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# A preliminary assessment of geological CO<sub>2</sub> storage in the Khorat Plateau, Thailand

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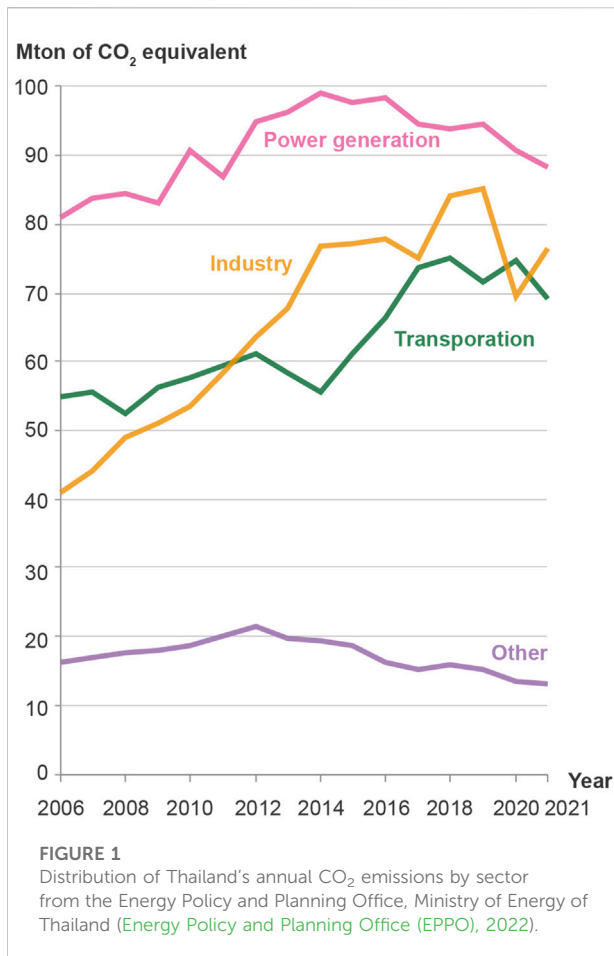
The main carbon dioxide (CO<sub>2</sub>) emissions in Thailand come from the energy sector. Gas-based power plants, including natural gas and biogas, are CO<sub>2</sub> point sources, and are mostly located in the Khorat Plateau. Geological CO<sub>2</sub> storage is an important element in the effort to reduce CO<sub>2</sub> emissions from CO<sub>2</sub> point sources. This study is a preliminary assessment of the geological CO<sub>2</sub> storage potential of the onshore Khorat Plateau. A potential geological formation is screened and ranked in terms of its suitability as a CO<sub>2</sub> storage site (storage optimization, risk minimization and feasibility). The results of this screening and ranking indicate that, among the tested sites in this study, the Khorat Permian carbonate is the most suitable for geological CO<sub>2</sub> storage, followed by the Khorat Group sandstone, and Khorat evaporite. However, the Khorat Cenozoic basalts are not suitable for geological CO<sub>2</sub> storage in the Khorat Plateau. The results from this study should advance the understanding of petroleum exploration and carbon capture and storage technology in Thailand, especially in the Khorat area. However, it should be noted that more subsurface studies are needed, and more criteria should be included in the future to improve the reliability of the assessment of geological CO<sub>2</sub> storage potential in the Khorat Plateau.

## KEYWORDS

carbon storage, Khorat Plateau, petroleum reservoir, evaporite, alkaline basalt

## 1 Introduction

Carbon dioxide (CO<sub>2</sub>) is primary cause of global warming. Over the last few decades, CO<sub>2</sub> levels in the atmosphere have been steadily increasing due to rapid economic growth and increasing energy demand. In fact, global CO<sub>2</sub> emissions increased by about 54.5% from 1990 to 2013 ([International Energy Agency, 2014](#)). As a party to the Paris Agreement, the Thai government has agreed to reduce CO<sub>2</sub> emissions by 20% before 2030 ([United Nations ESCAP, 2018](#); [Climate Analytics, 2019](#)). The main CO<sub>2</sub> emissions in Thailand come from the energy sector, especially



from fossil fuel-based power plants, followed by the transport and industry sectors (Figure 1; Energy Policy and Planning Office (EPPO), 2022). Due to increasing global energy demands, fossil fuels are expected to maintain their dominance in future global energy production. Thus, the reduction of CO<sub>2</sub> released into the atmosphere from the emission point sources could help to reduce the effects of climate change. Carbon capture and sequestration (CCS) is one approach that could play an important role in reducing CO<sub>2</sub> emissions into the atmosphere, and the technique can be applied in Thailand (e.g., Choomkong et al., 2017; Lau et al., 2021; Lau and Ramakrishna, 2021; Zhang et al., 2022). CO<sub>2</sub> sequestration is a process that involves four steps: CO<sub>2</sub> capture, separation, transportation, and storage. Geological CO<sub>2</sub> storage is a promising technique for mitigating the impact of CO<sub>2</sub> emissions, and has been successfully demonstrated in many case studies worldwide (Koide et al., 1993; Gale and Freund, 2001; Koide and Yamazaki, 2001; Bachu, 2003; Kempka et al., 2013). CO<sub>2</sub> emissions are captured and stored in a subsurface sedimentary basin where a suitable type of storage rock lies at depths ranging

from 800 to 1,000 m in a cold regime (geothermal gradient <30°C/km), and from 1,000 to 1,500 m for a warm regime (geothermal gradient >40°C/km) (Bachu, 2003; Mao et al., 2014). The geological CO<sub>2</sub> storage can be done in various ways, including trapping in depleted oil and gas reservoirs, solubility trapping in oil and water reservoirs, adsorption trapping in coal beds, cavern trapping in salt structures, or by mineral immobilization (Blunt et al., 1993; Gunter et al., 1997; Bachu, 2003; Dusseault et al., 2004; Riaz and Cinar, 2014; Lau et al., 2021). It is also necessary for the storage to be covered by a good seal rock that prevents the CO<sub>2</sub> from leaking to the surface through overburden rocks (Bachu, 2003).

Approximately 40% of Thailand's primary energy consumption is supplied by natural gas, including most of the country's power generation and growing vehicle fuel usage (Energy Policy and Planning Office (EPPO), 2022). The CO<sub>2</sub> emissions from natural gas-based power plants are of significant concern due to the massive discharge of greenhouse gases into the atmosphere, and their subsequent effect on global climate change (Bachu, 2003). The major natural gas-based and biogas-based power plants in Thailand are in northeastern Thailand or the Khorat Plateau (Figure 2), which extends over an area of 200,000 km<sup>2</sup> and consists of two sedimentary-filled basins known as Sakon Nakhon basin in the north and Khorat basin in the south (El Tabakh et al., 1999; Sone and Metcalfe, 2008; Tan et al., 2010). These two basins overlay Carboniferous to Triassic sequences, which constitute a main petroleum exploration target in the area (Figure 3). The Upper Paleozoic and Mesozoic sequences in the Khorat Plateau have been explored for petroleum and gas fields, which have been discovered in the Khorat Plateau (Figures 2, 3). To date, two commercial gas fields, Nam Phong and Phu Horm, are producing from Permian carbonate reservoirs (Figure 3; Booth, 1998; Sattayarak, 2005; Chantong et al., 2013). Thus, an existing gas pipeline network, suitable local drilling rigs, and potential active petroleum companies could facilitate CCS development in the future.

This study aims to provide a preliminary assessment, from existing subsurface and surface published data from an extensive review of peer-reviewed journals, conference proceedings, and published reports, of the suitability for geological CO<sub>2</sub> storage of the geological framework and stratigraphy in the Khorat Plateau. This is the first attempt to focus on the existence of these suitable lithologies (e.g., salt and alkaline igneous rocks) and petroleum reservoirs within the Khorat Plateau for geological CO<sub>2</sub> storage.

## 2 CO<sub>2</sub> emission point sources in Khorat Plateau

CO<sub>2</sub> emission point sources are considered as either mobile or stationary point sources (Zhang et al., 2022). Mobile CO<sub>2</sub> sources (e.g., cars, ships, and planes) are difficult to capture, while

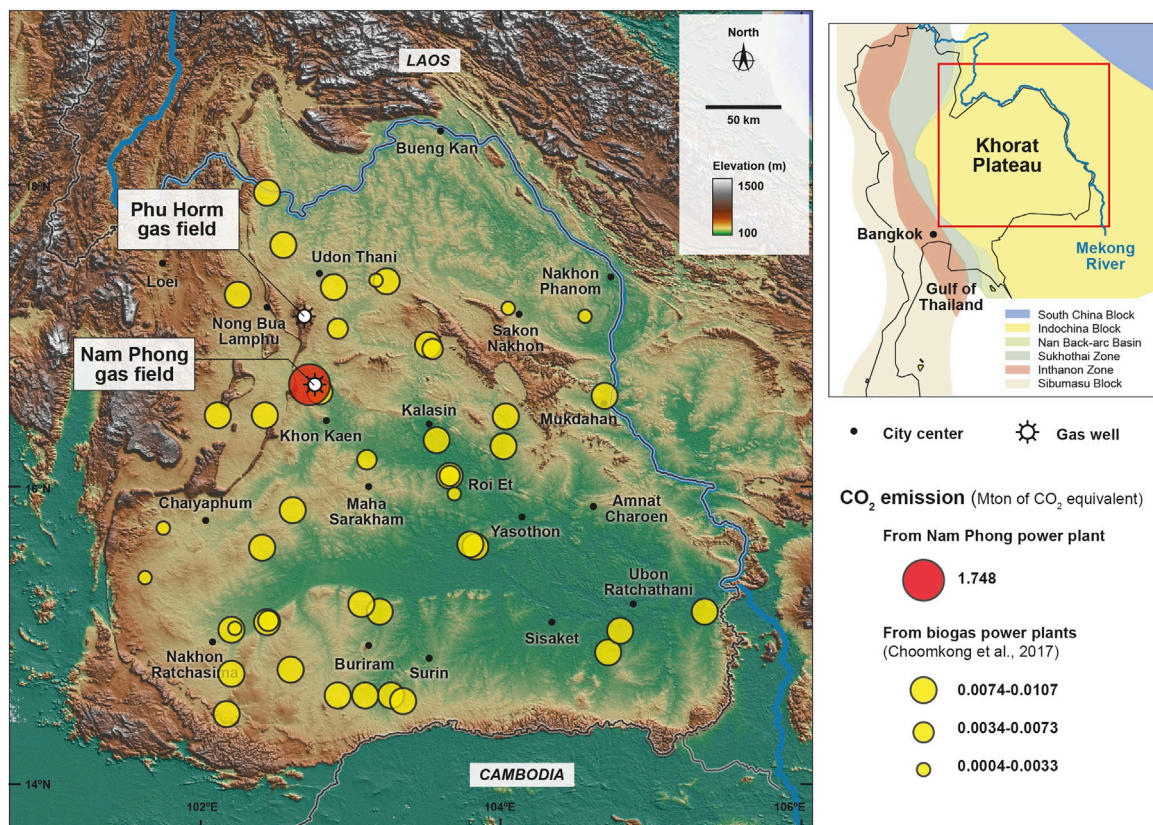


FIGURE 2

Location map of the Khorat Plateau, northeast Thailand, showing the major CO<sub>2</sub> emission point sources for geological storage (CO<sub>2</sub> emission data sourced from Choomkong et al., 2017).

