Review of sedimentary basin evolution in Cambodia based on tectonic setting and logical information

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ABSTRACT

The paper aims to synthesize the evolution of sedimentary basins in Cambodia based on a comprehensive information on tectonic setting and existing database of their formation and sedimentation. The study includes a review on tectonic setting of Indochina, the formation of sedimentary basins around Cambodia, and the accessible data on sedimentary basins in Cambodia. Indochina, as well as Cambodia, had been influenced by the collision of three different plates or terranes such as the South China, Sibumasu-Sukhothai, and Paleo-Pacific that are associated with the evolution of Paleozoic-Mesozoic Basins namely Khorat and Kampong Som Basins. These two oldest basins, are interpreted as a Paleozoic – Mesozoic foreland basin that initially formed due to rifting during the Late Carboniferous to Late Permian, and later basin inversion and erosion took place due to the Mesozoic to earliest Cenozoic uplift. Then, Cambodia was affected by Tertiary strike-slip fault movements that also influenced the formation of Tonle Sap, Svayrieng and Khmer Tertiary rift basins. Tonle Sap and Svayrieng Basins are interpreted to be formed by extension during the Middle Eocene – Early Oligocene and inversion, uplift and denudation during the Miocene. The Khmer Basin was formed by rifting during the Eocene to the Late Oligocene, followed by rapid thermal subsidence from the Early to Middle Miocene. Finally, Khmer basin was affected by the Middle – Late Miocene to Pleistocene inversion.

Keywords: *Cambodia, Indochina, tectonic setting, basin evolution*

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INTRODUCTION

Cambodia has seven sedimentary basins including the Khmer, Kampong Som, Tonle Sap, Khorat, Preah, Chung, and the Svayrieng Basins. The Khmer and some parts of Kampong Som Basins are located offshore, while the rest of the basins are located onshore. Based on geological field mapping work done by Polish geologists in the early 1960s, some oil and gas seepages are present in the central and southern Cambodia (Lim, 2006). About 300 to 400 barrels per day of oil and some gas were discovered in 1994 from Apsara-1 drilled in the Khmer Basin (Bishop, 2002). The International Monetary Fund (IMF) assessed that the oil reserves in Block A, Khmer Basin, to be around 700 MMBO (Resources for Development Consulting, 2015). Based on geophysical data, two deep sub-basins in the Tonle Sap Basin were defined from the airborne magnetic and gravity survey of Japan National Oil Corporation (JNOC) in 1996 (Lim, 2006). Moreover, Vysotsky et al. (1994) suggested those basins to be the potential basins for oil and gas exploration, which Khmer and Tonle Sap Basins are the most favorable.

Although the sedimentary basins in Cambodia have hydrocarbon potential, exploration activities or research related to hydrocarbon exploration are still limited. In contrast, the research on evolution of sedimentary basins around Cambodia is continuously conducted from outcrop studies, well data, and seismic cross-sections. Therefore, reviewing the sedimentary basins and tectonic setting around Cambodia is very important to clarify the tectonics of the basins which have scanty data. Moreover, this review paper is done as a preliminary step towards hydrocarbon exploration. For these reasons, this review will correlate the tectonic setting with the formation of sedimentary basins around Cambodia and combine it with the possible data to construct the geological evolution of sedimentary basins inside Cambodia. The paper focuses on reviewing the tectonic setting of Indochina and the sedimentary basins in and around Cambodia such as in Thailand, Malaysia, and Vietnam. Then, the discussion will be made to link the tectonic setting with the possible basins' evolution and sedimentation of five basins including the Khorat, Kampong Som, Tonle Sap, Svayrieng, and the Khmer Basins.

SEDIMENTARY BASINS INSIDE AND AROUND CAMBODIA

Five sedimentary basins inside Cambodia have been brought into the discussion. First, Khorat Basin is the southernmost part of the Khorat Plateau Basin. Second, Kampong Som Basin is the northern part of the Phu Quoc Basin. Third and fourth, Tonle Sap and Svayrieng Basins are located along the Tertiary strike-slip faults or fault strands (Mae Ping Fault) that link with other basins such as the Phitsanulok and Ayutthaya Basins in Thailand, as well as the Cuu Long and Nam Con Son Basins in Vietnam. Fifth, Khmer Basin is situated within the Cambodian sea, Gulf of Thailand, and is part of the same group as Pattani Basin in Thailand and Malay Basin in Malaysia. Hence, the basins formation and tectono-sedimentation will be discussed together with the tectonic setting, major or regional events and their associate basins of the aforementioned countries. All the basin's locations are illustrated in Figure 1. The profile of each basin is drafted based on the available data in Cambodia

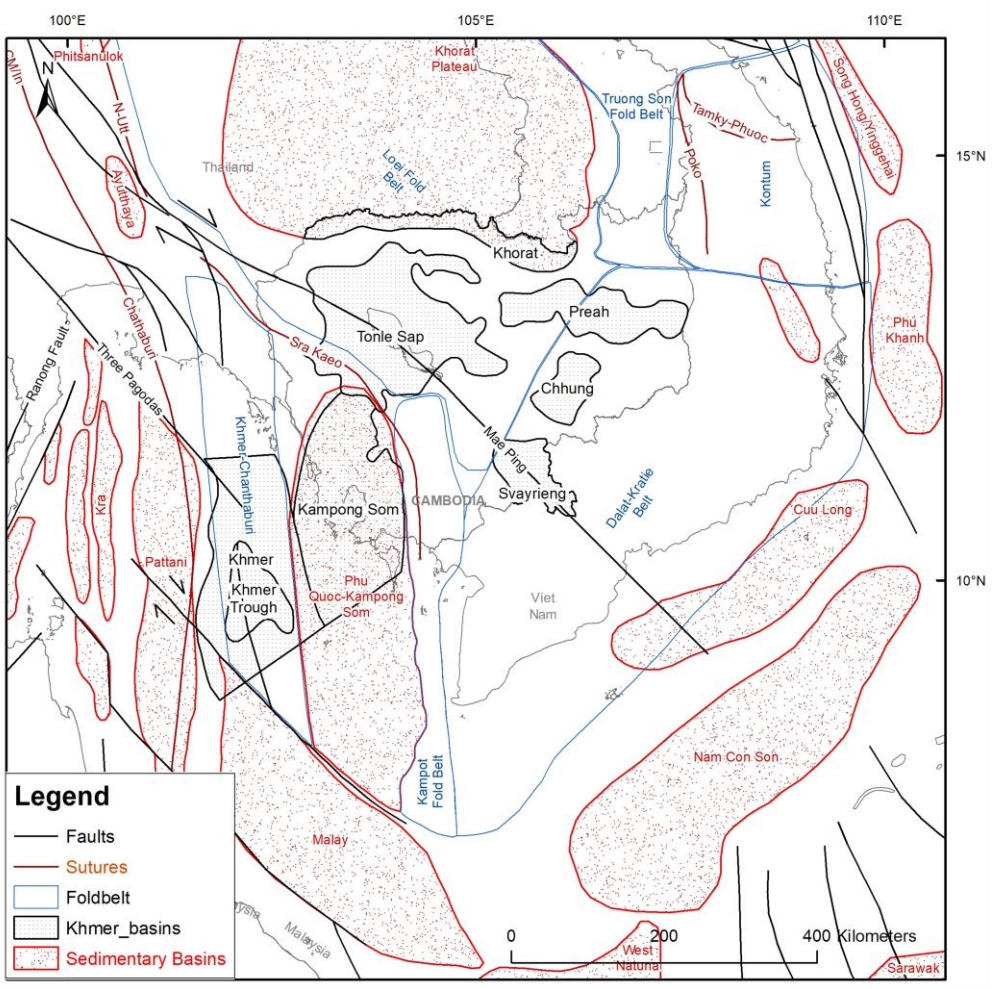


Figure 1: *Location of sedimentary basins inside and around Cambodia. Sources: most of data are revised from Metcalfe (2013, 2011), where additional data of sutures (San et al., 2009), Sra Kaeo Suture (Udchachon et al., 2018); most of sedimentary basins, additional structure and Kampot Fold Belt (Fyhn et al., 2016, 2010c), most of the Fold Belts (Zaw et al., 2014), Dalat-Kratie Belt (Cheng et al., 2019), Mae Ping Fault (Cheng et al., 2019; Fyhn et al., 2010b), Pattani and Malay Basins with structures in the Gulf of Thailand and northern Malaysia (Watcharanantakul and Morley, 2000), Phitsanulok Basin (Bal et al., 1992), Cambodian sedimentary basins (Mao et al., 2014; Vysotsky et al., 1994)).*

and the seismic profile of the nearby basin(s) in other countries such as structural styles and unconformities.

