A Preliminary Assessment of Geological CO_2 Storage in Cambodia

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ABSTRACT

This study screens and rank Cambodian sedimentary basins in terms of their containment, capacity, and feasibility for the geological storage of CO_2. The results of the screening and ranking procedure indicate that the Khmer Basin is the most suitable basin, followed by the Kampong Saom and Tonle Sap basins. A quantitative volumetric assessment-based evaluation of CO_2 storage capacity is performed on these three suitable basins. The evaluation yields a range in the national CO_2 storage capacity of 90 Mt (in structural traps) to 45 Gt (in hydrodynamic traps), representing low- and high-case estimates, respectively. The saline aquifers associated with this storage capacity should be considered prospective storage options as hydrodynamic traps because of containment and capacity issues associated with the structural traps. Eight major point sources of CO_2 are identified that have a combined output (estimated for 2008–2024) of 43.1 Mt annually and 82 billion m^3 in place, and the potentially-prospective matched storage capacity is assumed. Overall, a combination of the initial suitabilities of the basins and estimates of prospective matched storage capacity shows that the Khmer, Kampong Saom, and Tonle Sap basins may provide a solution to the problem of reducing future atmospheric emissions. The present results should assist both exploration geologists and experts in carbon capture and storage to gain a better understanding of the CO_2 storage resources of Cambodia. However, the results should be regarded as preliminary because of the limited available data on which the assessments were based; future geological and geophysical data should improve the reliability of the estimates of carbon storage capacity reported here.

Keywords: CO_2 storage, Khmer Basin, saline aquifer, hydrodynamic trap, matched storage capacity, Cambodia.

1. Introduction

Cambodia is located in the Indochina Peninsula and has a tropical climate in both offshore and onshore areas. The Cambodian National Petroleum Authority (CNPA) states that numerous CO_2 emission point sources are present in both the on- and off-shore environments of Cambodia, and there are significant concerns over the contribution of the CO_2 produced by these sources with respect to the abundance of greenhouse gases in the atmosphere and climate change.

The geological storage of CO_2 is a viable method to reduce CO_2 emissions into the atmosphere (Wilson et al., 2003; IPCC, 2005). The safe storage of CO_2 in a sedimentary basin requires that CO_2 is stored in favorable geological porous media at depth varies from 800–1000 m for a cold sedimentary basin (characterized by low geothermal gradient) to 1000–1500 m for a warm sedimentary basin (characterized by high geothermal gradient) (so that the stored CO_2 will be in the dense phase); the porous media also need to be covered by thick regional cap rocks so that CO_2 cannot penetrate vertically upwards through the overlying sedimentary sequence (Bachu, 2000, 2003; IPCC, 2005). The injection of CO_2 at shallower depths (<800 m) may result in storage in the gaseous phase, whereby the CO_2 will occupy much larger unit volumes of pore space compared with storage in the dense phase, and is more likely to result in the leakage of highly buoyant CO_2 to the surface, potentially with significant impacts on human health (IPCC, 2005). Effective storage capacity is limited by the need to avoid overly high injection pressures that can damage cap rock formations (Van Der Meer, 1992, 1993; Holloway and Savage, 1993; Hildenbrand et al., 2002, 2004; Höller and Viebahn, 2011). Theoretically, CO_2 geological storage is straightforward, although suitable storage areas need to be identified within specific reservoirs. This means that a number of different studies are required to assess the geological CO_2 storage suitability of individual reservoirs, including basin- to region-scale assessments that incorporate both qualitative and quantitative evaluations, risk assessments, and economic analysis. Basins suitable for effective CO_2 storage have previously been identified in, for example, Australia (Gibson-Poole et al., 2008), Canada (Bachu, 2000, 2003), and Greece (Koukouzas et al., 2009), and subsequent detailed assessment, site characterization, and economic analysis of such basins have been undertaken in Australia (Bradshaw et al., 2004) and in the Netherlands (Ramírez et al., 2010).

The subsurface geology of mature oil-producing countries is well known, compared with the relatively unexplored and restricted nature of knowledge of the subsurface geology in Cambodia. Bachu (2003) argued that both qualitative and quantitative parameters for the screening and ranking of basins need to be subjectively adjusted in accordance with the economic situation of the country concerned. The majority of sedimentary basins in Cambodia are still poorly explored and are located in areas without identified CO_2 sources, and many of them have no or limited infrastructure. Knowledge of the subsurface geology of Cambodia is currently restricted as a result of oil and gas exploration policy, the present research study aims to provide a preliminary assessment of the suitability of sedimentary basins in Cambodia for CO_2 storage by determining which basins have large effective pore volumes. The study examines and assesses the structural geological framework and stratigraphy of Cambodian basins using published data (Vysotsky et al., 1994; Okui et al., 1997; Fyhn et al., 2010), along with information obtained via the cooperation of the CNPA (part of the Ministry of Mines and Energy of the Government of Cambodia). This is the first study to focus on the existence of suitable aquifers and hydrocarbon reservoirs within the Cambodian subsurface for the geological storage of CO_2.