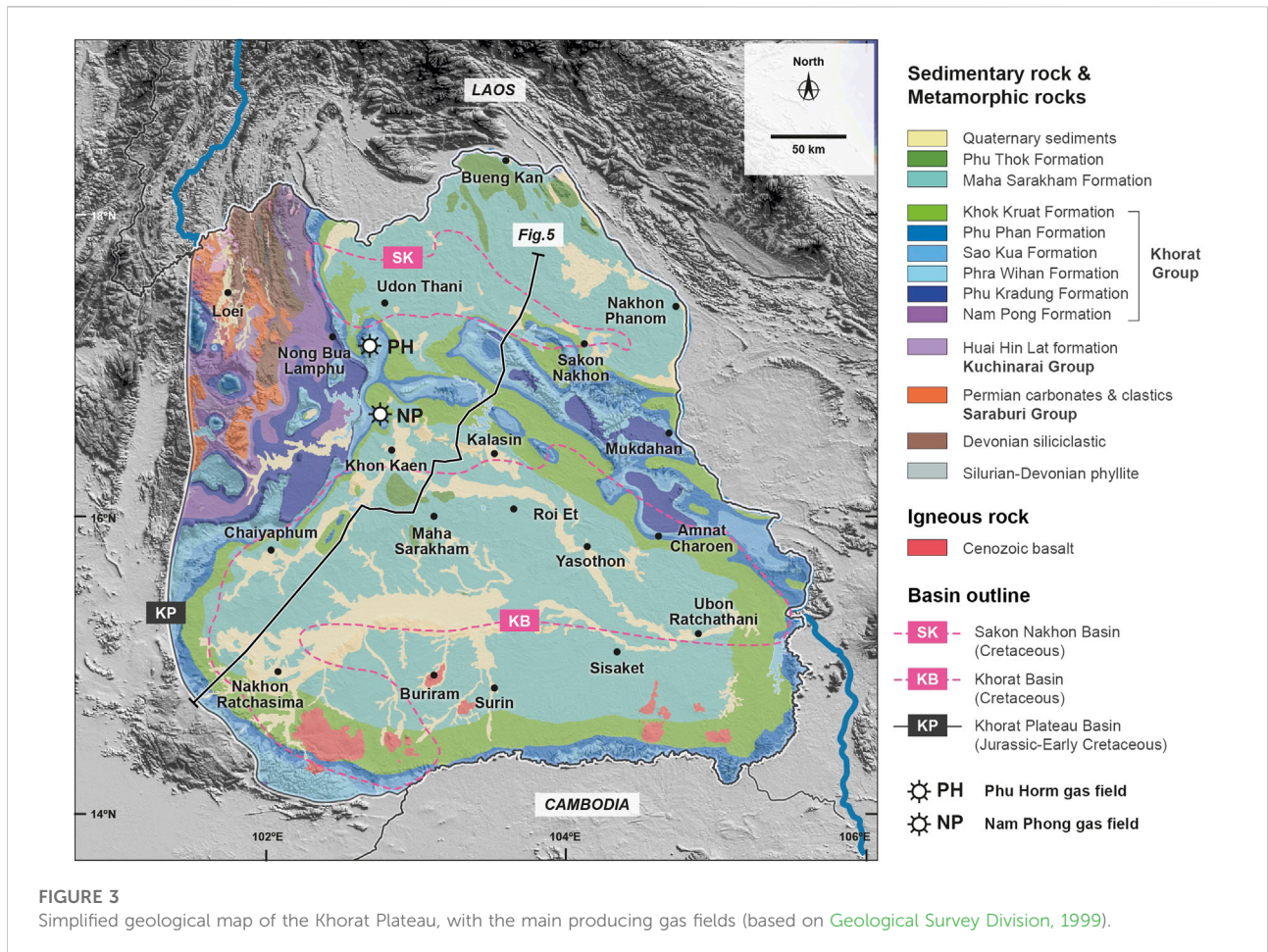
stationary CO<sub>2</sub> sources (e.g., production factories and processing plants) could be captured by CCS technologies (Zhang et al., 2022). Stationary CO<sub>2</sub> sources can come from various sectors, including cement factories, refineries, iron and steel mills, petrochemical plants, gas-based power plants and coal-based power plants. This study focuses on an assessment of subsurface geological storage of CO<sub>2</sub> in the Khorat Plateau. Thus, only stationary CO<sub>2</sub> sources from the energy and industry sectors are included for evaluation in this study.

Industrial plants and gas-based power plants are potential CO<sub>2</sub> emission point sources in the Khorat Plateau, including those powered by natural gas and biogas (Figure 2). In addition, the biggest CO<sub>2</sub> emitter in the Khorat Plateau is potentially the natural gas-based power plant in Khon Kaen (2.13 Mtpa), which is the Nam Phong power plant (Figure 2; Zhang et al., 2022). This is presently the largest power plant in the Khorat Plateau and the only power plant that uses natural gas fuel to generate electricity in Thailand. The gas fuel that is used to supply the Nam Phong power plant comes from the gas fields in Khon Kaen, including Nam Phong and Phu Horm fields (Figure 2).

### 3 Geological background

The Khorat Plateau is part of Sundaland, which was originally part of the northern margin of the supercontinent Gondwana, but which drifted to Eurasia during the Late Paleozoic through the Mesozoic (Barber et al., 2011; Metcalfe, 2011; Morley, 2012; Morley et al., 2013). The Khorat Plateau is believed to have formed as a foreland basin in front of the orogenic belts created by the Nan-Uttaradit Suture Zone in central-northern Thailand (Figure 3; Smith et al., 1996; Carter and Bristow, 2003), and has been controlled by the rift, drift, collision, and post-collision history of the Gondwana continental fragments. The present-day geothermal gradient in the Khorat Plateau is low, at about 28 C/km, based on data from the Si That petroleum exploration well.

The Early to Middle Triassic collision between the Shan Thai and the Indochina microplates along the Nan-Uttaradit Suture was followed by Late Triassic tectonic relaxation or extension, which created half-graben basins, where the non-marine sequences were deposited (Drumm et al., 1993). Fluvial and lacustrine facies filled these basins with conglomerates,

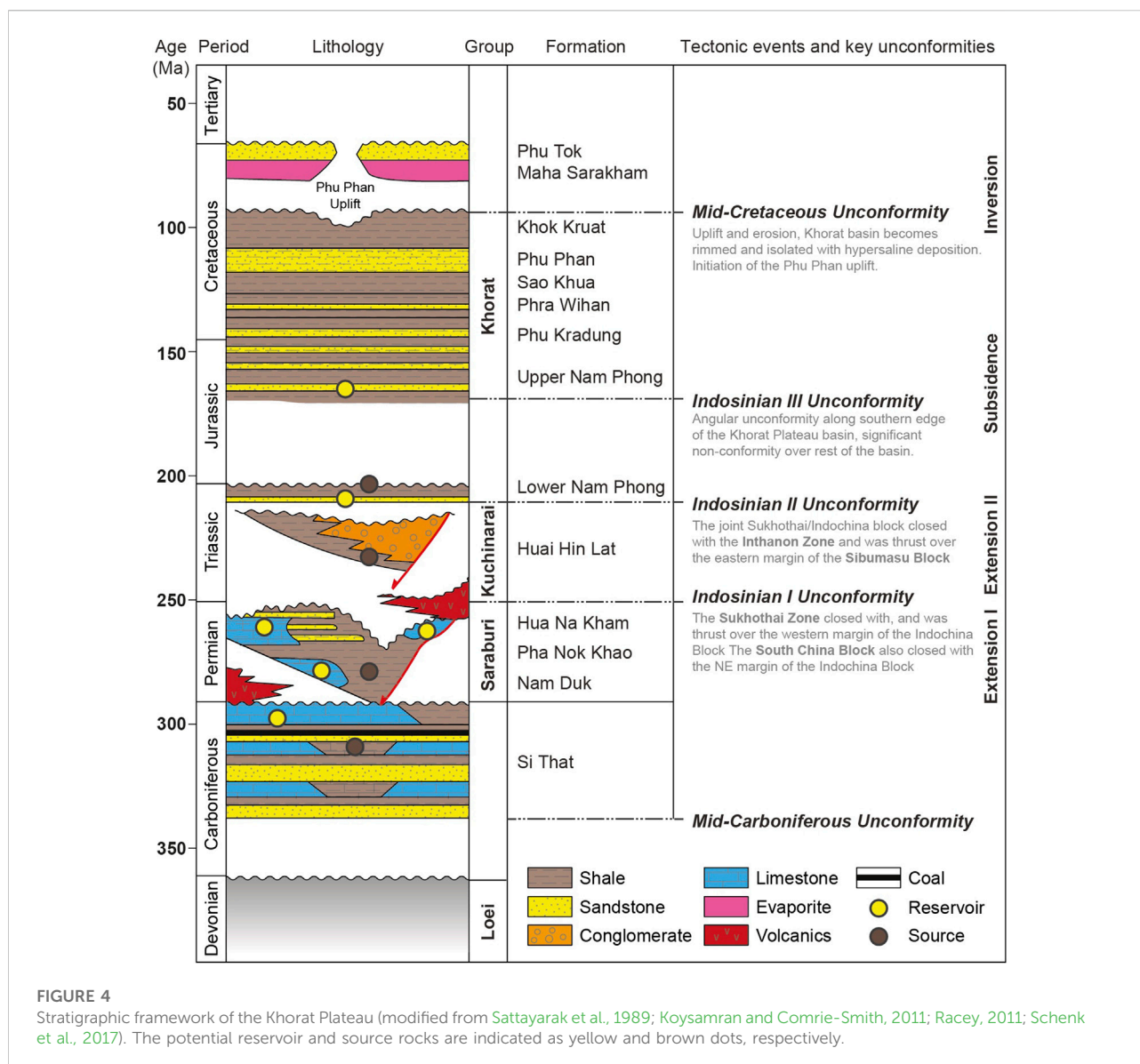


**FIGURE 3** Simplified geological map of the Khorat Plateau, with the main producing gas fields (based on Geological Survey Division, 1999).

sandstones, and mudstones that range in age from the latest Triassic to late-Early Cretaceous (Drumm et al., 1993). Provenance sources of the Khorat rocks in Thailand comprise material from erosion of the late-Palaeozoic rocks exposed in the Nan-Uttaradit Suture Zone (Bunopas and Vella, 1978; Hutchison, 1989), and possibly from eastern Laos and central Vietnam (Drumm et al., 1993). In addition, the Qinling Orogenic Belt in China is also believed to be a provenance source for the Khorat Plateau sediments (Carter and Bristow, 2003).