TECTONIC SETTING CORRELATED WITH SEDIMENTARY BASIN EVOLUTION

Based on the formation of many sedimentary basins in Indochina Terrane, around Cambodia, two types of basins have been classified, Paleozoic – Mesozoic basins and Tertiary basins. The Paleozoic – Mesozoic basins (Khorat Plateau Basin in Thailand, and Phu Quoc or Phu Quoc-Kampong Som Basin in Vietnam; Figure 1) are located inside the Indochina Terrane. The Tertiary basins are located at the terrane boundary, where the sutures and Cenozoic strike-slip faults took place,

starting from Song Hong/Yinggehai Basin along Song Ma and Red River Fault, continuing southward to Phu Khanh Basin along East Vietnam Fault, Cuu Long and Nam Con Son, followed by NW-SE Malay Basin along NW trend fault and continued northward following the Chanthaburi Suture by passing through Khmer, Pattani, Kra, and other nearby basins, and finally continued to Ayutthaya and Phitsanulok Basins along Nan-Uttaradit Suture (Figure 1).

From time to time, the terranes of the Gondwana supercontinent had rifted, drifted, and merged that lead to the opening and closing of Paleo-Tethys Oceans (Metcalfe, 2005, 2011, 2013) created rifting, subsidence, and inversion of intra-arc, fore-arc and back-arc basins (Minezaki, 2019; San et al., 2009).

Cambodia is located at the center of Indochina Terrane, one among other terranes (Figure 2) that rifted and separated from the eastern Gondwana during the Devonian time (Metcalfe, 2013) or the Early Silurian based on the alkali rhyolite U-Pb zircon dating in Loei Fold Belt (Zaw et al., 2014). Those terranes are collided within the Paleo-Tethys Ocean (Metcalfe, 2013) and most of the Indochina terrane was covered by shallow sea in the Early Carboniferous – Permian (Metcalfe, 2013, 2011).

DISCUSSION

Paleozoic – Mesozoic Basins

Paleozoic-Mesozoic basins were formed from the opening and closing of Paleo-Tethys Ocean associated with rifting, regional subsidence, and inversion of intra-arc, fore-arc, and back-arc basins (Metcalfe, 2013, 2011; Minezaki et al., 2019; San et al., 2009). Khorat Plateau Basin and Phu Quoc or Phu Quoc-Kampong Som Basin (Figure 1) are foreland basins that are considered to be one N-S elongate continuous basin (Fyhn et al., 2010c; Nguyen et al., 2014; San et al., 2009).

Khorat and Kampong Som Basins are discussed and linked with Khorat Plateau Basin and Phu Quoc or Phu Quoc-Kampong Som Basin due to the similar evolution and tectonic setting.

Khorat Plateau Basin was reported to rift in the Late Carboniferous to form host and graben system in the Permian, half- and full-grabens (Minezaki et al., 2019; Morley et al., 2013). While the Phu Quoc or Phu Quoc-Kampong Som Basin was probably rifted later in the Late Permian during the continental rifting (San et al., 2009). These two basins, Khorat Plateau and Phu Quoc are linked together inside the Indochina terrane and separated by the major strike-slip faults during the Tertiary (Fyhn et al., 2010b; San et al., 2009).

During the rifting period, Late Carboniferous – Permian, most of the Indochina terrane was covered by shallow sea (Metcalfe, 2013, 2011) that lead to the deposition of the Carboniferous – Permian fusuline carbonate complex (Metcalfe, 2013; San et al., 2009). Based on the stratigraphy correlated with well data of Khorat Plateau Basin and regional data, the sequence of Late Carboniferous and Permian are mainly thick carbonates and shales with some terrigenous deposits associated with shallow marine and littoral-fluvial environment (Minezaki et al., 2019).

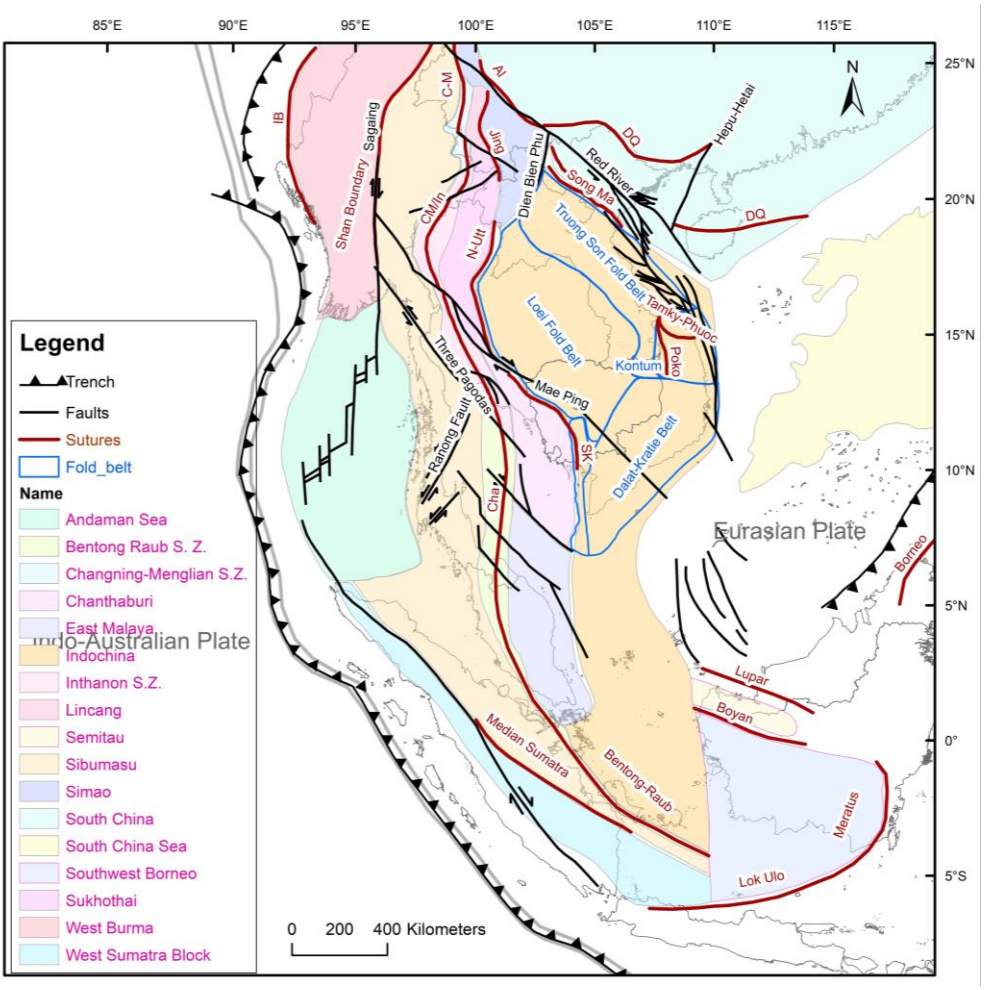


Figure 2: *Main SE Asia terranes, sutures, faults and trenches located in the Eurasian plates. IB: Indoburman, C-M: Changning-Menglian, CM/In: Chiang Mai/Inthanon, Jing: Jinghong, Al: Ailaoshan, N-Utt: Nan-Uttaradit, Cha: Chanthaburi, SK: Sra Kaeo, DQ: Dian Qiong. (Source: most of data are revised from Metcalfe (2013, 2011), where additional data of sutures (San et al., 2009), Sra Kaeo Suture (Udchachon et al., 2018), additional structure and Kampot Fold Belt (Fyhn et al., 2016, 2010c), most of the Fold Belts (Zaw et al., 2014), Dalat-Kratie Belt (Cheng et al., 2019), Mae Ping Fault (Cheng et al., 2019; Fyhn et al., 2010b), structures in the Gulf of Thailand and northern Malaysia (Watcharanantakul and Morley, 2000)).*

This is consistent with the statement that the sediments deposition consists of Late Carboniferous to Permian marginal-marine to outer-shelf siliciclastic and carbonates in the Khorat Plateau Basin, Thailand (Minezaki et al., 2019; Smith and Stokes, 1997) and the exposed outcrops of Permian limestones/ carbonates in NE, NW and southern Cambodia and the Late Carboniferous-Early Permian terrigenous-carbonates in the Kampong Som Trough (BRGM and GDMR-JICA, 2010; Vysotsky et al., 1994).

After rifting, these basins were influenced by the Indosinian Orogeny that associated with three regional tectonic events including the South China-Indochina subduction during the Late Permian – Middle Triassic (Cai and Zhang, 2009; Hu et al., 2015; Lepvrier et al., 2004; Zaw et al., 2014), the Sibumasu-Sukhothai-Indochina

collision during the Late Triassic – Early Jurassic (Lepvrier et al., 2008, 2004; Metcalfe, 2013, 2011; Morley et al., 2013), and the Paleo-Pacific westward subduction during the Mesozoic or up to the Paleogene (Cheng et al., 2019; Fyhn et al., 2016).