Table 1
Methodology for estimating CO_2 emissions from stationary sources (US DOE-NETL, 2012).

Methodology	Description
1. CO_2 emissions from cement plant: $C_{CO2} = 0.9 \times E_{cp}$	CO_2 emissions estimate based on cement production and combustion. Where: C_{CO2} = tons per year; E_{cp} = Cement production rate (tons per year)
2. CO_2 emissions from coal fired power plant: $CF_{CO2} = 3.664 \times C_{\%} \times F_t$	CO_2 emissions estimate via combustion. Where: CF_{CO2} = tons per year; $C_{\%}$ = carbon in the coal (weigh fraction; %); F_t = coal usage rate (tons per year)
3. CO_2 emissions from natural gas power plant: $NG_{CO2} = (1100 \times P) / (2000)$	CO_2 emissions estimate calculated using a value of 1100 lb of CO_2 per MWh. Where: NG_{CO2} = tons per year; P = annual plant generation (MWh)
4. CO_2 emissions from oil power plant: $H_{CO2} = (3.664 \times F_t \times C_{\%} \times D_F) / (2000)$	CO_2 emissions estimate via combustion. Where: H_{CO2} = tons per year; D_F = oil density (lb per gallon); $C_{\%}$ = carbon in the oil (weight fraction; %); F_t = oil usage rate (gallons per year)
5. CO_2 emissions from refinery plant: $R_{CO2} = 11 \times E_P$	CO_2 emissions estimate based on emission factor for petroleum refinery production (11 tons CO_2 per year per barrel per day petroleum). Where: R_{CO2} (tons per year); E_P = petroleum plant production rate (barrel per day)
6. CO_2 emissions from fertilizer production: $NH3_{CO2} = E_{NH3} \times (\theta_{NH3} + \theta_{fuel})$	Where: $NH3_{CO2}$ = tons per year; θ_{NH3} = CO_2 process emission factor for NH_3 production (1.2 tons CO_2 per ton NH_3); E_{NH3} = Production rate (tons per year); θ_{fuel} = CO_2 combustion emission factor (0.5 tons CO_2 per ton NH_3)
7. CO_2 produced from natural gas reservoir: $V_{CO2} = R_f \times$ volume of OGIP	Where: V_{CO2} = cubic meter; R_f = CO_2 recovery factor; OGIP = original gas in place

2. CO_2 emission point sources

The CO_2 point sources in Cambodia are identified as two large potential future natural gas plants (in Overlapping Claims Area (OCA) and Western Block A), four coal-fired power plants (Koh Kong, Sihanouk Ville II and III, and Kampot), one natural gas power plant (Sihanouk Ville I), one oil power plant (EDC (Electricite Du Cambodge) Phnom Penh), one refinery (Prey Nop), one cement kiln (Kampot Cement), and one fertilizer plant (Takmau Fertilizer). Regarding the installed and production capacity and type of industry (MME, 2009; IEEJ, 2011; 2b1st–consulting, 2013; OpenDevelopmentCambodia, 2013; CDRI, 2014; Energypedia, 2014; SCG, 2014; CNPA exploration documents), total CO_2 emissions were calculated using the methodology of US DOE-NETL (2012) (Table 1). Based on these sources, emissions for 2008–2024 are calculated to total 48.75 million tonnes (Mt) from industrial sources annually and 82 billion cubic meters (Gm^3) from natural gas in place. Fig. 1 shows the emission data, including the locations of emission point sources, types of stationary source, capacities, emission rates, and sedimentary basins. CO_2 gas is produced through processes involved in the national energy production, and amounts to 46.1 Mt per year; the amount potentially recoverable from high-CO_2-content natural gas reservoirs is 82 Gm^3 in total. The major stationary emissions are concentrated in the near- and off-shore areas (Kampot, Koh Kong, Prey Nob, Sihanouk Ville, OCA and Western Block A) of southwestern Cambodia, and represent 90% of the estimated 2008–2024 emissions. CO_2 from these major stationary point sources (about 43.1 Mt per year and 82 Gm^3 in place) has the greatest potential for geological storage.