There was a major displacement of the Khorat Plateau along the northwest-trending Red River Fault of about  $950 \pm 150$  km, with a  $20\text{--}25^\circ$  clockwise rotation relative to the South China plate during Early Cretaceous through to Early Neogene times (Charusiri et al., 2006). Inversion structure has been observed and is proposed to have occurred during the Mid-Cretaceous in a continental collision to the west between Western Burma and Shan Thai (Metcalf, 1996). The Khorat sediments were intruded by Cretaceous granites (Campanian and Cenomanian) that had resulted from thermal subsidence of the Khorat Plateau (Smith et al., 1996).

During the Late Cretaceous to Early Paleocene, compression from the northeast due to continental collision of the Indochina microplate with the southeast China plate, and from back-arc compression of the Shan Thai microplate to the west, resulted in uplift and erosion of about 3,000–3,500 m of the Upper Cretaceous sequences, and the formation of the NW-SE-trending Phu Phan anticlinorium in the central part of the Khorat Plateau (Cooper et al., 1989; Bunopas and Vella, 1992; Mouret et al., 1993; El Tabakh et al., 1999). During the Cretaceous, the Indochina microplate is suggested to have been located near  $20^\circ\text{N}$  latitude, with arid climatic conditions (Achache et al., 1983). The compression regime that created the inversion structures in this area is thought to have continued until the earliest Paleocene. From the Paleocene time onwards, the transtension regime was dominant in the South China Sea, Thailand Central Plain, and Gulf of Thailand, creating rift basins during the Oligocene-Miocene (Daly et al., 1991). However, there is no evidence of a rift basin or Tertiary sediments, including a lack of major syn-depositional faulting, in the Khorat Plateau (Smith et al., 1996). Finally, the Pliocene–Pleistocene basalts were



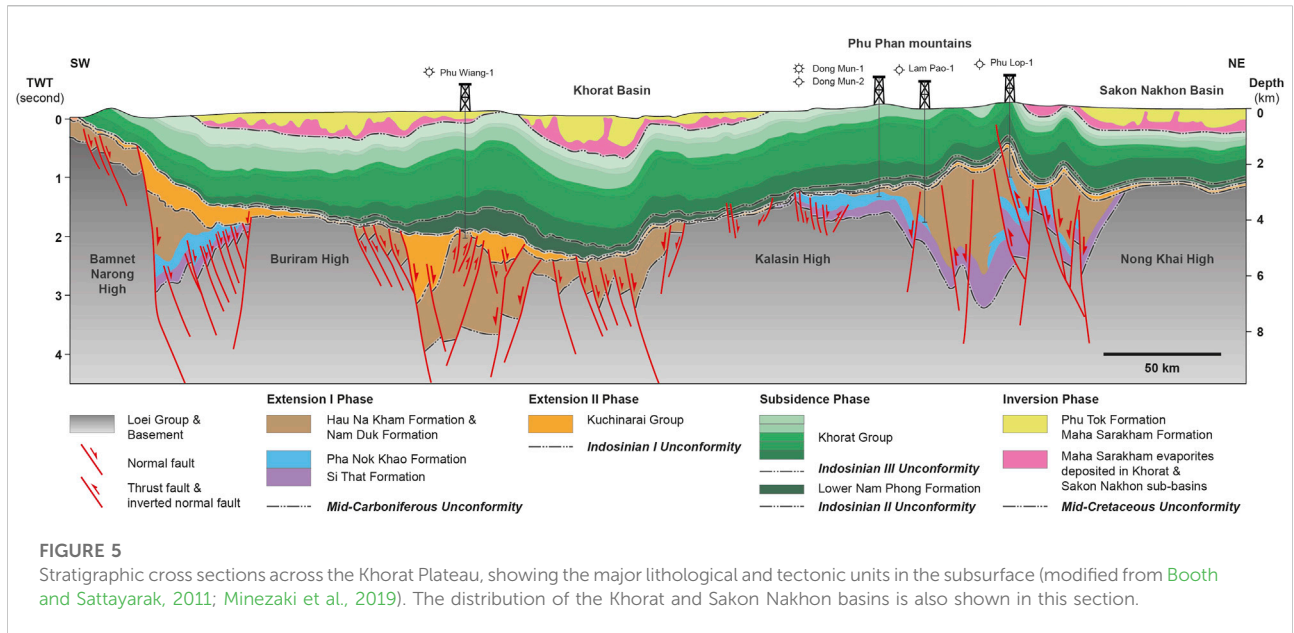
subsequently extruded, and unconformably overlay the Cretaceous sequences.

### 3.1 Regional tectonic history

The continental fragments of Indochina and South China that formed the Khorat Plateau were separated from the northern margin of Gondwana in the Late Devonian and drifted over the Palaeotethys Ocean through the Late Permian. The two continental fragments, Indochina and South China, then collided in the Late Permian (Hutchison, 1989; Metcalfe, 1996).

There are five depositional sequences that are separated by unconformities related to major orogenic events (Figures 4, 5;

Booth and Sattayarak, 2011). The Indosinian I unconformity is the oldest unconformity related to the Permo-Triassic (P-T) boundary (Figures 4, 5), and resulted from compressional uplift and erosion events of the Nan-Uttaradit Suture between Indochina and Shan Thai that had been fully sutured in the Middle Triassic (Bunopas and Vella, 1983; Cooper et al., 1989; Metcalfe, 1996). In addition, Indosinian I is the most regionally extensive, as recognized from subsurface data, and is followed by the Indosinian II unconformity, which is generally believed to be from the Late Triassic (Figures 4, 5; Sone and Metcalfe, 2008; Metcalfe, 2011; Metcalfe, 2013). However, the Late Jurassic time has been recently proposed for the closure of the Indosinian II unconformity (Ahrendt et al., 1993). A crustal extension event in the Late Triassic caused the development of localized half-



graben structures between the Indosinian I and II unconformities in the Khorat area (Cooper et al., 1989; Sattayarak et al., 1989; Booth and Sattayarak, 2011). These half-grabens were then filled by Triassic sediments, which are preserved as the Kuchinarai Group (Figures 4, 5).

The Khorat Plateau area then became relatively stable and was dominated by fluvial and floodplain deposits in the foreland basin from the Jurassic to Early Cretaceous (Horiuchi et al., 2012), when thick continental sediments (Khorat Group) were slightly deformed as long-wavelength folds and overlaid the Indosinian III unconformity (Figures 4, 5). In the Late Jurassic to Mid-Cretaceous formations, the Khorat Plateau exhibits thermal subsidence with an almost complete absence of syn-depositional faulting. The long-wavelength folding structures of the rock strata in the Khorat Plateau resulted from a combination of Mid-Cretaceous and Tertiary episodes of thick-skinned inversion (Figures 4, 5; Smith and Stokes, 1997) that formed during the suturing of West Burma with Shan Thai at the Early Cretaceous, which would have started a compression regime in the Khorat area (Metcalf, 1996). As a result of this compression during the Mid-Cretaceous, the Phu Phan range was uplifted, forming two sedimentary-filled basins inside the Plateau: the Sakon Nakhon and Khorat basins (Booth and Sattayarak, 2011). However, several studies argue that the Phu Phan range was actually uplifted during the Tertiary (e.g., Chuaviroj, 1997; Meesook, 2000).

Regional uplift and second inversion events during the continental collision between India and Eurasia (Himalayan orogeny) in the early Paleocene are proposed to have been the most recent uplift events (Mouret et al., 1993; Smith et al., 1996;

Chuaviroj, 1997). The deformation events in this period, including the Phu Phan Uplift, strike-slip faults, thrusts, and folds on the southern and eastern margins affected the Khorat rocks (Morley, 2012). The uplift event would have resulted in a height, at the start of the regional erosion period, of around 1,500 m in the Khorat area (Mouret et al., 1993). Today, the maximum thickness of rock strata is about 4,000 m at the Phu Phan Uplift (Mouret et al., 1993; Canham et al., 1996).

### 3.2 Stratigraphic framework

The Khorat Plateau comprises sedimentary formations from the Carboniferous to Cretaceous ages (Figures 4, 5). The Upper Paleozoic rocks form the basement for the Khorat Plateau and comprise Devonian to Carboniferous mixed siliciclastic-carbonate sediments, the Permian Pha Nok Khao carbonate platform, and the Permian siliciclastic sediments of the Hau Na Kam and Nam Duk Formations. The Pha Nok Khao comprises extensive, distally-steepened ramps composed of varying proportions of carbonates and lesser siliciclastics, and is the main target for petroleum reservoir in the Khorat Plateau. The Pha Nok Khao Formation overlies unconformably on the Devonian-Early Carboniferous sandstone, mudstone, limestone, and coal of the Si That Formation (Figures 4, 5; Burret et al., 2014). The Upper Paleozoic strata are separated from overlying Mesozoic sediments by the Indosinian I unconformity (Figures 4, 5). Moreover, most Paleozoic strata in the Khorat Plateau and adjacent areas were widely deformed during the Indosinian I event (Ridd et al., 2011). The Huai Hin Lat Formation comprises

non-marine petroleum source rock distributed along the western margin of the Khorat Plateau (Figures 4, 5; Booth, 1998; Booth and Sattayarak, 2011). The depositional environment of the Huai Hin Lat Formation is broadly interpreted to have been a fluvial and lacustrine setting during the extension and half-graben development (Chonglakmani and Sattayarak, 1978). The age of the Huai Hin Lat Formation is Late Triassic (Norian), based on the *Estheria* fauna, spore, and pollen found there (Haile, 1973; Kobayashi, 1975; Kon'no and Asama, 1973; Chonglakmani and Sattayarak, 1978).