During the Triassic, alluvial-fan and fluvial coarse-grained sandstones, and lacustrine shales interbedded with volcaniclastic rocks were deposited in the Khorat Plateau Basin. And it is overlain by the Jurassic – Early Cretaceous thick terrestrial-fluvial red beds (conglomerates, sandstone, and mudstones) and the Late Cretaceous evaporite deposits (Minezaki, 2019). San et al. (2009) mentioned similar depositional environments such as fluvio-lacustrine, terrestrial-volcanic complex, lacustrine, and terrigenous red formations (fluvio-deltaic and lacustrine) with salt and gypsum from the Late Triassic to the Late Cretaceous in the Khorat Plateau and Phu Quoc Basins. This statement is also consistent with the stratigraphy in Cambodia that the Triassic terrigenous rocks, including basal conglomerates, breccias, sandstones, marl-shales, and shales are overlain by the Late Triassic-Middle Jurassic red terrigenous rocks that came from lacustrine or lagoonal origin, and covered by the Late Jurassic-Cretaceous upper sandstones of Bokor or Phu Quoc Formation (Fyhn et al., 2010b) with interlayers of siltstones, green clays and gypsum, and volcaniclastic sandstones (Vysotsky et al., 1994). The sedimentary units of the Khorat Group are similar to the Late Jurassic-Early Cretaceous Bokor Formation (or Phu Quoc Formation in Vietnam) exposed along the Elephant and Bokor Mountain, Cambodia (Fyhn et al., 2010b) that consist of lateral continuous fluvial cross-bedded sandstones interbedded with subordinate lacustrine and floodplain mudstones with minor shallow-marine sandstones. In the Kampong Som Trough, the Late Permian-Middle Triassic terrigenous carbonates and volcaniclastic were overlain by the Late Triassic-Middle Jurassic terrigenous units with minor transgressive silt and clays, followed by the Late Jurassic – Cretaceous terrestrial sediments (Vysotsky et al., 1994). According to the seismic profile, thin Cenozoic strata have been interpreted at the base of Bokor Mountain (Fyhn et al., 2016) that should be mainly sandstone and some claystone based on the stratigraphy of Kampong Som Trough (Figures 3 & 4, Mao et al., 2014; Vysotsky et al., 1994). Moreover, it is also consistent with the Miocene regional transgression in southern Indochina that constitute fluvio-lacustrine sediments (Charusiri and Pum-Im, 2009; Kaewpradit, 2018; Nguyen et al., 2014).
During the Indosinian Orogeny that occurred in most of the Mesozoic, the Paleozoic – Mesozoic Basins, Khorat Plateau and Phu Quoc-Kampong Som, are affected by the inversion producing occasional uplift and erosion-related unconformities (Fyhn et al., 2010b, 2016; Minezaki et al., 2019; Morley et al., 2013). Based on the tectonic setting, structure, stratigraphy, well and seismic data of the Khorat Plateau, Phu Quoc Basin, and southern Cambodia, the erosion-related unconformities of the Khorat and Kampong Som Basins is assumed to occur above the Mid-Carboniferous, at the Permo-Triassic boundary (Indosinian I), at the Late Triassic (Indosinian II), and at the Aptian-Albian of the Cretaceous as added in Figure 3 (Fyhn et al., 2016; Lepvrier et al., 2004; Minezaki et al., 2019; Morley et al., 2013). This statement is also consistent with the exhumation and denudation of approximately 6 – 11 km in the Kampot Fold Belt, Cambodia, and 2.5 – 4.5 km in

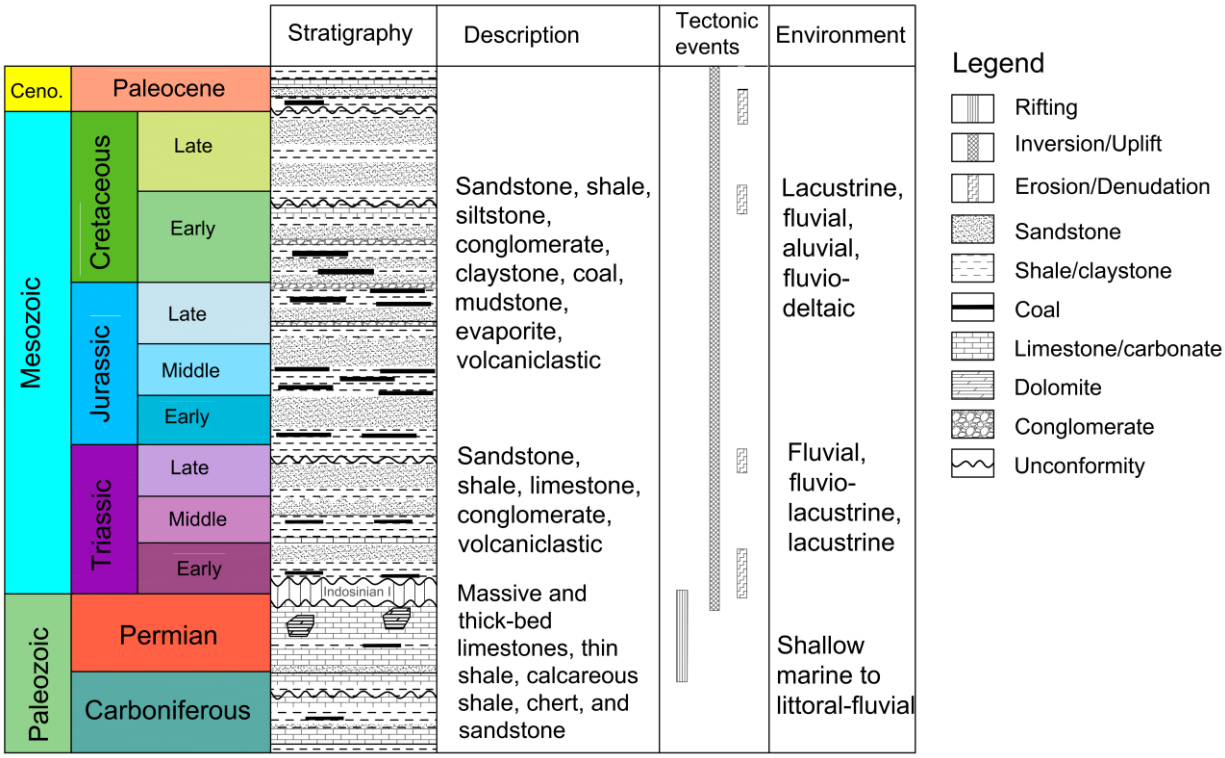


Figure 3: *Summarized stratigraphy and sedimentary basin evolution of the Khorat and Kampong Som Basins. (Sources: stratigraphy, description, environment (Fyhn et al., 2010b; Minezaki et al., 2019; San et al., 2009; Vysotsky et al., 1994); formation (Cai and Zhang, 2009; Cheng et al., 2019; Fyhn et al., 2016; Hall, 2011; Metcalfe, 2013; Minezaki et al., 2019; San et al., 2009; Zaw et al., 2014); unconformity (Fyhn et al., 2016; Mao et al., 2014; Minezaki et al., 2019; San et al., 2009).*

the Phu Quoc-Kampong Som Basin (Fyhn et al., 2016).

According to the tectonic setting of the Indochina during the Mesozoic, the Khorat Plateau and Phu Quoc Basins should have been connected as the subduction and collision occurred around these two basins to create major compression, however the inversion of Khorat Plateau Basin should have started earlier in the Triassic because of the early influence of northern major tectonic events, South China – Indochina subduction (Cai and Zhang, 2009; Hu et al., 2015; Lepvrier et al., 2004; Zaw et al., 2014). And the southern inversion of Phu Quoc-Kampong Som Basin, should started later and continued until the Paleogene because of the major influence of Sibumasu-Sukhothai-Indochina ollision (Lepvrier et al., 2008, 2004; Metcalfe, 2013, 2011; Morley et al., 2013) and Paleo-Pacific Ocean westward subduction (Cheng et al., 2019; Fyhn et al., 2016; Hall, 2011). These statements are also consistent with the uplift and erosions of the Khorat Plateau Basin described above and the latest Cretaceous to Paleocene uplift and erosion of the Kampot Fold Belt and surrounding region, also included Phu Quoc-Kampong Som Basin (Fyhn et al., 2016). For these reason, the latest Cretaceous to Paleocene could be major event related to the tectonic setting that is completely eroded in the