3. Sedimentary basins of Cambodia

A number of sedimentary basins of various ages are present both onshore and offshore Cambodia (Fig. 1). The earliest-formed basins are associated with Paleozoic–Mesozoic regional uplifts and Permian–Jurassic folding and thrusting of the Indosinian Orogeny or Sundaland Accretion during collision between Indochina and the Sibumasu and South China plates; these basins are associated with Mesozoic granite magmatism (Fig. 2; Workman, 1977; Hayashi, 1988; Vysotsky et al., 1994; Lepvrier et al., 2004; Fyhn et al., 2010). These granites form a north–south-trending magmatic arc that is thought to enter the Gulf of Thailand to the east of the Kampong Saom Fold Belt and can be traced from the offshore extent of this fold belt across the eastern Cambodia border to south China and farther to the northeast. This structure confines Mesozoic Cambodian basin development to a once continuous, large basin (the Cambodian Basin) that covered the entire area of the modern country (Fig. 2 and the index map of Indochina with selected structures of Fyhn et al., 2010). This basin is dominated by uppermost Permian–Triassic syn-rift sediments and overlying post-rift Jurassic to Cretaceous sediments of the Bokor Formation (Vysotsky et al., 1994; Fyhn et al., 2010). The Cambodian Basin is structurally subdivided into the Khorat, Tonle Sap, Preah, Chhung, Svaryrieng, and Kampong Saom troughs.