Cretaceous rocks are widespread in the Khorat Plateau, and all are clastic non-marine sediments (Figures 4, 5). They are called the Khorat Group and are composed of (from the oldest to youngest) the Phu Kradung, Phra Wihan, Sao Khua, Phu Phan, Khok Kruat, Maha Sarakham, and Phu Tok Formations (Figure 4).

The Nam Phong Formation varies in thickness from 2,500 m to several meters (Nulay and Arjwech, 2021). The area of maximum thickness is located in the central portion of the Khorat Plateau, and gradually thins or disappears along the flanks of the plateau. The Nam Phong Formation is divided into the Upper and Lower Nam Phong Formations, which are separated by an unconformity (Figure 4). The Lower Nam Phong Formation dates to the Late Triassic (Rhaetian), based on palynology, while the Upper Nam Phong Formation is considered to be no older than Early Jurassic (Pliensbachian), based on petroleum-well correlation (Racey and Goodall, 2009). The Formation consists of reddish-brown micaceous sandstone, conglomerate, siltstone, and mudstone. The depositional environment is considered to be fluvial, with deposit activity commencing after the end of the deformation event (Indosinian II) of the half-graben basin of the Huai Hin Lat Formation (Nulay and Arjwech, 2021).

The Phu Kradung Formation lies conformably on the upper Nam Phong, separated by a hiatus, and it varies in thickness from 1,200 m in the basin center to around 500 m on the basin flanks (Racey, 2009; Nulay and Arjwech, 2021). The hiatus at the base of the Phu Kradung Formation is generally considered to be the base of the Khorat Group (e.g., Racey, 2009; Booth and Sattayarak, 2011). However, some authors place the base of the Khorat Group at the base of the Lower Nam Phong Formation (e.g., Meesook and Saengsrichan, 2011). The Phu Kradung Formation is dominated by maroon siltstone and claystone, while sandstone and conglomerate are subordinate in the Phu Kradung Formation (Meesook and Saengsrichan, 2011). Coarsening-upward sequences have been observed throughout the Phu Kradung Formation from subsurface study (Booth and Sattayarak, 2011). Thus, the environmental deposition is considered to be alluvial at the lower part and grade into fluvial in the upper part, under what was once a meandering river system in a semi-arid paleoclimate (Racey et al., 1996; Booth and Sattayarak, 2011; Meesook and Saengsrichan, 2011). The age

of the Phu Kradung Formation is Late Jurassic to Early Cretaceous, based on palynology (Racey and Goodall, 2009).

The Phra Wihan Formation lies conformably on the Phu Kradung Formation and varies in thickness from around 50–300 m (Nulay and Arjwech, 2021). The Phra Wihan Formation is generally composed of white, coarse-grained, well-sorted arkosic to orthoquartzitic sandstone, but siltstone, mudstone, and conglomerate are also found (Nulay and Arjwech, 2021). Because of its dominant sandstone beds, the Phra Wihan Formation is believed to have been deposited by a high energy braided river, with a subordinate meandering river in a subtropical to tropical palaeoclimate during the Early Cretaceous (Barriasian to Barremian), based on palynology (Racey et al., 1996; Meesook, 2000; Racey and Goodall, 2009; Horiuchi et al., 2012).

The Sao Khua Formation lies gradationally and conformably on the Phra Wihan Formation, and varies widely in thickness from around 100–700 m (Nulay and Arjwech, 2021). The Sao Khua Formation is generally composed of reddish-brown conglomeratic sandstone with calcrete and silcrete layers at the base of the Formation (Meesook, 2000). Siltstone and mudstone are also found within this formation, which is believed to have been deposited by a low-energy meandering river and extensive flooding under a warm and cool semi-arid paleoclimate. The age of the Sao Khua Formation is the Early Cretaceous (Hauterivian to Late Barremian), based on palynology, and vertebrate and bivalve fossils (Racey and Goodall, 2009; Nulay and Arjwech, 2021).

The Phu Phan Formation lies conformably on the Sao Khua Formation and varies in thickness between 50 and 100 m (Nulay and Arjwech, 2021). The Formation is dominated by light-buff to brown, medium-to coarse-grained, well-sorted sandstone, while siltstone and mudstone are subordinated. Pebbly conglomerate with well-rounded quartz pebbles and minor mudstone intraclasts are found in some places (Racey et al., 1996). The depositional environment is interpreted to be from a high energy braided river for the sandstone, and floodplain deposits for finer-grained sediments (Racey et al., 1996). The age of the Phu Phan Formation is the Early Cretaceous based on palynology (Racey et al., 1996).

The Khok Kruat Formation lies conformably on the Phu Phan Formation and exhibits variations in thickness from 200 m in the northwestern part of the Khorat Plateau to 850 m in the in the southeastern part of the Khorat Plateau, possibly due to erosion events (Sattayarak and Polachan, 1990; Smith et al., 1996; Racey, 2009). The Khok Kruat Formation consists mainly of light grey to light brown, thin-to thick-bedded, fine-to medium-grained micaceous or arkosic sandstone with clay rip-up clasts in several places. Siltstone, mudstone, and conglomerate beds are also found in this formation (Meesook, 2000). The Khok Kruat Formation is believed to have been deposited by meandering rivers on a floodplain. The age of the Khok Kruat Formation is

the late Early to Middle Cretaceous (Aptian), based on freshwater bivalves in sandstone (Racey and Goodall, 2009).

The Maha Sarakam Formation lies unconformably on the Khok Kruat Formation, showing an angular unconformity, which is well-imaged from seismic data, between the Khok Kruat and the Maha Sarakam Formations. The unconformity extends throughout the region and indicates non-deposition or extensive erosion during the Mid-Cretaceous (Smith et al., 1996; Charusiri et al., 2006). The unconformity was formed by an inversion during Mid-Cretaceous, leading to a deposition of red-bed clastic rocks and evaporite rocks in a hypersaline land-locked basin under an arid paleoclimate (Figures 4, 5; Racey et al., 1996; Meesook, 2000). Consequently, the Maha Sarakham Formation consists of red-bed clastic rocks and evaporites, including halite, sylvite, carnallite, tachyhydrite, anhydrite, and borate minerals (Sattayarak et al., 1991; Hansen et al., 2002, 2016). The age of the Maha Sarakam Formations is the Mid-Cretaceous (Cenomanian), based on palynology (Sattayarak et al., 1991). Subsequently, the Khorat Plateau was covered by the Phu Tok Formation in the Late Cretaceous under an arid desert environment (Meesook, 2000; Hasegawa et al., 2010; Hasegawa et al., 2012).

## 4 Khorat evaporites

Evaporite caverns have been studied for CO<sub>2</sub> storage worldwide because of their low permeability and self-healing ability, which can prevent the leakage of CO<sub>2</sub> (e.g., Pajonpai et al., 2019). In the Khorat Plateau, thick evaporites are preserved within the Maha Sarakham Formation. Hence, Khorat evaporite is one of the possible geological CO<sub>2</sub> storage sites in the Khorat Plateau.

The Maha Sarakham evaporites in the Khorat Plateau are present in the Khorat and the Sakon Nakhon basins within an area of 50,000 km<sup>2</sup> (Suwanich, 2007). The resources of the potash deposit could be as much 400 billion tons of carnallite and 7 billion tons of sylvite, making it one of the largest potash deposits in the world (Hite and Japakasetr, 1979; Yumuang et al., 1986; El Tabakh et al., 1999; Shen and Siritongkham, 2020). These two basins are separated by the northwest-southeast striking Phu Phan anticline. The deposit of the evaporites can be correlated to the extensive Late Cretaceous potash deposits in the Lanping-Simao Basin in southwestern China, due to the worldwide high sea level in the Late Cretaceous (Haq et al., 1987; Qin et al., 2020; Rattana et al., 2022). The evaporite deposit in the Khorat Plateau is proposed to primarily be of marine origin, based on the geochemical data, sedimentary features, mineral sequences, and stratigraphic ages (e.g., Qin et al., 2020; Rattana et al., 2022); however, hydrothermal and continental fluids could have affected the evaporite basins (El Tabakh et al., 1999; Zhang et al., 2015; Li et al., 2018; Rattana et al., 2022).

The evaporites in the Khorat Plateau have a thickness of about 250 m to 1,100 m in some areas, and have been deformed by complex tectonics leading to different salt features in the subsurface, such as domes, anticlines, ridges, and mini-basins (Figure 5; El Tabakh et al., 1999; Suwanich, 2007). Salt deformations can be found at the shallow subsurface, approximately 50 m below the surface, due to salt movement caused by thick overburden sediments (Figure 5; El Tabakh et al., 1999). The evaporites are thickest in the depocenter of the evaporite basins and they gradually become thinner at the margins of the basins. The evaporites can be divided into three depositional members (El Tabakh et al., 1999; Shen et al., 2021):

- 1) The Lower Salt Member is well preserved throughout both evaporite basins and consists of massive halite, potash minerals (carnallite and sylvite), and banded colored salt (El Tabakh et al., 1999; Hansen et al., 2016; Rattana et al., 2022). This salt member is highly deformed, resulting in significant local differences in thickness from place to place (Figure 5).
- 2) The Middle Salt Member is mainly composed of two halite units that are separated by an anhydrite marker bed, with little to no potassic salt in this member (El Tabakh et al., 1999).
- 3) The Upper Salt Member is mainly composed of halite with minor anhydrite. In most cases, the Upper Salt Member is absent in the Khorat Plateau because of its shallow burial depth and wet climate. It seems that at least half of the salt of this member has been leached and dissolved (Shen and Siritongkham, 2020). Therefore, this member is either completely absent or very thin, with a thickness ranging from 3 to 17 m at the present day (Shen et al., 2021).