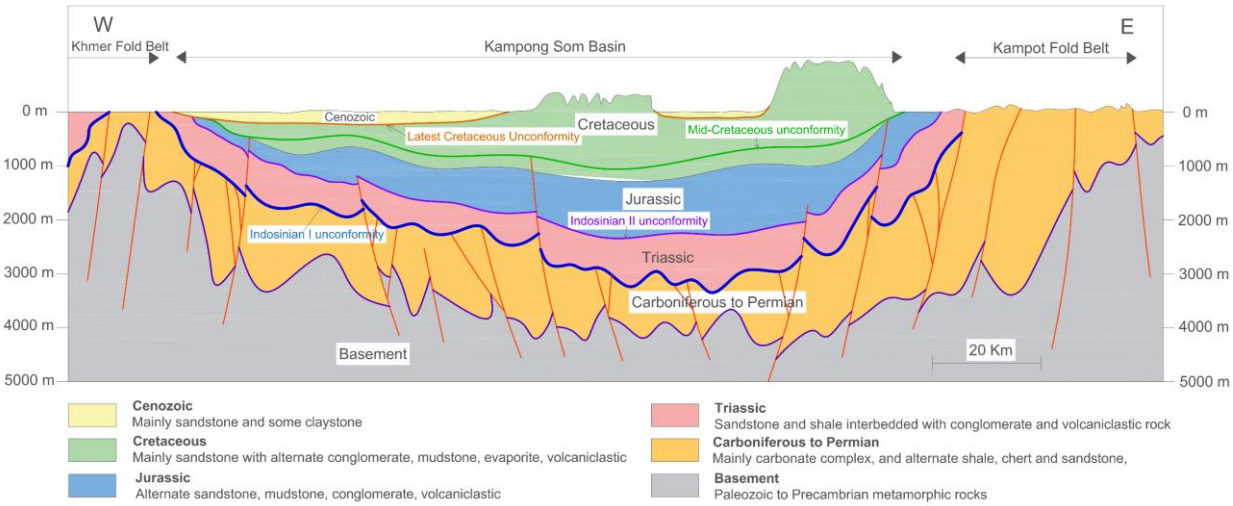


Figure 4: *Simplified profile of Kampong Som Basin compiled from data of Cambodia (Fyhn et al., 2016; Mao et al., 2014; Vysotsky et al., 1994), Khorat Plateau Basin (Minezaki et al., 2019), and Phu Quoc Basin (Fyhn et al., 2016, 2010c; San et al., 2009).*

Khorat Plateau Basin in Thailand as we cannot see in the stratigraphy or well data (Minezaki et al., 2019). Hence, the uplift has been marked until the Paleogene and the last unconformity-related erosion is placed at the latest Cretaceous and earliest Cenozoic, Figure 3.

The profile of Kampong Som Basin (Figure 4) was constructed from E to W based on the simplified geological cross-section and stratigraphy of Kampong Som Basin (Fyhn et al., 2016; Mao et al., 2014; Vysotsky et al., 1994) combined with some data of Khorat Plateau Basin (Minezaki et al., 2019) and Phu Quoc Basin (Fyhn et al., 2010c, 2016; San et al., 2009) as described in the above section.

Meanwhile the profile of Khorat Basin, Figure, was generated from the available cross-section of Khorat Basin (Vysotsky et al., 1994) and the above discussion compiled with Khorat Plateau Basin drill well data and seismic data (Minezaki et al., 2019), in the N-S direction.

Tertiary Basins

Tertiary basins are the sedimentary basins that formed during the Tertiary period and associated with the Cenozoic strike-slip faults, mostly occurred along the suture zones or terranes' boundary.

After the Indosinian Orogeny occurred, the Indochina, as well as Cambodia, was affected by many major Cenozoic tectonic events, including the escape tectonic of Indian-Eurasian Plate during the Middle Eocene – Present (Metcalfe, 2013) together with the rollback subduction of Indo-Australian Plate beneath the Eurasian Plate during the Oligocene/Miocene to the Present (Hall, 2011), and the seafloor spreading of South China Sea Plate during the Early Oligocene – Middle Miocene (Yin et al., 2018; Zhang et al., 2016). Those major tectonic events were probably the leading causes that controlled the major strike-slip faults inside the Indochina Terrane such as Wang Chao or Mae Ping, Three Pagodas, Red River, and Dien Bien Phu Faults (Figures 1 & 2, Charusiri et al., 2007; Fyhn et al., 2016, 2010a, 2010c;

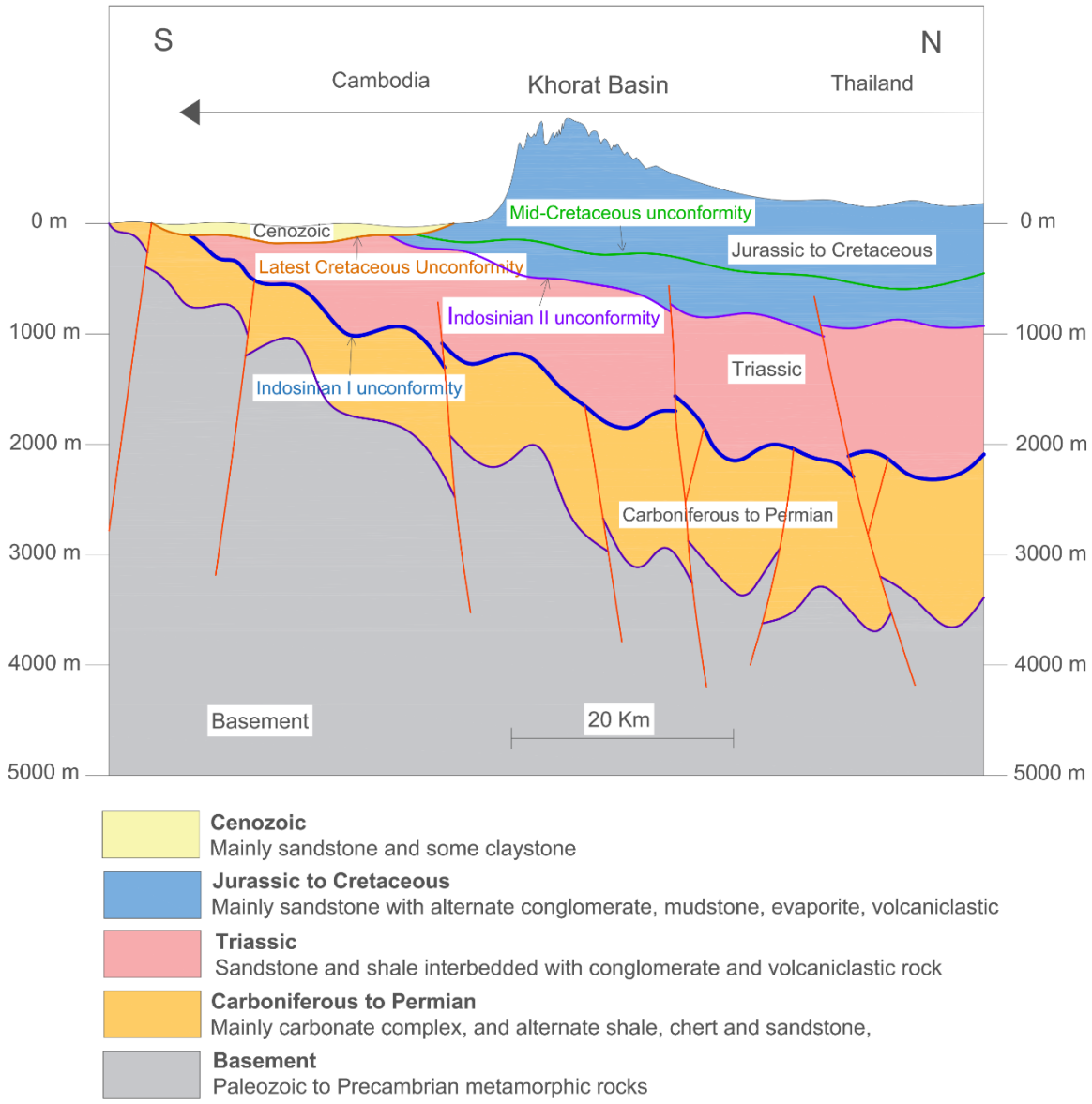


Figure 5: *Simplified profile of Khorat Basin compiled from data in Cambodia (Mao et al., 2014; Vysotsky et al., 1994) and Khorat Plateau basin in Thailand (Minezaki et al., 2019).*

Morley, 2001; Nguyen et al., 2014) that are the main cause of sedimentary basins formation. Those major strike-slip faults had changed its movement from right to left or left to right movement after the Middle Miocene (Charusiri et al., 2007) that were probably caused by the extrusion of Indian-Eurasian, and/or convection currents in the mantle, and seafloor spreading of the South China Sea that also produced 20^0 to 30^0 clockwise rotations of Indochina Terrane (Nguyen et al., 2014; Nielsen et al., 1999).

Tertiary basins are divided into two types, one is related to faults/faults strands and faults systems (onshore, Tonle Sap and Svayrieng Basins), and another one is related to thermal subsidence and conjugate faults (offshore, Khmer Basin).

Tonle Sap and Svayrieng Basin

Tonle Sap and Svayrieng Basins are discussed and correlated with the evolution of Phitsanulok, Ayutthaya, Cuu Long, and Nam Con Son Basins since they are located in the same fault trend and formed associated with the Mae Ping Fault Zone.