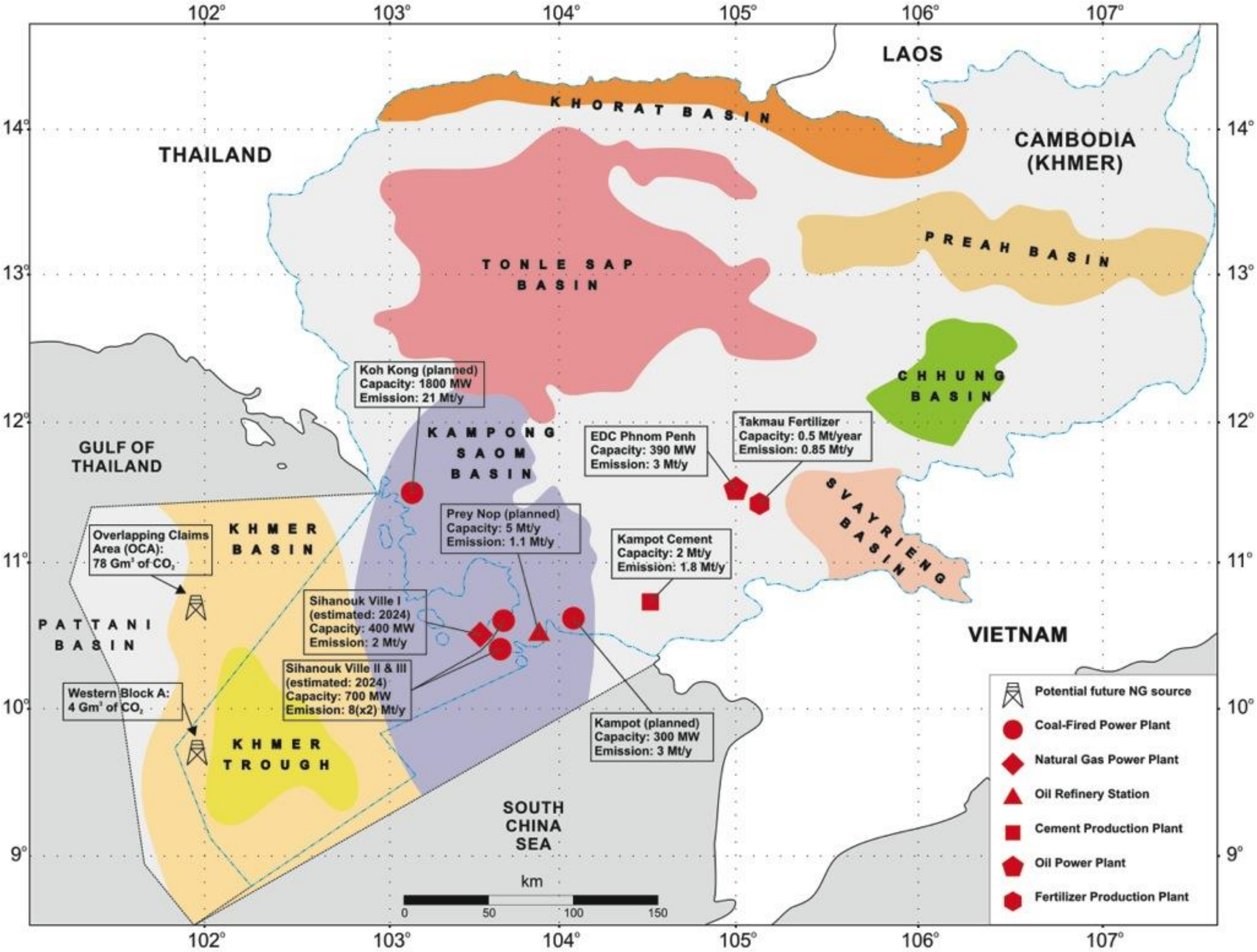

Fig. 1. Location map of Cambodia showing the major CO_2 emission point sources for geological storage (data sourced from CNPA) with the sedimentary basins analyzed in the present study (after Vysotsky et al., 1994; CNPA internal technical report). This study made estimates of emissions for 2008–2024.

After its formation, the Cambodian Basin was divided as a result of Paleocene–early Eocene left-lateral transpression and erosion associated with collision between India and Eurasia (i.e., the Himalayan Orogeny), and the accretion of western Myanmar onto the Indochina platform (Morley, 2002; Fyhn et al., 2010). The north–south-directed thrusting and uplift were concentrated along the Khmer and Kampong Saom fold belts and merged with the Mae Ping and Three Pagoda fault zones, which confine the onshore and offshore basins (see Fig. 2 and the index map of Indochina with selected structures of Fyhn et al., 2010). The activation of the Mae Ping Fault Zone has been linked with right- and subsequent left-lateral displacements (Morley, 2002; Lepvrier et al., 2004; Fyhn et al., 2010). In addition, the Three Pagoda Fault Zone appears to link up with the Khmer Fold Belt (Fyhn et al., 2010), suggesting a connection between the rifting of the western Kampong Saom Trough and late Eocene left-lateral fault motion (Hall, 1996; Watcharanantakul and Morley, 2000). This indicates that the Kampong Saom Trough in the central Gulf of Thailand underwent both extensional faulting and left-lateral motion along the Three Pagoda Fault Zone, causing the southwestern part of the trough to open as a pull-apart basin. In turn, this led to the formation of a new Cenozoic Khmer Trough through the genesis of half-graben complexes that accumulated thick marine sediments during the

Cenozoic; these sediments overlie unidentified Mesozoic units equivalent to the Kampong Saom sediments (data sourced from CNPA).

The geology of these basins is described in more detail in Section 5, including evaluation of the suitability of these basins for geological CO_2 storage and estimates of their storage capacity.