## 5 Khorat basaltic rocks

Large igneous provinces around the globe have been documented for CO<sub>2</sub> storage due to their internal fractures formed during the cooling of lava and their chemical reaction between mineral compositions and CO<sub>2</sub> (Raza et al., 2022). The suitable igneous rocks for effective carbon mineralization are mafic or ultramafic compositions, due to their high content of divalent cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, Fe<sup>2+</sup>), such as the pilot project in Iceland (McGrail et al., 2017; Raza et al., 2022). Thus, basaltic provinces in the Khorat Plateau could be an advantage for geological CO<sub>2</sub> storage sites.

Basaltic rocks are widely distributed in Thailand, including in the Khorat Plateau, especially those dating to the Cenozoic Era. The Cenozoic basalts in Thailand can be divided into three main groups: 1) Basanitoid basalt, 2) Hawaiiitic basalt, and 3) Tholeiitic basalt. Cenozoic basalts on the Khorat Plateau are distributed among several provinces, including Nakhon Ratchasima, Ubon Ratchathani, Buriram, Surin and Sisaket, and are mostly located on the southernmost edge of the





**FIGURE 6**

An example of the vesicular basalt from the Buriram-Nakhon Ratchasima area in the Khorat Plateau.

Khorat Plateau (Figure 3; Thanachit et al., 2006; Atayos et al., 2021; Singtuen and Phajan, 2021; Singtuen et al., 2021). The basaltic rocks in the Khorat Plateau usually show vesicular texture formed during the cooling of lava, which enhance the porosity and permeability of the rock matrix (Figure 6).

Nakhon Ratchasima basalts are classified as sub-alkali basalt, and are composed mostly of olivine, clinopyroxene and plagioclase phenocrysts (Barr and James, 1990; Atayos et al., 2021). Groundmass is composed of lath-plagioclase intergranular by clinopyroxene and opaque mineral. Alteration product found in the sample is normally iddingsite and sericite (Atayos et al., 2021), while Buriram basalts are classified as basaltic trachyandesite and alkali basalt (Barr and James, 1990), and show porphyritic texture. Phenocrysts are composed mostly of olivine, clinopyroxene, and plagioclase (An40-50: andesine), with minor amounts of iddingsite. Groundmass is composed of trachytic textured plagioclase intergranular, with clinopyroxene and opaque mineral (magnetite?) (Atayos et al., 2021).

The Surin basalts demonstrate trachytic texture with olivine phenocryst and groundmass of plagioclase intergranular, with clinopyroxene (Atayos et al., 2021). Glass is intersertal in the groundmass (Atayos et al., 2021). Ubon Ratchathani basalts are composed of olivine and clinopyroxene phenocrysts embedded in plagioclase, showing as intergranular/intersertal with olivine, clinopyroxene, opaque mineral, and glass (Atayos et al., 2021).

Srisaket basalts are classified as olivine basalt and nephelinite, showing brownish-red weathered surfaces with a high alteration rate. Olivine basalts are characterized by aphanitic, porphyritic, and vesicular textures with holocrystalline, while nephelinites show porphyritic and vesicular textures with holocrystalline. The mineral compositions in the olivine basalts are mainly plagioclase

with high anorthite content (66–85), ranging from labradorite to bytownite, associated with minor forsterite, ilmenite, and clinopyroxene. The nephelinites are composed mainly of plagioclase, with very high anorthite content (81–94), ranging from bytownite to anorthite and nepheline associated with forsterite, diopside, augite, pigeonite, iddingsite, and ilmenite. These basaltic rocks in Srisaket show 5.62–11.07 wt% MgO and 7.63–10.17 wt% CaO. Thus, the Srisaket basalts are highly alkaline and alkaline volcanic rocks (Singtuen et al., 2021; Singtuen and Phajan, 2021).

## 6 Petroleum plays in the khorat plateau

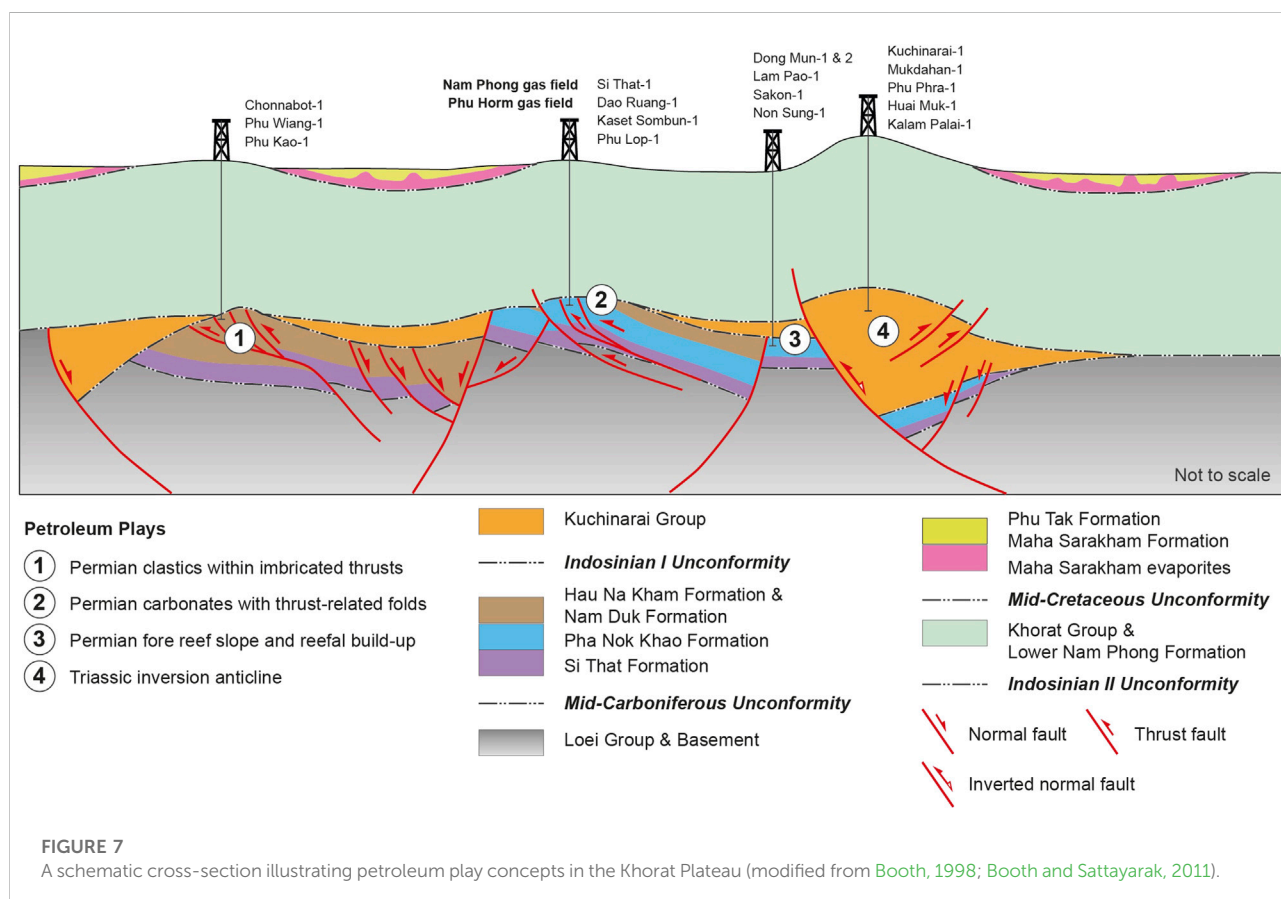
Another option for geological CO<sub>2</sub> storage is to inject the CO<sub>2</sub> into petroleum reservoirs at active or abandoned petroleum fields (e.g., Godec et al., 2011; Zhou et al., 2020). Petroleum exploration and production have been operated in the Khorat Plateau for a long time. Hence, petroleum plays and elements are reviewed in this section to assess the carbon storage sites related to petroleum fields in the Khorat Plateau.

### 6.1 Source rocks

There are three possible hydrocarbon source rocks in the Khorat Plateau: 1) Lower Cretaceous siliciclastic rocks of the Khorat Group, which contain a few centimeters of woody organic materials in the lateral red-bed sequence, producing minimal gas by locally mature stage; 2) Triassic Huai Hin Lat organic-rich

TABLE 1 The porosity and permeability of the potential reservoir rocks in the Khorat Plateau.

Reservoir rock	Porosity	Permeability
Permian carbonate rocks	2–2.5% Booth (2005)	1 to 2 mD Racey (2011)
Dolomitized and fractured carbonate rocks	Up to 15% Racey (2011); Warren et al. (2014)	~2,000 mD Racey (2011); Warren et al. (2014)
Fluvial sandstones of the Khorat Group	3–5% Smith and Stokes (1997)	Up to 18 mD Smith and Stokes (1997)
Fractured basement rocks	No available data	No available data

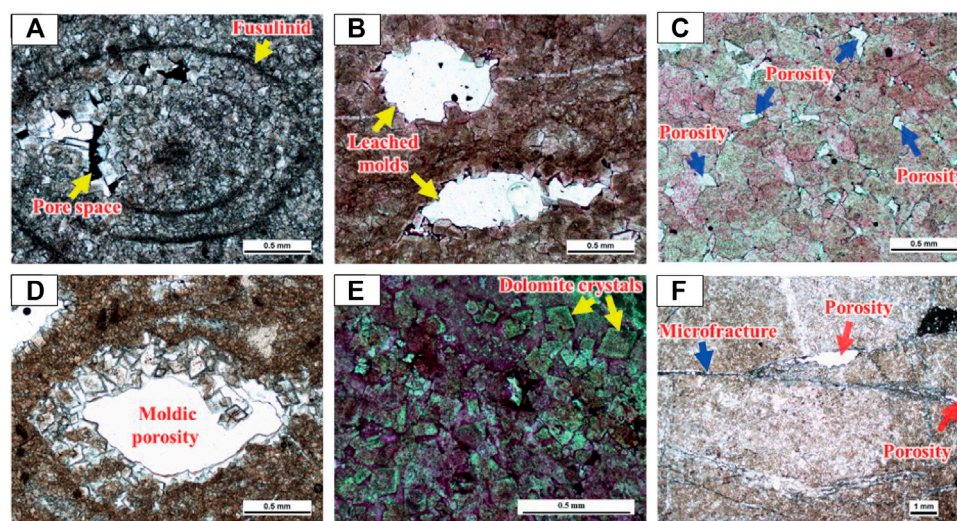


shale (Kuchinarai Group); and 3) Upper Carboniferous - Upper Permian of the Saraburi Group (Figure 4; Sattayarak et al., 1989; Racey, 2011). It should be noted that the Huai Hin Lat Formation is a significant source rock for petroleum gas fields in the Khorat Plateau. Upper Carboniferous - Upper Permian of the Saraburi Group is also identified as a major source rock in the Khorat Plateau and is expected to be regionally extensive throughout the Permian carbonate platforms. The Carboniferous-Triassic source-rock intervals experienced several phases of deformation, uplift and erosion that may have affected petroleum preservation in some areas, comprising tight sandstones, siltstones, and shale reservoirs. These source rocks

are believed to have a hydrocarbon peak generation in the Late Triassic (Kozar et al., 1992).

