barge for oil, gas and water processing [37] [38].

Keppel Shipyard, subsidize of Keppel Offshore & Marine, awarded the contract value of $21 M to modify and upgrade the production barge, Ingenium II (**Figure 8**), for the processing up to 30,000 barrels of fluid a day. Process System of Ingenium II was include Separation System, Interstage Heater, Oil Export Pump, Fuel Gas system, Produced Water Treatment Package, Heating Medium System, Diesel Flushing System, flare Gas System, Open and Closed Drain System (Slop Tank) [39].

6. Fiscal Regime

The final agreement of production sharing contract (PSC) between the operator of the CBA and the government of Cambodia was suggested to remain the original agreement as enforce with Chevron [40]. Cambodia operates the hybrid production sharing system that includes a royalty, the corporate income tax, production sharing and the option for the government to hold the working interest in a particular project, called state participation [4] [14] [40] [41] [42]. The structure for calculating the revenues for the operator and the government is engaged with these four main fiscal elements as shown in **Figure 9**.

The revenue sharing can be calculated when only the production oil is started by counting the volume of gross oil production in barrels in a day. The Government of Cambodia shall retain petroleum royalty, 12.5%, before allowing KrisEnergy to recover the petroleum cost, limit to 90%, and before allocating produced petroleum, called profit oil. After retaining royalty and recovering petroleum cost, profit oil shall be allocated between the government and the operator

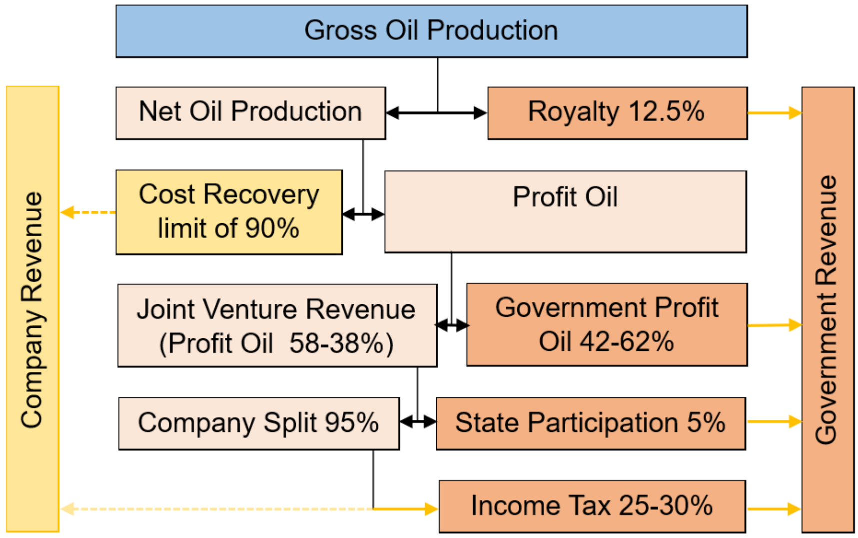


Figure 9. Fiscal system for the CBA development [4] [14] [38] [39] [40].

Table 2. Oil production splits for CBA development in the PSC of KrisEnergy and Government of Cambodia [4].

Barell of Oil Per Day	Company	Government
0 - 10,000	58%	42%
>10,000 - 25,000	53%	47%
>25,000 - 50,000	48%	52%
>50,000	38%	62%

in accordance to the petroleum agreement (PA), which was agreed the oil split ranges in the prior negotiation by the parties as shown in **Table 2** [4] [41].

Table 2 shows accumulative oil produce in a day in ranges which related to the profit oil sharing to the government and KrisEnergy. At the lowest productive volume of below 10,000 bpd, profit oil shall be shared in 58% and 42% to KrisEnergy and the government respectively and when increasing up to more than 50,000 bpd, profit oil shall be 38% and 62%.

The portion profit oil of operator must be the joint venture revenue which shall be allocated to the correspond of state participation 5% in working interest. So, an actual 95% of the joint venture becomes an exclusive revenue to operator before the deduction the operator's income tax. Among the elements for calculating the production sharing system, the royalty is mentioned a fix number 12.5% while the other oil split, state participation and income tax are the matters to negotiate for binding in the PSC [40].

7. Discussions

The country has been potentially reported resourceful hydrocarbon deposits in the continental shelf since the earlier stage as other countries adjacent to the GoT. Thailand produced first gas and condensate in the Erawan field in 1981 and subsequently more than 20 oil and gas fields have been discovered and have continued producing hydrocarbons till the current date [29]. The Peninsular Malaysia continental shelf was drilled and found the significant quantity of oil and non-associate gas in the Malay Basin since 1975 [43], that contribute Malaysian oil production to be the 25th world ranking recently. Their first oil success seemed motivate the followed projects to be more successful.