The onshore of Cambodia is mainly influenced by a major strike-slip fault, Mae Ping Fault Zone (Figures 1 & 2) or its fault strands that extended from Thailand in the NW trend passing through NW Cambodia, Tonle Sap Lake, and continuing southeastward into the Vietnamese Sea (Charusiri et al., 2007; Fyhn et al., 2010b, 2010a; Morley, 2001; Nguyen et al., 2014). Mae Ping Fault is a major left-lateral strike-slip fault from the Middle Eocene – Early Oligocene (*ca.* 40-30 Ma), that ended the movement at *ca.* 30 Ma, the Early Oligocene (Fyhn et al., 2010a; Lacassin et al., 1997; Morley, 2001).

The Tonle Sap and Svayrieng Basins are pull-apart basins associated with Mae Ping Fault zone or fault strands that also passing through southern Phitsanulok, northern Ayutthaya Basin, Cuu Long, and Nam Con Son Basins in the NW-SE trend (Figure 1). The activation of Mae Ping (combined with other faults) created the rapid extension in the Phitsanulok and Ayutthaya Basins (Bal et al., 1992; Kaewpradit, 2018; Pinyo, 2010) and produced rifts in the Cuu Long and Nam Con Son Basins (Nguyen et al., 2014). Therefore, the sinistral movement of the Mae Ping Fault or its fault strands might create rifting and extension in the Tonle Sap and Svayrieng Basins during the Middle Eocene-Early Oligocene, as defined in the Phitsanulok, Ayutthaya, Cuu Long, and Nam Con Son Basins (Bal et al., 1992; Kaewpradit, 2018; Nguyen et al., 2014; Pinyo, 2010). This extension led to the deposition of sediments from the basement high and the surrounding terrigenous sediments (Vysotsky et al., 1994) that are associated with lacustrine environment (lacustrine delta or fluvio-lacustrine) during probably the Oligocene to the Miocene as defined in other sedimentary basins such as the Phitsanulok (Oligocene to Early Miocene, Lawwongngam and Philp, 1993; Pinyo, 2010), Ayutthaya (Early – Middle Miocene, Kaewpradit, 2018), Cuu Long (Oligocene, Bojesen-Koefoed et al., 2009; Nguyen et al., 2014), Pattani, Malay and Khmer Basins (Eocene – Oligocene – Middle Miocene, Morley et al., 2011; Nguyen et al., 2014; Okui et al., 1997).

In the Early Miocene, Mae Ping Fault changed its direction from left- to right-lateral (Charusiri et al., 2007; Fyhn et al., 2010a; Lacassin et al., 1997) that might produce Tonle Sap and Svayrieng Basins' inversion during the Early – Middle Miocene (Figure 5) as defined in Phitsanulok (Middle Miocene), Ayutthaya (Middle – Late Miocene), Cuu Long (Late Oligocene – Early Miocene), and Nam Con Son (Middle – Late Miocene) (Du Hung and Van Le, 2004; Kaewpradit, 2018; Lawwongngam and Philp, 1993; Lee et al., 2001). The basin inversion may also be associated with the uplift and erosion unconformities or denudation due to the climate change supported by Fyhn et al. (2016, 2013) and Lawwongngam and Philp (1993), who have mentioned the erosion unconformities or denudation occurrent in southern Cambodia, central Vietnam, and Phitsanulok Basin respectively. So, this erosion or denudation related to the unconformities, regional scale, has also been added to the summary of basin formation in Figure 6, such as at the Mid – Miocene to the early Late Miocene as

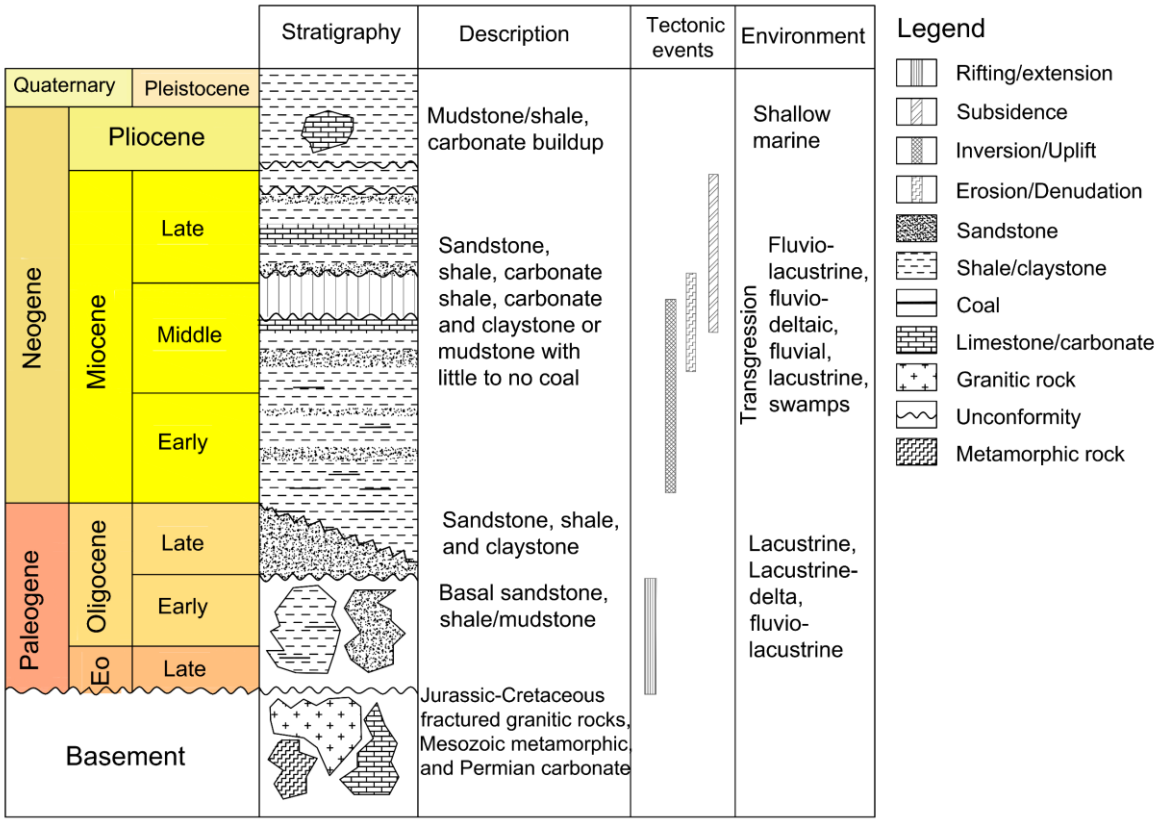


Figure 6: *Summarized stratigraphy and basin evolution of Tonle Sap and Svayrieng Basins. (Sources: formation (Bal et al., 1992; Fyhn et al., 2010a; Nguyen et al., 2014; Pinyo, 2010) supported by (Charusiri et al., 2007; Fyhn et al., 2016, 2013; Jitmahantakul et al., 2020; Lacassin et al., 1997; Lawwongngam and Philp, 1993; Lee et al., 2001; Morley, 2015, 2001; Morley et al., 2011; Palin et al., 2013); stratigraphy, description, environment (Bal et al., 1992; Bojesen-Koefoed et al., 2009; Charusiri and Pum-Im, 2009; Du Hung and Van Le, 2004; Fyhn et al., 2013; Kerimov et al., 2019; Lawwongngam and Philp, 1993; Mao et al., 2014; Matthews et al., 1997; Minezaki, 2019; Morley, 2015; Nguyen et al., 2014; Pinyo, 2010; Vysotsky et al.,*

defined also in the Gulf and Central Thailand from the geophysics data (Kaewpradit, 2018), at the Pre-Tertiary, top of basement, at the top of Oligocene, at the Late Miocene and Early Pliocene according the seismic and well data of Cuu Long and Nam Con Son Basins (Fyhn et al., 2009; Lee et al., 2001; Nguyen et al., 2014).

Southern Indochina was affected by regional transgression associated with early post-rift deep subsidence and the South China Sea opening/spreading that could constitute to the successions of transgressive sandstones & shales, carbonate reef, carbonate platform, and calcareous shales during the Early Miocene (Charusiri and Pum-Im, 2009; Fyhn et al., 2013; Giao et al., 2016; Nguyen et al., 2014). The transgression and marine deposit were also extended to the Gulf and central Thailand basin in the Late Miocene (Charusiri and Pum-Im, 2009; Kaewpradit, 2018) therefore it could also reach Svayrieng and Tonle Sap Basins during probably the Middle – Late Miocene that could lead to the deposition of sandstones, shales, and carbonate rocks.

The subsidence was assumed to occur in Tonle Sap and Svayrieng Basins as regional slow uniform subsidence during the Middle – Late Miocene because the surrounding subsidence as described above and the subsidence within Phitsanulok and Ayutthaya Basins during the Mid – Miocene (Jitmahantakul et al., 2020; Kaewpradit, 2018; Morley, 2015, 2001), and the rapid subsidence of Khmer, Pattani and Malay Basin in the Neogene (Morley, 2015; Morley et al., 2011).

According to Vysotsky et al. (1994) and the tectonic setting, Tonle Sap and Svayrieng Basins were expected to be Paleozoic – Mesozoic basins because they are located at the same trend as Khorat and Kampong Som Basins, however, these basins were cut by Mae Ping Fault Zone or strands that make these basins Tertiary basins or both types where the pre-Tertiary rocks are also played as an important source and reservoir rocks.