## 6.2 Reservoir rocks

There are three petroleum potential reservoirs in the Khorat Plateau: 1) Permian carbonate of the Pha Nok Khao Formation of the Saraburi Group; 2) fluvial sandstones of the Khorat Group; and 3) basement reservoirs (Racey, 2011). The porosity and permeability of the potential reservoir rocks in the Khorat Plateau are listed in Table 1. Permian fractured carbonates of



**FIGURE 8**

Photomicrographs of the dolomitized limestone from the Permian carbonate outcrops (modified from Kananusak, 2020). (A) a partially dolomitized fusulinid fossil with porosity, (B) dissolution pores with partially filled by dolomite, (C) intercrystalline pores (blue arrows) at crystal junctions, (D) crystal growths in moldic pore with partially filled by dolomite, (E) planar dolomite porphyrites in dolomitized limestone, and (F) pores related to fractures (red arrows).

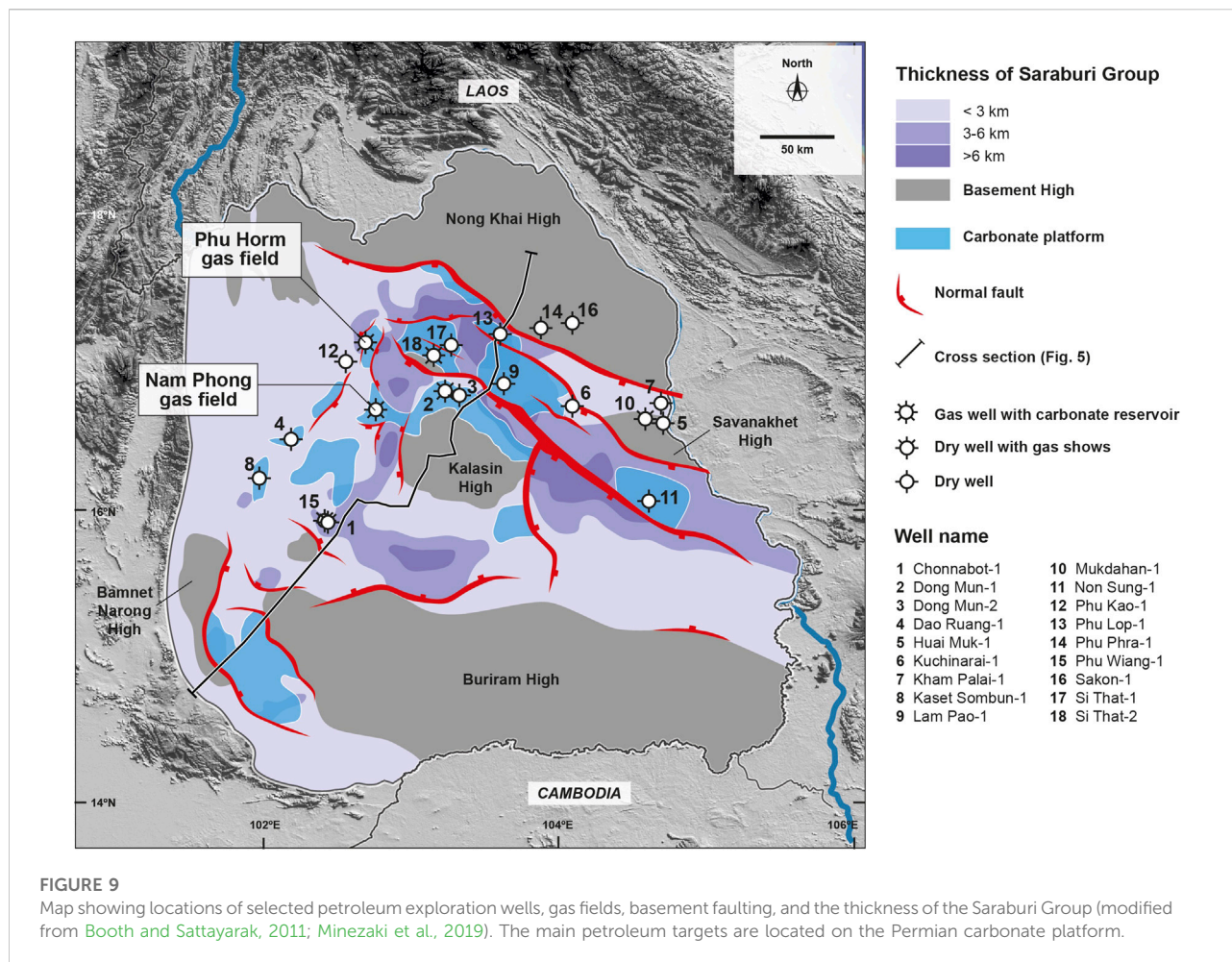
the Saraburi Group are the main proven reservoir to have been encountered to date (Racey, 2011). The reservoir in the two gas fields is comprised of carbonate rocks from the Pha Nok Khao Formation, providing dry gas with almost no CO<sub>2</sub> in the reservoirs (Booth, 1998). These carbonate rocks are generally of low porosity, with a field wide average effective porosity of only 2–2.5% (Booth, 2005). The interplay of the petroleum system elements gives various petroleum plays in the Khorat Plateau, as presented in Figure 7. Potential carbonate reservoirs in the Khorat Plateau include fore reef slope and reefal build-up (Figure 7). However, there is clearly an extensive fracture network within the gas fields, which have been drained from various structural trap styles (Figure 7; Booth, 2005). The fracture network has been shown to enhance the reservoir quality, but the effect varies from place to place (Figure 7; Smith and Stokes, 1997). The proven carbonate reservoirs in Nam Phong area are mostly related to surface exposure and freshwater-related diagenesis during deposition and early burial (Kozar et al., 1992). The occurrence of dolomitization and fracture that enhance the reservoir quality of the Permian carbonates can be observed in several outcrops (see examples in Figure 8). Hence, Permian palaeo-highs are most likely to have a good-quality reservoir and are the main reservoir targets in the Khorat Plateau. However, several petroleum exploration wells have failed due to a complex deformation, such as inverted Permo-Triassic grabens (Figure 9; Assavaritiprom et al., 1995; Smith and Stokes, 1997). The complex deformation also causes porosity- or

fracture-occluding calcite cement, which makes it difficult to predict the structure and composition of the subsurface.

The reservoir quality of the Khorat Group sandstones decreases with increasing depth of burial due to the diagenesis process (Canham et al., 1996). Maximum values of around 20% porosity and 18 mD permeability have been observed from outcrop studies, and the porosity of the sandstones likely decreases to 3–5% at greater depths (Figure 10; Smith and Stokes, 1997; Suteerapongpan, 2018). Thus, the Khorat Group sandstones should provide fair- to good-quality gas reservoirs. Moreover, conglomerates, sandstones, or claystones at the base of the Khorat Group are associated with Indosinian erosion surface, and overlie Permian limestones and dolomites. Gas was detected from these rocks in the Phu Horm-1 well at rates of 4 MM SCF gas per day (Assavaritiprom et al., 1995). These rock strata can provide a proven seal in some areas within the Khorat Plateau (Smith and Stokes, 1997), although the basement rocks in the Khorat Plateau are Lower Carboniferous granite and are unproven with respect to gas reservoirs (Sattayarak et al., 1989; Smith and Stokes, 1997). Nevertheless, there have been some positive results from fractured basement reservoirs in Tertiary basins in Thailand (e.g., Madon et al., 2020).

### 6.3 Petroleum traps

A complex tectonic history may have affected the development and preservation of viable petroleum trap



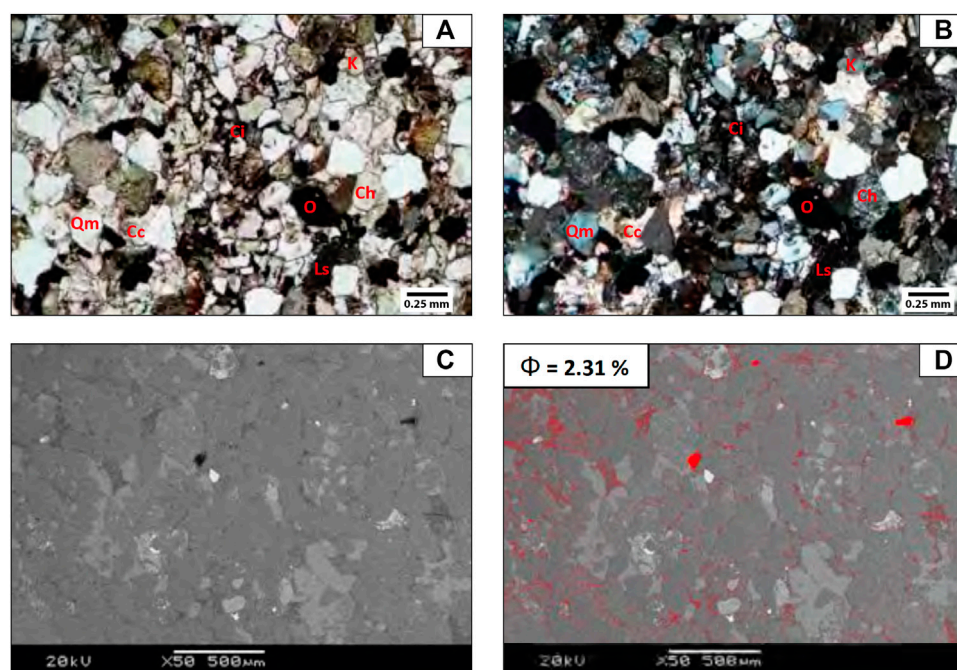
styles and petroleum plays, such as Permian carbonate fault-reactivated anticline, shallow carbonate anticline, thick Permian carbonate syncline, Permian reverse fault related fold, Triassic inversion-anticline, Triassic truncation, and Triassic pinch out (Figure 7). Due to the limitations of the published subsurface data, only the main petroleum traps are described in this study; and are presented in Figure 11. Although most trap formations are reactivated by Tertiary deformation after the main period of hydrocarbon generation, the structural traps in this area have been proven to contain gas (e.g., Nam Phong gas field).