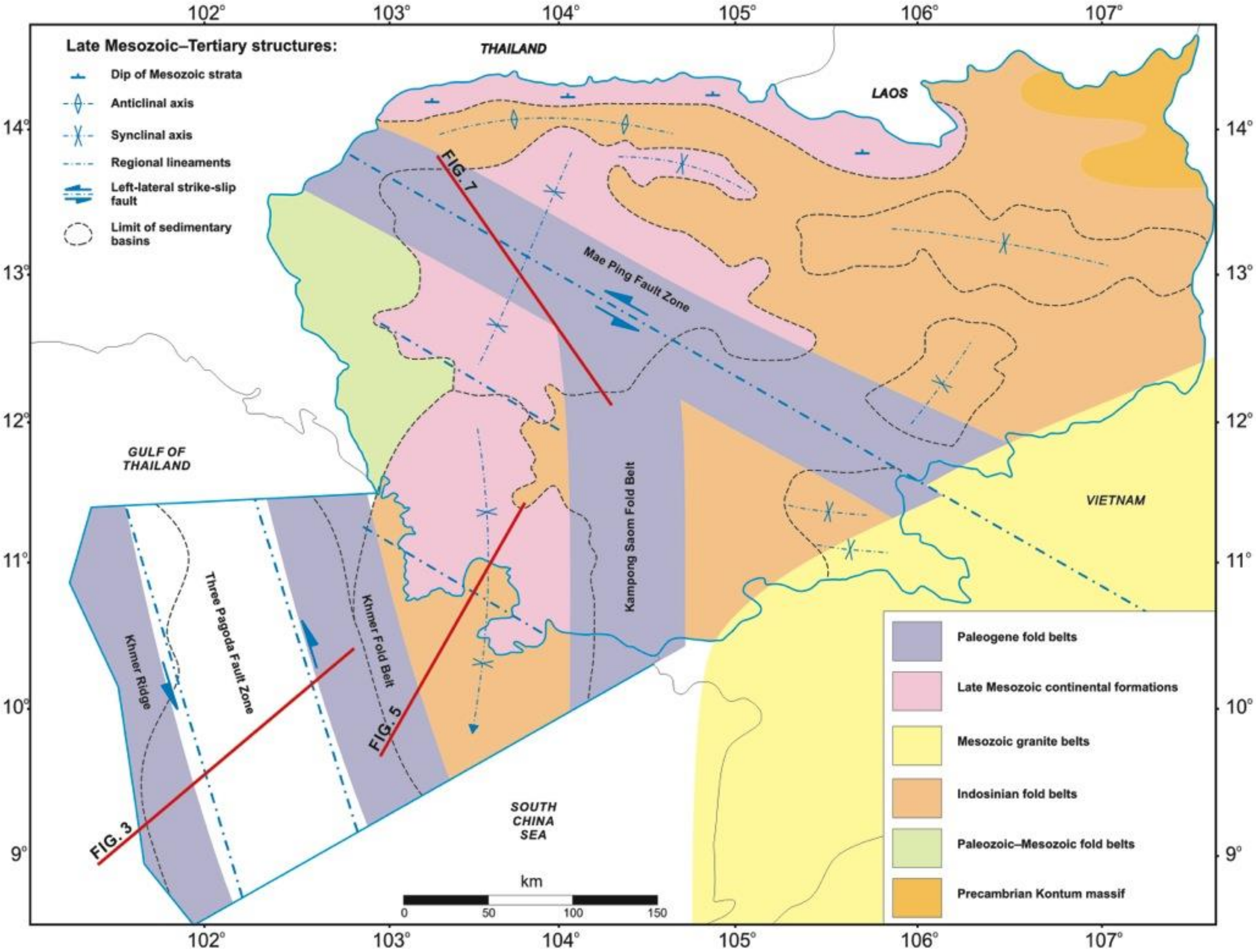

Fig. 2. Simplified geological map of Cambodia with elements of the major geological structure (based on a CNPA internal technical report; Workman, 1977; Vysotsky et al., 1994; Hall, 1996; Watcharanantakul and Morley, 2000; Morley, 2002; Fyhn et al., 2010). Prior to the development of late Mesozoic–Tertiary structures, the large Cambodian Basin formed in association with granite belts and regional uplifts. During basin segregation, Paleogene fold belts outlined the boundaries of Mesozoic basins. The Three Pagoda Fault Zone was activated, possibly as a late Eocene left-lateral fault, opening an offshore Mesozoic trough as a pull-apart basin, forming a new Cenozoic basin. The section lines shown in Figs. 3, 5 and 7 are shown as labeled red lines.

4. Methodology of basin assessment

4.1 Basin screening and ranking

The method of assessing the suitability of basins in Cambodia for their CO_2 storage potential was adapted from the basin screening criteria of Bachu (2003) as modified by Gibson-Poole et al. (2008). Both Mesozoic and Cenozoic basins were evaluated using the criteria in Table 2; these criteria include tectonic setting, basin size and depth, faulting intensity, aquifer systems, geothermal regime, basin resources, and industry maturity and infrastructure. The criteria were classified into three groups (based on Gibson-Poole et al., 2008) that focus on CO_2 containment (tectonic setting of the basins, faulting intensity, depth of the basin, and presence of evaporites), CO_2 storage capacity (basin size, hydrocarbon potential, coal and coal bed methane (CBM), deep aquifers, and geothermal regime), and the technological feasibility of CO_2 storage (location onshore or offshore, basin accessibility, existing infrastructure, CO_2 sources, industry maturity, and the climate of the area).

Each of the criteria presented in Table 2 was given a value based on criterion-specific defined classes, where the lowest and highest values characterize the least and the most suitable classes, respectively. An exponential parameterization of a function (F_i) was used to define the range of numerical values for each class of that criterion. The numerical values of F_i were assigned to define classes for the criteria given in Table 2, where $F_{i,1}$ = the minimum value, $F_{i,n}$ = the maximum value, and n = the number of the class (n = 3, 4, 5).