By considering the tectonic setting, the formation of Tonle Sap and Svayrieng Basins, and the stratigraphy of Cambodia (Mao et al., 2014; Vysotsky et al., 1994), the basement of Tonle Sap and Svayrieng basins (Figure 6) should be Mesozoic metamorphic rocks related with Indosinian Orogeny, granitic intrusion of the Jurassic – Cretaceous and Permian carbonates (Kaewpradit, 2018; Kerimov et al., 2019; Mao et al., 2014; Minezaki, 2019; Nguyen et al., 2014; Vysotsky et al., 1994).

Finally, the profile of Tonle Sap Basin, Figure 7, is produced from the stratigraphy and available basin data in Cambodia (Mao et al., 2014; Vysotsky et al., 1994) combined with the above discussion, the seismic and well data of Ayutthaya Basin (Kaewpradit, 2018) and Phitsanulok Basin (Morley, 2015) due to their nearby location.

Svayrieng Basin's profile, Figure 8, is compiled from the above discussion combined with well data and seismic profile of Cuu Long and Nam Con Son Basins

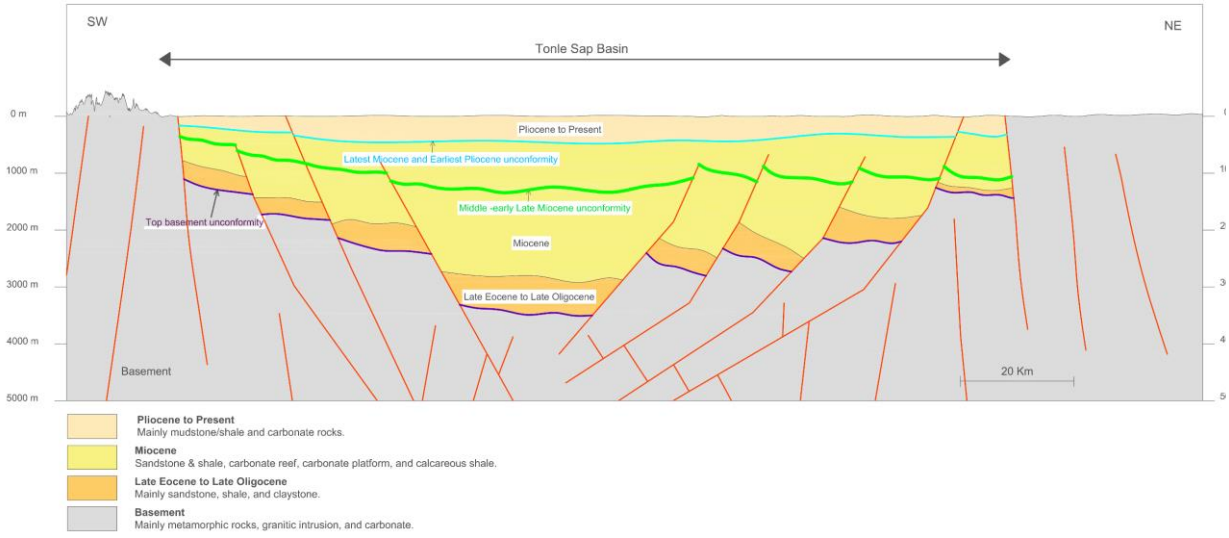


Figure 7: *Simplified profile of Tonle Sap Basin compiled from data of Cambodia (Mao et al., 2014; Vysotsky et al., 1994) combined with data from Ayutthaya Basin (Kaewpradit, 2018) and Phitsanulok Basin (Morley, 2015).*

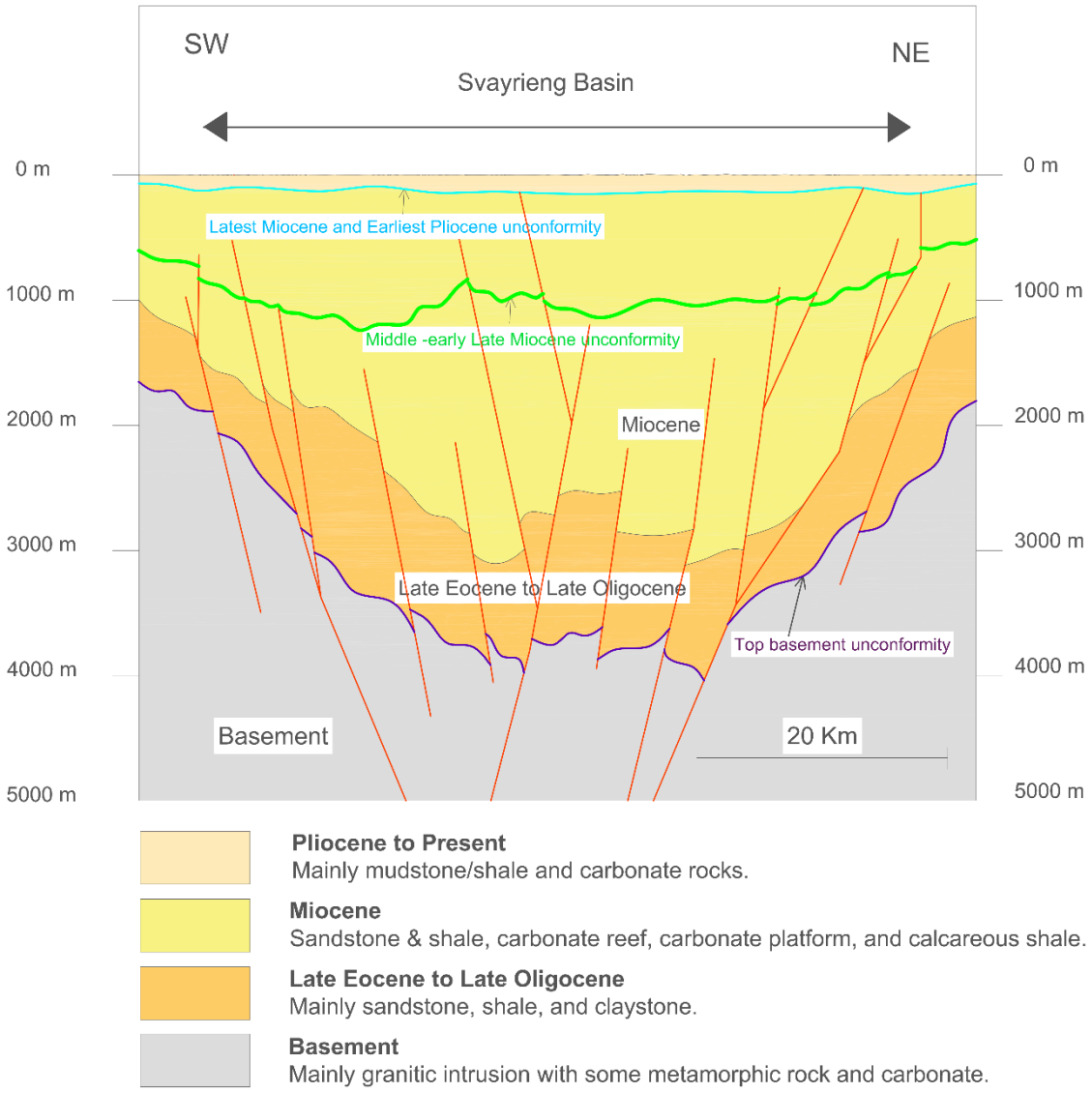


Figure 8: *Simplified profile of Svayrieng Basin compiled from available data of Cambodia, Cuu Long Basin (Fyhn et al., 2009) and Nam Con Son Basin (Tran et al., 2016).*

(Fyhn et al., 2009; Tran et al., 2016) since they are closer.

Khmer Basin

Khmer Basin is discussed and associated with the Pattani and North Malay Basin due to its nearby locations, similar formation, and tectonic setting. Khmer Basin, Figure 1, is the northern extension of Malay Basin (Bishop, 2002) and separated from Pattani Basin on the west by Khmer Ridge (Okui et al., 1997). Khmer, Pattani and Malay Basins were influenced by conjugate faults and rapid thermal subsidence (Bishop, 2002; Mansor et al., 2014; Morley, 2016, 2015; Nguyen et al., 2014; Okui et al., 1997).

The offshore of Cambodia as well as Khmer Basin is possibly influenced by few major Tertiary strike-slip faults such as the Three Pagodas Faults strands/splay, the Mae Ping Faults strands, and the Axial Malay

Fault (Bishop, 2002; Lacassin et al., 1997; Mansor et al., 2014; Nguyen et al., 2014; Tjia, 2014) because their trends could reach Khmer Basin (Bishop, 2002; Morley, 2016), see Figure 1. Those majors faults are left lateral strike-slip fault in the Paleogene and change to right lateral strike-slip fault in the Miocene (Charusiri et al., 2007; Fyhn et al., 2010a; Lacassin et al., 1997; Rhodes et al., 2005; Tjia, 2014).