The Nam Phong structure consists of a north-south trending, fault-bounded, inversion anticline overlying a reactivated and eroded, tilted Permian fault block (Smith and Stokes, 1997). Carbonate reservoirs are associated with the inversion anticline structure and a regional lower Khorat Group top-seal. Additionally, the down-flank closure of the anticline structure is overlaid by the Triassic Group and Upper Permian clastics (Figure 11A).

The Si That structure is also an anticline with SSW-NNE trend, resulting from inversion and reactivated faulting (Figure 11B). The Permian carbonate reservoirs are located beneath the Khorat Group and the Huai Hin Lat Formation. The anticline was formed before the deposition of the Huai Hin Lat Formation, based on seismic interpretation. The Si That structure is interpreted as being a paleo-high of Permian carbonate that could provide a good-quality reservoir, similar to Nam Phong gas field; however, without fracture networks, the Permian carbonate in this field would be a very dense and poor reservoir rock.

The SSW-NNE Phuwiang structure is a larger Permian platform than is the Nam Phong structure, but it has a similar structural history and trapping style (Figure 11C; Smith and Stokes, 1997). A petroleum exploration well was encountered at the top of a porous Permian carbonate formation, with the presence of a gas “kick” (Kozar et al., 1992).

The Phu Horm gas field is now the largest gas field in the Khorat Plateau. The Phu Horm structure exhibits an anticline



**FIGURE 10**

Photomicrographs of outcrop study from the Nam Phong sandstones (the base of the Khorat Group) in plane-polarized light (A) and in cross-polar (B). Note: K is potassium feldspar, Ci is iron oxide cement, Ch is chert, O is opaque mineral, Ls is sedimentary lithic fragments, Qm is monocrystalline quartz, and Cc is calcite. The backscattered electron image of the Nam Phong sandstones shows thresholding to binary image of pore space (C). Red marks cover pore space during thresholding operation for porosity analysis (D). These images are modified from Suteerapongpan (2018).

with a northwest-southeast trend and lies at the eastern part of the Khorat Plateau (Figure 11D). This structure is also similar to the Nam Phong structure overlying a thin Huai Hin Lat Formation. The carbonate reservoirs are associated with faulting and folding, and are laid on the clastic Si That Formation. There are minor faults within the Permian carbonates that could enhance porosity and permeability in the reservoirs.

A potential stratigraphic trap of the Permian carbonate reservoirs is observed in the Dong Mun area, with a platform-margin carbonate build-up (Figure 11E; Kozaret al., 1992). The Kalasin structure is a northwest-southeast trending Permian carbonate that lies beneath the Khorat Group. The Kalasin structure is an extension of the Dong Mun Structure in the northwest. Similar to the Dong Mun Structure, the reefal structure is well recognized from seismic facies data.

## 6.4 Petroleum seal

The regional top-seal in the gas fields (Nam Phong, Dong Mun and Phu Horm) is the lower part of the Khorat Group, consisting of conglomerates, claystones, siltstones, and tight

sandstones that are geometrically conformable with the inversion traps (Kozar et al., 1992; Mouret et al., 1993; Canham et al., 1996; Racey et al., 1996). Additional potential seals would be found in the Permian clastic Formation or the Triassic rocks over the crests of the Permian carbonate traps, or as down-flank wedges, such as in the Nam Phong gas field (Smith and Stokes, 1997).

## 7 Assessment and ranking of potential lithological formations

This section discusses the screening criteria that help to address a suitable CO<sub>2</sub> storage site in the Khorat Plateau. The selection of criteria and indicators (e.g., storage optimization, risk minimization, and feasibility) is basically used for assessment and evaluation to develop a safe and effective geological CO<sub>2</sub> storage site. Thus, a set of 13 criteria for the assessment and ranking of geological formations in the Khorat Plateau in terms of their suitability for CO<sub>2</sub> storage sites is presented in Table 2. These criteria have been selected to facilitate the determination of the ease and feasibility of deploying CO<sub>2</sub> storage sites in the Khorat Plateau. The criteria were adapted from Bachu (2003), and the

TABLE 2 Evaluation criteria for preliminary assessment of geological CO<sub>2</sub> storage in the Khorat Plateau (adapted from Bachu, 2003).

Criterion (i)	Classes (j)										Weight
	1	Score	2	Score	3	Score	4	Score	5	Score	
Depth	Very shallow (<300 m)	1	Shallow (300–800 m)	3	Very deep (>3,500)	5	Intermediate (800–1,500 m)	9	Deep (1,500–3,500 m)	15	0.1
Hydrocarbon potential	None	1	Small	3	Medium	7	Large	13	Giant	21	0.08
Maturity	Unexplored	1	Exploration	2	Developing	4	Mature	8	Over mature	10	0.1
Climate	Arctic	1	Sub-Arctic	2	Desert	4	Tropical	7	Temperate	10	0.08
Geothermal	Warm basin (>40°C/km)	1	—	—	Moderate (25–40°C/km)	3	—	—	Cold basin (<25°C/km)	7	0.1
Faulting	Extensive	1	—	—	Moderate	3	—	—	Limited	7	0.08
Reservoir seal	Poor	1	—	—	Moderate	3	—	—	Excellent	7	0.1
Salt	None	1	—	—	Domes	2	—	—	Beds	3	0.05
On/off shore	Deep offshore	1	—	—	Shallow offshore	4	—	—	Onshore	10	0.05
Size	Small	1	Medium	3	—	—	Large	5	Giant	9	0.06
Accessibility	Inaccessible	1	Difficult	3	—	—	Acceptable	6	Easy	10	0.05
Infrastructure	None	1	Minor	3	—	—	Moderate	7	Extensive	10	0.05
CO <sub>2</sub> sources	None	1	Few	3	—	—	Moderate	7	Major	15	0.1

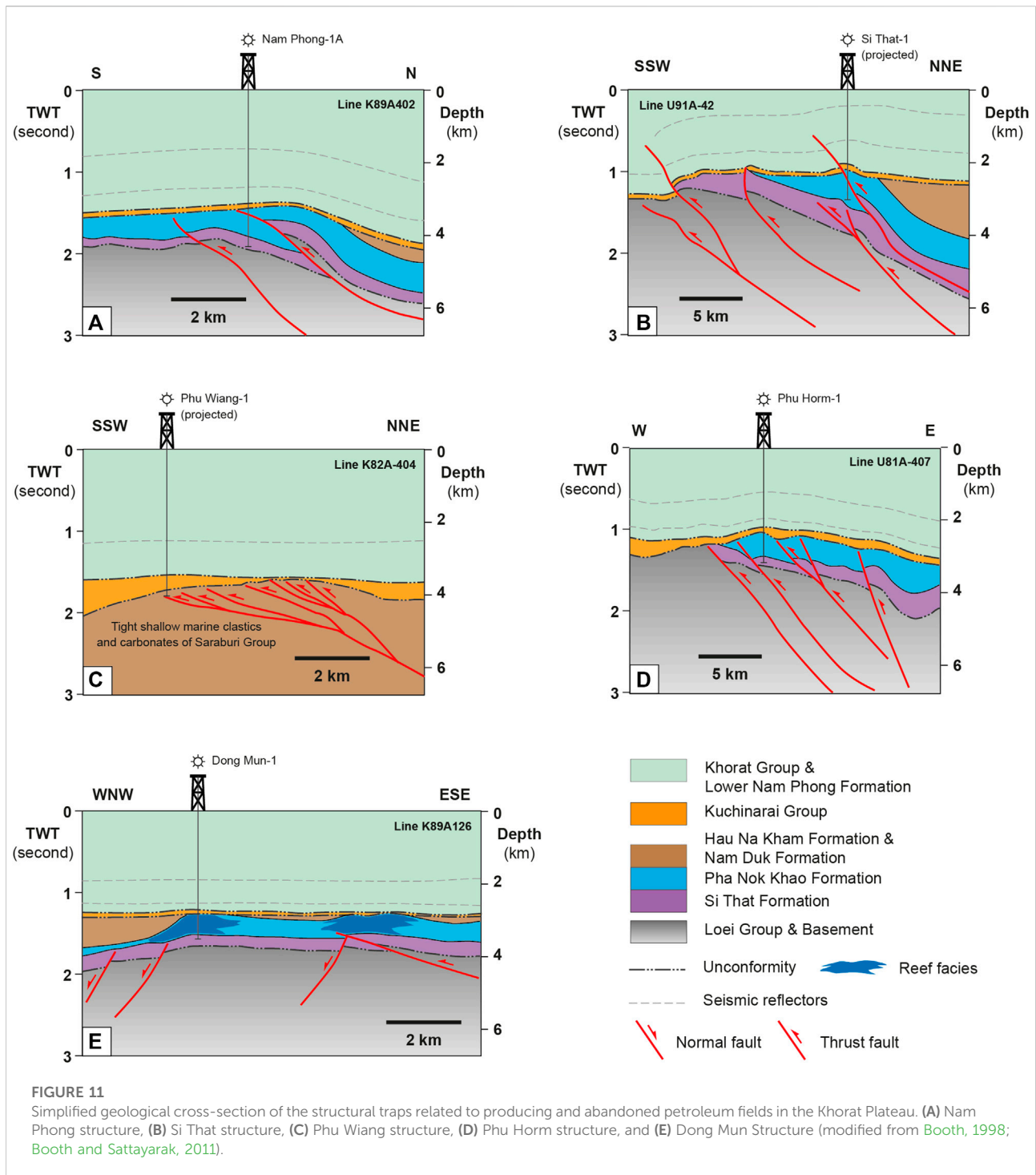
TABLE 3 Criterion scores and ranks of the potential lithological formations in the Khorat Plateau for geological CO<sub>2</sub> storage.