After years of work by operators like Chevron and KrisEnergy, first oil was finally achieved with a Mini Phase 1A for Cambodia in the late 2020 from the Apsara oil field. Unfortunately, production rates were below expectation which indicates clearly the complexities and uncertainties of geological characteristics within the Khmer Basin.

Fiscal terms agreed for revenue sharing were typical for the CBA, as seen in **Figure 9**. Whenever other project starts or re-produces, the operator is encouraged to negotiate and propose the essential advantages in order to provide both parties better benefits and more successful oil industry in Cambodia.

For Cambodia, the stopped-producing status for the Country expresses an unsuccessful oil industry and cannot be grouped into the oil producing nations. The unsuccessful operator, KrisEnergy, can be discussed as the following:

1) Even though Cambodia has started to explore the hydrocarbon resources as early as neighboring countries, it is still weak in national expertise of oil and gas industry. Because the country has gone through the unstable political and civil war [6] that led to be very difficult for human resource development, and the investment, resulted in slower petroleum activities.

2) The phase approach of oil development plan in the CBA is a smart decision of both government and operator for developing such a marginal oil field. But the launching of Mini Phase 1A instead of Phase 1A looked like inappropriate scenario. A minimum facilities wellhead with six development wells might not possible to produce the oil reaching 7500 bpd as the Phase 1A with twenty-two production wells does.

3) All the basins in the east of Ko Kra Ridge (**Figure 2(b)**) consist of Pattani basin (exclusive water to Thailand), Malay basin (Peninsular of Malaysia), and Khmer basin (exclusive water to Cambodia).The Khmer basin is the smallest in size and shallowest in sedimentary deposition, approximately 150 km × 60 km × 8 km, compared to the Pattani and Malay basin, approximately 300 km × 80 km × 10 km and 500 km × 200 km × 12 km respectively [7] [29] [44]. All these basins in the GoT are similar structural complexity, age and type of source rock, age and type of reservoir rocks, and structural trapping styles. As seen the Malay basin is the most successful discovery and follows by Pattani basin in Thai water. These could be proved that geometry of each basin controls partially the economical hydrocarbon accumulation.

4) The influences of Indian plate collision created the GoT to accommodate similar basin features including the elongate N-S and NW-SE rift basins and sub-basins, regional faults to form graben fault blocks and the existing shearing

faults, and compression and extension to form basement highs and rifting [8] [15] [26] [27] [29] [45]. In spite of the fact these features are similar, the individual basin has significantly different degree of influences which should be taken into account.

5) The regime of sedimentation respects to a hosting environment which relates very much to each individual basin feature. Of these, thickness, packing, sediment species, variety sediment grains are major parameters to characterize the source rock to generate the hydrocarbon and quality of reservoir rock to store the fluids in place. The CBA consisting of the Khmer Basin is located in the east of the gulf where sedimentary strata are thinner compared to the thicker basins as Pattani and Malay Basin to the west and the south [8] [46]. Deep and thick source rocks are subjected to higher potential of hydrocarbon generation, and a coarser grain sediment enhances the fluids to store and to flow better.

8. Conclusions

This review paper provides a comprehensive look at a long history of oil and gas exploration in Cambodian waters, culminating in the recent oil from the Apsara Area, which is a journey of about fifty years of first oil for the country.

In addition, Cambodia is still high possibility to produce oil and gas successfully in the Khmer Basin and/or the overlapping claim area (OCA) with Thailand. There are six other geological trends where potential oil and gas to be trapped in the CBA (**Figure 6(a)**). So, the failure of Apsara oil field becomes an experience for more realization.

More extensive appraisal drilling and testing is likely required to de-risk remaining prospects like Bokor, Poulo Wai and Basit. This will improve understanding of reservoir properties and help forecast oil and gas production potential for the future projects.

Most producible reservoirs in the Khmer Basin are in fine to medium sand, silt, coal and limestone from the Upper Oligocene (sequence 3) to the Lower Miocene (sequence 4), as seen in **Figure 5**.

The geological uncertainties are the key issue for oil and gas development in the GoT. Structural complexities, oil spreading in small pockets over stacked channel sandstone were recognized and added into the assumption by produced oil basins in the gulf. This analogue information for the assumption of the Khmer Basin was not so effective, then the exploration program likely 3D seismic and appraisal wells should be conducted more in order to understand the different uncertainties and different complexities in the Khmer Basin.

Further academic study of the Khmer Basin in similar way to adjoint producing basins could uncover insights and the research of optimal development strategies for marginal fields in this setting would be useful future development in the CBA.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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