Each individual basin was assigned a score, $F_{i.c}$, for each criterion. Individual scores ($F_{i.c}$) were normalized using the approach of Bachu (2003) and by considering comparative values of the function F_i for the least suitable ($F_{i,1}$), most suitable ($F_{i,n}$), and corresponding scores ($F_{i,c}$) for each criterion:

$$P_i = (F_{i,c} - F_{i,1})/(F_{i,n} - F_{i,1}) \qquad (1)$$

where P_i is the normalized score for each criterion (i = 1…15) ranging between P_i = 0 (least suitable in a class) to P_i = 1 (most suitable in a class) for a given sedimentary basin. This normalization procedure transformed the characteristics of each basin into quantitative data that vary between 0 and 1. This procedure was subsequently incorporated into the basin-ranking process using weights that express the relative importance of each criterion to produce a general ranking score (R), which was calculated using the approach of Bachu (2003) as follows:

$$R = sum\ (w_i\ P_i) \qquad (2)$$

where w_i is a weighting function that satisfies the general condition sum w_i = 1. These weights were assigned to various criteria relating to the economic conditions currently prevailing in Cambodia. The parameterization of the various classes and weights of each criterion used in the present study were adapted from Bachu (2003) by adjusting them to the specific circumstances for in Cambodia. The weightings of criteria including tectonic setting (from 0.07 to 0.08), size of basin (from 0.06 to 0.08), depth of basin (from 0.07 to 0.10), faulting intensity (from 0.07 to 0.10), aquifers (from 0.08 to 0.09), hydrocarbon potential (from 0.06 to 0.10), coals and CBM (from 0.04 to 0.06), and evaporites (from 0.01 to 0.02) were increased.

This in turn meant that to satisfy the $w_i = 1$ relationship (Equation 2), weightings expressing the relative importance of other criteria were lowered.

Table 2
Basin criteria used for screening for CO_2 geological storage (modified from Bachu, 2003; Gibson-Poole et al., 2008). These criteria were classified into three groups, namely containment, capacity, and feasibility, and the weight of each criterion and the scores of the classes were determined based on their relative importance with respect to Cambodian Basins.

Criteria and weights			Classes and scores									
			Class 1		**Class 2**		**Class 3**		**Class 4**		**Class 5**	
Containment	Tectonic setting	0.08	Oceanic Basin	1	Fore-Arc Basin	3	Intra-Arc Basin	7	Foreland Basin	15	Cratonic Basin	15
	Faulting intensity	0.10	Extensively faulted and fractured	1	Moderately faulted and fractured	4	Limited faulting and fracturing	12				
	Evaporites	0.02	None	1	Domes	3	Beds	7				
	Depth of basin	0.10	Shallow (<1000 m)	1	Intermediate (1000–3500 m)	4	Deep (>3500 m)	4				
Capacity	Size of basin	0.08	Small (1000–5000 km²)	1	Medium (5000–25,000 km²)	3	Large (25,000–50,000 km²)	7	Giant (>50,000 km²)	15		
	Aquifers	0.09	Short flow systems	1	Intermediate flow systems	4	Regional flow systems	12				
	Geothermal regime	0.07	Warm basin (>40°C/km)	1	Moderate (30–40°C/km)	4	Cold basin (<30°C/km)	10				
	Hydrocarbon potential	0.10	None	1	Small	3	Medium	6	Large	12	Giant	25
	Coals and CBM	0.06	None	1	Deep (>900 m)	2	Shallow (300–900 m)	5				
Feasibility	Industry maturity	0.04	Unexplored	1	Exploration	2	Developing	3	Mature	5	Over-mature	8
	On/offshore	0.07	Deep offshore	1	Shallow offshore or nearshore	4	Onshore	12				
	Climate	0.04	Arctic	1	Sub-arctic	2	Desert	4	Tropical	7	Temperate	10
	Accessibility	0.03	Inaccessible	1	Difficult	2	Acceptable	5	Easy	10		
	Infrastructure	0.04	None	1	Minor	3	Moderate	7	Extensive	15		
	CO_2 sources	0.08	None	1	Few	3	Moderate	7	Major	15		

4.2 Estimation of basin-wide storage capacity

This paper focuses on the identification of basins suitable for geological CO_2 storage. However, regional extrapolations and calculations of basin-wide CO_2 storage capacities were also undertaken. This approach follows those outlined in previous research (Koide et al., 1992; Bachu et al., 1994; Hendriks et al., 2004; Bachu et al., 2007; CSLF, 2008; US DOE-NETL, 2012), although some assumptions were made to simplify the estimates of storage capacity, namely that the CO_2 within the geological media of the Cambodian subsurface is assumed to be trapped within depleted hydrocarbon reservoirs without aquifer support (based on oil and gas production testing; CNPA), or within migrating plumes associated with the large-scale flow systems present in shallower aquifers. The use of both hydrocarbon and aquifer volumes in determining the available pore volume for CO_2 storage is outlined below.