From the Late Eocene to the Oligocene, Khmer Basin is affected by left lateral movement of the strike-slip faults (probably Three Pagodas strand, Mae Ping strand and Axial Malay Faults splay or strands) that created multi-stage of extension as defined in the Eastern Graben (part of Khmer Basin when plotted, (Morley, 2016)), in Pattani Basin (Late Eocene – Early Miocene, (Kornsawan and Morley, 2002; Morley, 2016)), and in North Malay Basin (Eocene – Oligocene, (Mansor et al., 2014; Morley, 2016)).

These major sinistral strike-slip faults have created rift and extension in Khmer Basin led to the deposition of terrigenous clastic that consists mainly of lacustrine deposits and continental clastic such as delta floodplain, and fluvial from the Oligocene to the Early Miocene (Bishop, 2002; Charusiri and Pum-Im, 2009; Morley, 2015; Morley et al., 2011; Okui et al., 1997). The rock units of the Early Oligocene are claystone, middle and basal sandstone covered by Late Oligocene organic-rich claystone, calcareous claystone, and sandstone (Mao et al., 2014; Okui et al., 1997).

During the Early – Middle Miocene, Khmer Basin is affected by regional post-rift rapid thermal subsidence due to high heat flow and geothermal gradients that produced low displacement conjugate fault sets as defined in Pattani and Malay Basins as well (Bishop, 2002; Kornsawan and Morley, 2002; Morley, 2015; Morley et al., 2011; Okui et al., 1997). Through this major post-rift rapid thermal subsidence, the entire Gulf of Thailand was affected by Miocene transgression of the South China Sea (Bishop, 2002; Fyhn et al., 2013; Nguyen et al., 2014) that led to the Miocene swamp deposits associated with fluvial-deltaic to paralic clastic sediment of coarse- to fine-grained and coal-rich (Charusiri and Pum-Im, 2009; Morley, 2016, 2015; Morley et al., 2011; Nguyen et al., 2014; Okui et al., 1997; Vysotsky et al., 1994). Based on the stratigraphy of Khmer Through, the Miocene rock units are alternate claystone, channel and overbank sandstone with occasional coal bed and thin limestone/dolomite (Mao et al., 2014; Okui et al., 1997).

Then, Khmer Basin was effected by inversion with slightly subsidence from the Middle Miocene to the Pleistocene (Bishop, 2002; Fyhn et al., 2010a; Madon and Watts, 1998; Mansor et al., 2014; Morley et al., 2011; Ngah et al., 1996; Nguyen et al., 2014) caused by major events, probably the change of fault direction, the mantle convection currents, the South China Sea seafloor spreading, and the subduction of Indo-Australian plate that produced inversion structures and unconformities (Mansor et al., 2014; Nguyen et al., 2014). From the Late Miocene to the Pliocene/Recent, shallow or marginal marine was deposited that leads to the succession of fine- to medium-grained sandstones, marine shales, and carbonate rocks/limestones (Charusiri and Pum-Im, 2009; Nguyen et al., 2014). According to the stratigraphy of Khmer Trough, the Late Miocene-Pliocene units consist mainly of claystone and coal with occasional

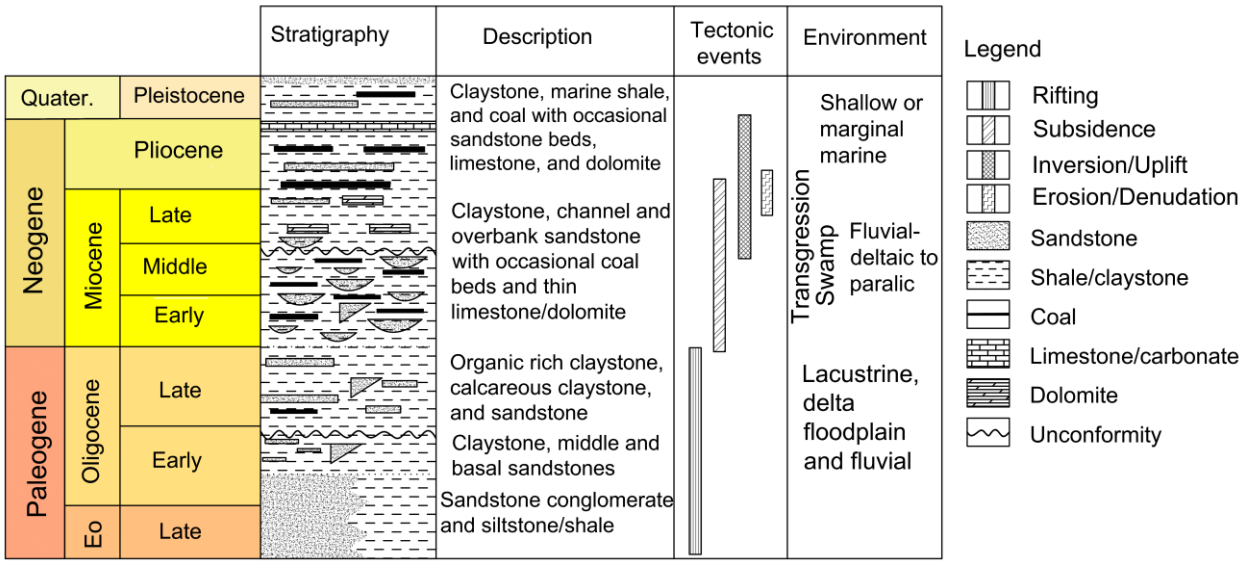


Figure 9: *Summarized stratigraphy and evolution of Khmer Basin. (Sources: tectonic events (Bishop, 2002; Fyhn et al., 2013, 2010a; Madon and Watts, 1998; Morley, 2015, 2004; Morley et al., 2011; Nguyen et al., 2014; Vysotsky et al., 1994; Watcharanantakul and Morley, 2000); unconformities (Bustin and Chonchawalit, 1995; Fyhn et al., 2013; Okui et al., 1997; Rattanasriampaipong, 2016); stratigraphy, description, and environment (Bishop, 2002; Charusiri and Pum-Im, 2009; Fyhn et al., 2013; Madon and Watts, 1998; Mao et al., 2014; Morley et al., 2011; Nguyen et al., 2014; Okui et al., 1997; Vysotsky et al., 1994).*

sandstone beds, limestone, and dolomite at the base (Mao et al., 2014; Okui et al., 1997). The formation, sedimentation, and depositional environment of the Khmer Basin are summarized in Figure 9.

The erosion related unconformities, Figure 9, are occasionally taking place at the Middle Miocene as define in Pattani Basin in the Mid – Miocene (Bustin and Chonchawalit, 1995; Rattanasriampaipong, 2016) consistent with the Middle Miocene uplift and denudation occurred in the central and southern Indochina (Fyhn et al., 2013), and at the Early Oligocene according to the angular unconformity in the vicinity of well L-1, Khmer Basin (Okui et al., 1997).

A profile of Khmer Basin was created from the simplified geological cross-section of Khmer Basin (Mao et al., 2014; Vysotsky et al., 1994) and its stratigraphy (Okui et al., 1997) combined with the seismic data interpretation of North Malay Basin, Pattani Basin and Eastern Graben (Mansor et al., 2014; Morley, 2016, 2015; Morley et al., 2011) from WSW to ENE, Figure 10.

To get the general idea of the relationship between the major tectonic events, unconformities, and basin's evolution, Figure 11, have been created as below.

CONCLUSIONS

Cambodia as well as Indochina is affected by the subduction of South China beneath the Indochina, the collision of Sibumasu-Sukhothai and Indochina, and the westward subduction of Paleo-Pacific beneath the Indochina, during most of the Mesozoic, that associated with the