Criterion	Khorat group sandstones	Khorat permian carbonates	Khorat evaporites	Khorat cenozoic basalts
Depth	15	5	3	1
Hydrocarbon potential	3	7	1	1
Maturity	2	8	4	1
Climate	7	7	7	7
Geothermal	7	7	7	7
Faulting	3	1	7	7
Reservoir seal	3	7	7	1
Salt	1	1	3	1
On/off shore	10	10	10	10
Size	5	5	9	3
Accessibility	10	6	10	6
Infrastructure	3	10	3	1
CO <sub>2</sub> sources	7	15	3	7
<b>Score</b>	<b>5.94</b>	<b>7.05</b>	<b>5.44</b>	<b>3.98</b>

weight and score of each criterion were determined based on its relative importance with respect to evaluation of the Khorat Plateau as a CO<sub>2</sub> storage site. In addition, the Khorat Plateau has been designated as low- to non-seismic hazard region (Harnpattanapanich and Luddakul, 2011). Being located in a non-seismic hazard zone is important for safe CO<sub>2</sub> storage and protection against potential leakage or catastrophic escape, which could potentially cause environmental problems. Although there has been low to moderate ground shaking from a large

earthquake outside the Khorat Plateau, subsurface geological storage for CO<sub>2</sub> in the plateau is considered to be safe from natural hazards that might jeopardize the storage security.

The assessment of the potential lithological formations is based on a screening analysis to identify sites that should be suitable for CO<sub>2</sub> utilization and storage in the future. One key criterion is CO<sub>2</sub> point sources within a 100-km radius, such as the Nam Phong power plant (Figure 2). Based on this criterion, the potential lithological formations are the Khorat Group



sandstones, Khorat Permian carbonates, Khorat evaporites, and Khorat Cenozoic basalts. Because these potential lithological formations are all in the Khorat Plateau, several screening conditions are assumed to be the same, including tectonic setting, geothermal gradient, and climate (Table 3).

By compiling data on the criteria in this study, different lithological units can be compared, contrasted, and ranked for their suitability for geological storage of CO<sub>2</sub> (Table 3). In this study, the selected potential sites are evaluated based on their lithologies and available published data; however, more criteria

and detailed geological information should be included in the assessment of potential CO<sub>2</sub> storage sites in the future as more criteria are developed and more data are made available for the assessment.

All of the potential geological formations evaluated in the Khorat Plateau are located in the same geological setting, giving them identical scores of 10 for the criterion of onshore/offshore, as they are all located in an onshore stable area (Tables 2 and 3). Similarly, each is in a tropical area on the Khorat Plateau, meaning that each receives an identical score of 7 for the climate criterion (Tables 2 and 3). Although geothermal heat flow may be different in the subsurface due to different lithologies, all of the evaluated lithologies and sites for geological CO<sub>2</sub> storage are assumed to be in moderate geothermal regime with 25–40 C, which means that each one scored 7 for the geothermal criterion (Tables 2 and 3). Other criteria are assigned for different potential geological formations, suggesting that the Khorat Permian carbonate is the most suitable for geological CO<sub>2</sub> storage in the Khorat Plateau (Table 3).

The storage capacity of the potential lithological formations cannot be determined in this study due to lack of critical information, such as size, thickness, net-to-gross ratio, effective porosity, and CO<sub>2</sub> storage efficiency factor. Thus, we cannot compare the storage capacity between the potential lithological formations. In this case, existing information was primarily derived from outcrop observations, published data, seismic sections, and petroleum exploration wells, which are mostly located within the gas field in the Khorat Plateau. The criterion scores and ranks of the potential lithological formations are summarized in Table 3 and discussed below.

## 7.1 Khorat Permian carbonates

The Permian carbonate reservoirs demonstrate good storage capability with 2–2.5% effective porosity, and are the highest ranked of the potential locations, based on criterion scores in Table 3 (Booth, 2005). CO<sub>2</sub> can be stored as a gas, liquid, or supercritical fluid. The advantage of storing CO<sub>2</sub> as a supercritical fluid is that a larger amount can be stored due to the increase in density as temperature and pressure rise with depth. The supercritical fluid state of CO<sub>2</sub> requires a critical temperature of 31.1°C and a critical pressure of 7.39 MPa (Bachu, 2003). The depth of the Permian carbonate reservoirs is greater than 2,000 m, which is suitable for the supercritical phase of CO<sub>2</sub> (Figure 11). However, it should be noted that CO<sub>2</sub> sequestration and subsequent storage in sites at depths exceeding 2,500 m are relatively much more costly. Thus, the depths of the Permian carbonate reservoirs should be taken into account in assessing the geological CO<sub>2</sub> storage suitability of the Khorat Plateau. Therefore, the different geological structures that affect the depths and distributions of the Permian carbonate reservoirs should be carefully investigated. Although the Permian carbonate

reservoirs are located at great depths that increase costs associated with CO<sub>2</sub> sequestration, the Permian carbonate reservoirs have been subjected to hydrocarbon exploration, with gas fields being produced that may have post-depletion CO<sub>2</sub> storage potential. In addition, the main two gas fields are also located close to the main CO<sub>2</sub> point source, the Nam Phong power plant, with existing infrastructure in place between the power plant and the gas fields. Abandoned exploration fields are interesting for geological CO<sub>2</sub> storage, due to the existing infrastructure and potential storage capacity. Thus, the criterion scores are higher than those of the other three potential lithological formations in the Khorat Plateau. Furthermore, the Permian carbonate reservoirs from the gas fields Phu Horm, Dong Mun, and Nam Phong, in the Khorat Plateau have been evaluated to have average CO<sub>2</sub> storage capacity at 0.1 Gt (Minezaki et al., 2019). Because the best potential storage reservoir in Khorat is Permian carbonate, the analysis of the reservoir quality and caprock integrity must be performed carefully before CO<sub>2</sub> sequestration due to more chemically reactive between CO<sub>2</sub> and carbonate rocks when compared to sandstone reservoirs (e.g., Siqueira et al., 2017).

## 7.2 Khorat Group sandstones

The Khorat Group sandstones are the second ranked option, based on criterion scores shown in Table 3. The Khorat Group sandstones are likely to provide effective geological CO<sub>2</sub> storage in the Khorat Plateau. The sandstones are considered to offer a good-quality reservoir, especially given that the Upper Triassic–Upper Jurassic sandstones have a gross thickness of 300 m and an average porosity of 15% (Canham et al., 1996; El Tabakh et al., 1999). However, the reservoir quality of these sandstones is decreased at deep burial (Smith and Stokes, 1997). A potential good seal is, however, problematic because there is no proven good seal due to well-stacked fluvial systems in the Khorat Group sandstones. In fact, the Indosinian III unconformity within the Nam Phong Formation is the only potential seal for these sandstones; thus, vertical and lateral migrations of CO<sub>2</sub> need to be of concern with regard to CO<sub>2</sub> sequestration. Although there are some trap structures that can be developed for geological CO<sub>2</sub> storage sites in the Khorat Group sandstones, studies of the suitability of the Khorat Group sandstone as a petroleum reservoir are limited. Moreover, the Khorat Group sandstones have not been developed for petroleum fields; thus, several criterion scores are lower than those of the Khorat Permian carbonate reservoirs.

## 7.3 Khorat evaporites

The Khorat evaporites are widely distributed in the Khorat Plateau, with mixed clastic sediments and evaporites of the Maha



Sarakham Formation layering at the depocenter of the Plateau; which achieves the third rank, based on criterion scores shown in Table 3. The Maha Sarakham Formation consists of three members: Upper, Middle, and Lower. The thickness and depth of the massive layers of rock salt present in the Lower Member make them suitable for the excavation of salt caverns and long-term storage of CO<sub>2</sub>. In the Khorat Plateau, at a depth of more than 800 m, the salt layers of the Maha Sarakham Formation fulfill the criteria for storage of CO<sub>2</sub> as a supercritical fluid. Although the Khorat evaporites are at shallow depths, the salt cavern stability modeling indicates that safe storage can be relied upon for a time span of at least 500 years (Pajonpai et al., 2019).

## 7.4 Khorat Cenozoic basalts

The Khorat Cenozoic basalts are locally exposed in the western margin of the Khorat Plateau. Although the Khorat Cenozoic basalts have an alkaline composition, these basalts either comprise outcrops or have no clear seal to prevent leakage of CO<sub>2</sub> and cannot be considered for geological CO<sub>2</sub> storage in the Khorat Plateau. The outcrops are usually at the surface and possibly extend to shallow depths, which are unsuitable for the storage of CO<sub>2</sub>. In addition, porosities in the Cenozoic alkaline basalts typically comprise less than 1% in unfractured outcrops. Little to no subsurface data in the western margin of the Khorat Plateau makes these alkaline basalts insufficient for the storage of CO<sub>2</sub> as a supercritical fluid. Thus, the Khorat Cenozoic basalts are placed in the last rank (Table 3).

## 8 Conclusion

This study provides the first assessment of the potential for geological CO<sub>2</sub> storage in the Khorat Plateau, Thailand. There are four potential lithological formations that can be developed as CO<sub>2</sub> storage sites. The potential lithological formations are the Khorat Group sandstones, Khorat Permian carbonates, Khorat evaporites, and Khorat Cenozoic basalts. A set of criteria is applied for the assessment and ranking of the potential lithological formations in terms of the suitability of each as a possible CO<sub>2</sub> storage site, based on storage optimization, risk minimization, and feasibility. The results suggest that the Khorat Permian carbonates are the most suitable for geological CO<sub>2</sub> storage in the Khorat Plateau. The Khorat Group sandstones and

Khorat evaporites are assessed as being in the second and third ranks, respectively. The Khorat Cenozoic basalts are not suitable for geological CO<sub>2</sub> storage. The criteria scores that identify the Khorat Permian carbonate as the best choice are the maturation of petroleum exploration, the existing infrastructure, and a location close to a CO<sub>2</sub> point source. However, chemical reaction between CO<sub>2</sub> and carbonate rocks could be problematic. Thus, more subsurface studies should be carried out and more detailed criteria should be considered before CO<sub>2</sub> sequestration is undertaken in the Khorat Plateau.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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