4.2.1 Oil reservoirs

Oil reservoirs were assigned a baseline storage efficiency of 7% (following Bachu and Shaw, 2003, 2005; Haszeldine, 2006), based on general CO_2–Enhanced Oil Recovery (EOR) considerations (listed by Holt et al., 1995), thereby yielding a theoretical storage capacity $M_{CO2\ hydrocarbon}$ as follows (Bachu et al., 2007; CSLF, 2008):

$$M_{CO2\ hydrocarbon} = Ce \times \rho_{co2r} \times ((R_f \times OOIP)/(B_f)) \tag{3}$$

where Ce is the storage (sweep) efficiency factor, ρ_{co2r} is the average CO_2 density within the reservoir (assumed to be 620 kg/m^3; Ennis-King and Paterson, 2002; MIT, 2008), R_f is the recovery factor, $OOIP$ is oil originally in place, and B_f is a formation volume factor determined as the volume of oil extracted to the surface from the reservoir multiplied by 1.5 (based on Morton-Thompson and Wood, 1992; Satter et al., 2008).

4.2.2 Aquifers

A different estimation method was used for aquifers, in which the surface area (areal extent) of the sedimentary basin, the average porosity of the aquifer, and the gross thickness of the aquifer were used to determine storage potential (Koide et al., 1992; Bradshaw et al., 2007). The technique for estimating aquifer CO_2 storage capacity used here is based on that of Hendriks et al. (2004) and Bachu et al. (1994), and includes both safety (E_s) and efficiency factors (E_e). As the CO_2 is unlikely to fill an entire aquifer, the theoretical storage capacity $M_{CO2aquifer}$ can be calculated using:

$$M_{CO2\ aquifer} = \rho_{co2r} \times A \times h \times \Phi \times (N/G) \times E_e \times E_s \tag{4}$$

where ρ_{co2r} is the CO_2 density within the reservoir (assumed 620 kg/m^3 is considered across all the basins to ensure the consistency with the storage capacity estimation in oil reservoirs, e.g. Koukouzas et al., 2009), A is the surface area of the sedimentary basin, h is the gross thickness of the aquifer, Φ is the average porosity across the entire aquifer, N/G is the net sand thickness, E_e is the storage efficiency factor, and E_s is the safety factor.

5. Basin screening

The Cambodian sedimentary basins were evaluated according to the screening method presented above. The limited information available means that the screening procedure focuses on the location, geological setting, size and depth, faulting intensity, geothermal regime, and paired reservoir–seal systems of these basins. The criteria are discussed below, and Table 3 summarizes the results of the basin suitability screening for geological CO_2 storage in terms of containment, storage capacity, and feasibility.

Table 3
Results of basin screening for CO_2 storage suitability in Cambodia.

Criteria \ Basins		Khmer	Kampong Saom	Tonle Sap	Preah	Chhung	Svaryrieng	Khorat
Containment	Tectonic setting	Foreland	Foreland	Foreland	Foreland	Foreland	Foreland	Foreland
	Faulting intensity	Limited faulting and fracturing	Limited faulting and fracturing	Moderately faulted and fractured	Extensively faulted and fractured	Extensively faulted and fractured	Extensively faulted and fractured	Extensively faulted and fractured
	Evaporites	Beds	Beds	Beds	None	None	None	None
	Depth of basin	Deep	Deep	Deep	Shallow	Shallow	Shallow	Shallow
Capacity	Size of basin	Large	Large	Large	Medium	Small	Medium	Medium
	Aquifers	Assumed regional flow aquifers	Assumed regional flow aquifers	Assumed regional flow aquifers	Assumed regional flow aquifers	Assumed short flow aquifers	Assumed short flow aquifers	Assumed short flow aquifers
	Geothermal regime	Warm basin	Assumed warm basin	Cold basin	Assumed warm basin	Assumed warm basin	Assumed warm basin	Assumed warm basin
	Hydrocarbon Potential	Large	Medium	Medium	Small	None	Small	Small
	Coal and CBM	Shallow	Shallow	Shallow	None	None	None	None
Feasibility	Industry maturity	Mature	Exploration	Exploration	Unexplored	Unexplored	Unexplored	Unexplored
	On/offshore	Deep offshore	Shallow offshore	Onshore	Onshore	Onshore	Onshore	Onshore
	Climate	Tropical	Tropical	Tropical	Tropical	Tropical	Tropical	Tropical
	Accessibility	Assumed easy	Assumed acceptable	Assumed difficult	Assumed inaccessible	Assumed inaccessible	Assumed inaccessible	Assumed inaccessible
	Infrastructure	Extensive	Minor	None	None	None	None	None
	CO_2 sources	Major	Major	None	None	None	None	None