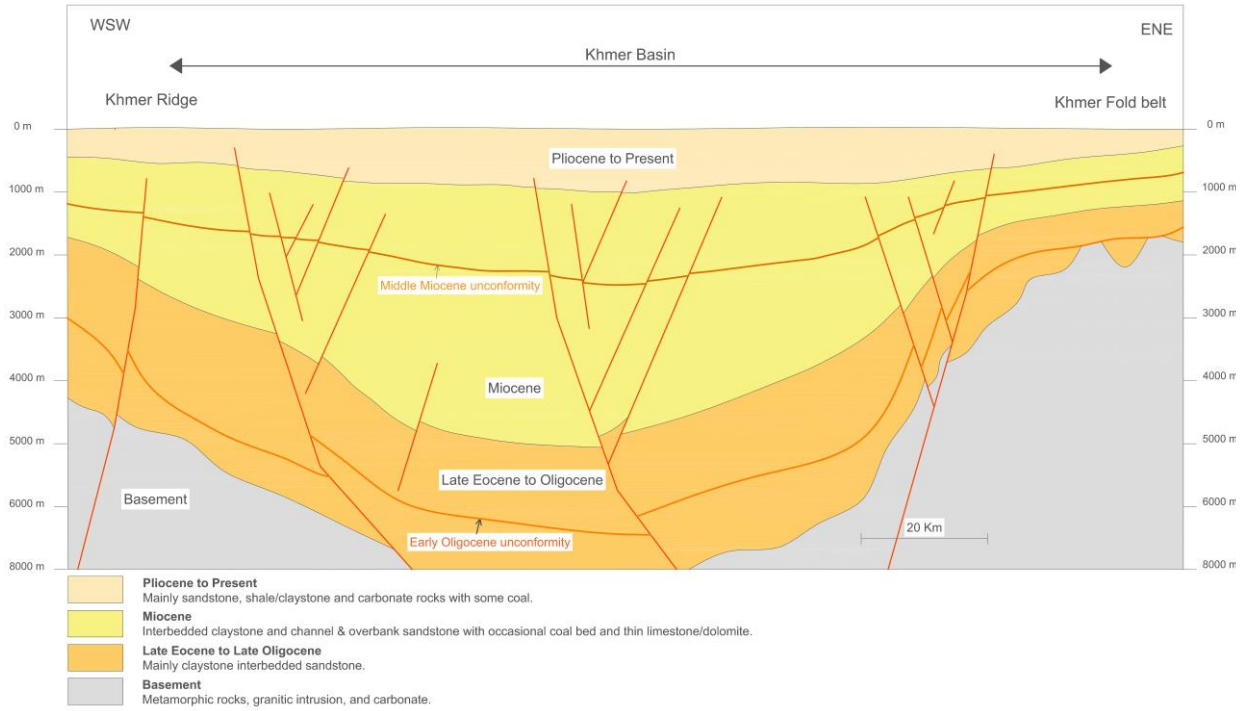


Figure 10: *Simplified Profile of Khmer Basin compiled from data of Cambodia (Mao et al., 2014; Okui et al., 1997; Vysotsky et al., 1994) combined with data of Pattani and Malay Basin (Mansor et al., 2014; Morley, 2016, 2015; Morley et al., 2011).*

formation of Paleozoic – Mesozoic Basin. Later, Cambodia is influenced by the Tertiary strike-slip faults such as Mae Ping and Three Pagodas Fault that associated with the Tertiary rift basins.

The Khorat and Kampong Som Basins are part of Paleozoic – Mesozoic Khorat Plateau-Phu Quoc foreland basins that is assumed to be one elongated continuous basin. It was formed from the amalgamation of Sibumasu-Sukhothai, Indochina, South China, and the Paleo-Pacific Ocean Plate. First, the rifting started from the North (Khorat Plateau) since the Late Carboniferous and continued to the South (Phu Quoc) in the Late Permian. During this period, the basins were covered by mostly shallow sea with limit terrigenous source associated with massive carbonate and siliciclastic. Then, it was followed by Mesozoic basin inversion that associated with the Indosinian Orogeny. The basin inversion continued until the Paleogene, due to the cessation of Paleo-Pacific subduction. During the inversion, the sediment is mainly terrestrial sources associated with mainly sandstones, shale, and volcaniclastic. Finally, the uplift and erosion related with unconformity have occurred simultaneously at the Permo-Triassic boundary, at the Late Triassic, at the Early Cretaceous, and at the latest Cretaceous – earliest Cenozoic.

Tonle Sap and Svayrieng Basins are located between Khorat Plateau Basin and Phu Quoc or Phu Quoc-Kampong Som Basins that are Paleozoic-Mesozoic basins, but they are considered as Tertiary rift basins because they are associated with later Tertiary strike-slip fault, Mae Ping Fault

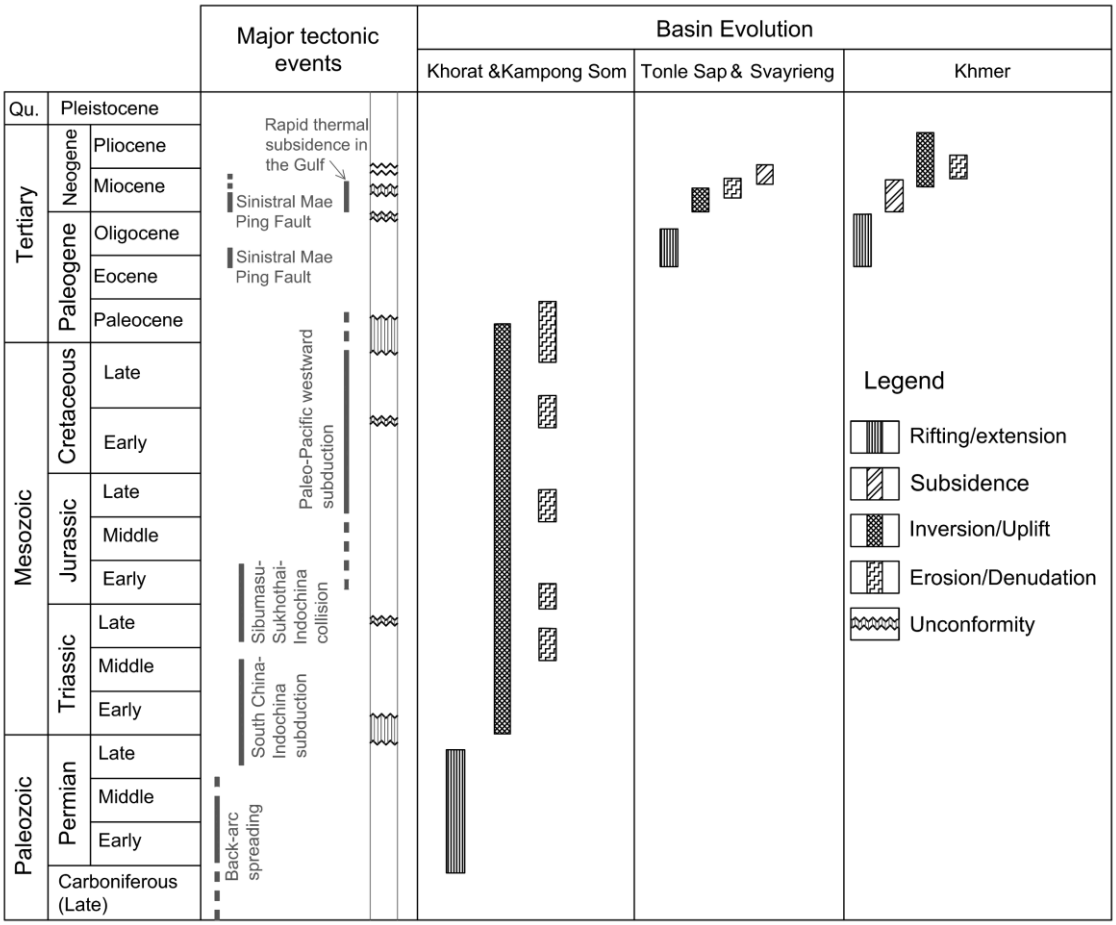


Figure 11: *Summarized the majors tectonic events correlated with the sedimentary basins' evolution in Cambodia.*

Zone or its faults strands. However, the source rocks in Khorat and Kampong Som Basins are playing an important role in these basins as well. The formation of these two basins started with Middle Eocene – Early Oligocene rifting and extension due to Mae Ping Fault's left-lateral movement. During rifting and extension, the basin is covered mainly by lacustrine sediments including sandstone, shale or claystone. Then, it was affected by Early – Middle Miocene inversion due to the direction change of Mae Ping Faults. During this inversion, the uplift, and denudation related unconformity was occasionally took place at the Mid – Miocene to the early Late Miocene, at the top basement of Pre-Tertiary, at the top Oligocene, and at the boundary of Miocene - Pliocene. Due to the regional subsidence in southern Indochina, these basins have also been influenced by slow uniform subsidence during the Middle – Late Miocene in association with the deposition of transgressive sandstone, shales, and carbonate rocks.

The Khmer Basin is classified as a Tertiary rift basin because it was formed in associated with the Tertiary strike-slip faults that could be the Three Pagodas Faults strand/splay, Mae Ping Faults strands, and Axial Malay Fault that produced rift and extension from the Late Eocene to the Oligocene due to its sinistral

movement. During the rifting and extension, the basin was covered by lacustrine, fluvial, and delta flood plain in associated with claystone, sandstone, and calcareous claystone/ sandstone and organic rich claystone. Next, it was affected by post-rift rapid thermal subsidence due to high heat flow and high geothermal gradients during the Early – Middle Miocene leading to fluvial-deltaic to paralic classic and coal-rich sediments. Finally, this basin is influenced by the inversion with slightly subsidence from the Middle – Late Miocene to the Pleistocene caused by the change of strike-slip faults' direction. Although the inversion took place, this area was still covered by shallow marine during the Late Miocene to the Pliocene/Recent due to rapid thermal subsidence.

For Preah and Chung Basins, there is very limited data that could not be brought into the discussion. It needs further research to confirm the evolution of these two basins.

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