5.1 Khmer Basin

5.1.1 Geological setting and reservoir–seal systems

The Khmer Basin is thought to be a foreland basin (Vysotsky et al., 1994; Fyhn et al., 2010). The basin is located in the eastern Gulf of Thailand and covers an area of ~8600 km^2. The basin trends north–south and is bounded to the east by the Khmer Fold Belt and to the west by the Khmer Ridge, which separates the Khmer Basin from the Pattani Basin in Thailand (Fig. 3). This basin contains >6000 m of Mesozoic–Cenozoic sediments including ~2000 m of Triassic–Cretaceous basement. Cenozoic sediments within the Khmer Trough are dominated by sandstones interbedded with clays, shale, silts, and coals (Fig. 4). Lower Miocene sandstones are the most effective reservoirs for hydrocarbon accumulations within the central trough. These lower Miocene sandstone reservoirs were charged vertically by upper Oligocene shales (Okui et al., 1997), although there is a lack of vertical connections between middle–upper Miocene sandstones and upper Oligocene source rocks, so the majority of uppermost middle to upper Miocene reservoirs are depleted in hydrocarbons and therefore can be treated as saline aquifers.

The absence of a route for significant long-distance vertical hydrocarbon migration within the Khmer Trough suggests that the top seals to the reservoirs consist of intraformational shales, indicating that each individual hydrocarbon-charged sand compartment is sealed by the overlying shale horizons. Regional seals distal from hydrocarbon-bearing sediments in the basin may also be present within upper Miocene and lower Pliocene sedimentary sequences that are dominated by thick mudstones (data sourced from CNPA).

5.1.2 CO_2 storage potential

The Khmer Basin is currently undergoing hydrocarbon exploration and production, and is thought to be tectonically stable, with no recorded earthquake activity (Giardini et al., 1999). Geological cross-sections (see Vysotsky et al., 1994) indicate that minimal faulting has occurred within Miocene sediments, and those faults that are present have not been reactivated and therefore may act as seals where they juxtapose sands and clays (Okui et al., 1997). These geological features indicate that Miocene sediments within this basin may be favorable for CO_2 storage without posing problems for fault bounded closures (hydrocarbon traps within the Y-shape structure) in the basin. Structural geometry results in reduced areas of closure with depth, and this would not regionally compartmentalize the shallower saline aquifer formation (Fig. 3).

Economic oil and gas reservoirs have been discovered within Miocene sediments in the Khmer Trough, and are at various stages of development (data sourced from CNPA). The reservoir formation, discussed in Section 5.1.1 above, consists of interbedded thin sandstones and clays with minor coal beds. The sandstone reservoirs are thought to be present as a stacked sandstone sequence with a gross thickness of ~500–1000 m, and an average net thickness of 300 m; these reservoirs may have been both oil and gas charged and sealed by interbedded shale source rocks (data sourced from CNPA). The reservoirs could potentially be used for geological CO_2 storage once they are depleted. Other opportunities for CO_2 storage may also exist in saline aquifers within Miocene successions. Saline aquifers with high potential for CO_2 storage are assumed to be present in the uppermost middle to upper Miocene sediments (Figs. 3 and 4); these saline aquifers have large lateral extents, a gross thickness of ~400 m, and a net sand thickness of ~80 m. A petrophysical interpretation established as part of a table review of CNPA exploration documents estimates that these reservoirs have an average porosity of 26% and a permeability of 250 md, indicating that they may be good targets for CO_2 injection. These indicate that injected CO_2 would migrate horizontally as a plume over several kilometers laterally and hundreds of meters vertically, to be trapped by uppermost Miocene seals (Fig. 3). In reality, this large horizontal CO_2 plume may be trapped within hydrodynamic systems, with structural traps (measuring 1–20 km^2) providing an additional safety net for CO_2 storage (data sourced from CNPA).

Abundant coal seams are also present within Miocene sediments. These coals are black to very dark brown, vary from <1 to 3 m in thickness, and are associated with clays and siltstones (intervening layers). Natural gas (dominantly methane with minor ethane and propane) has been detected from these coals, with drilling data indicating background gas concentrations of 0.2%–0.5% at depths of 700–1000 m (Okui et al., 1997). Well data show that the basin has a geothermal gradient of between 45°C/km and 55°C/km with a sea-bed temperature of 22°C (data sourced from CNPA), indicating that in terms of geothermal effects on CO_2 storage, this is a warm basin. However, the geothermal gradient within the Khmer Basin varies very significantly.

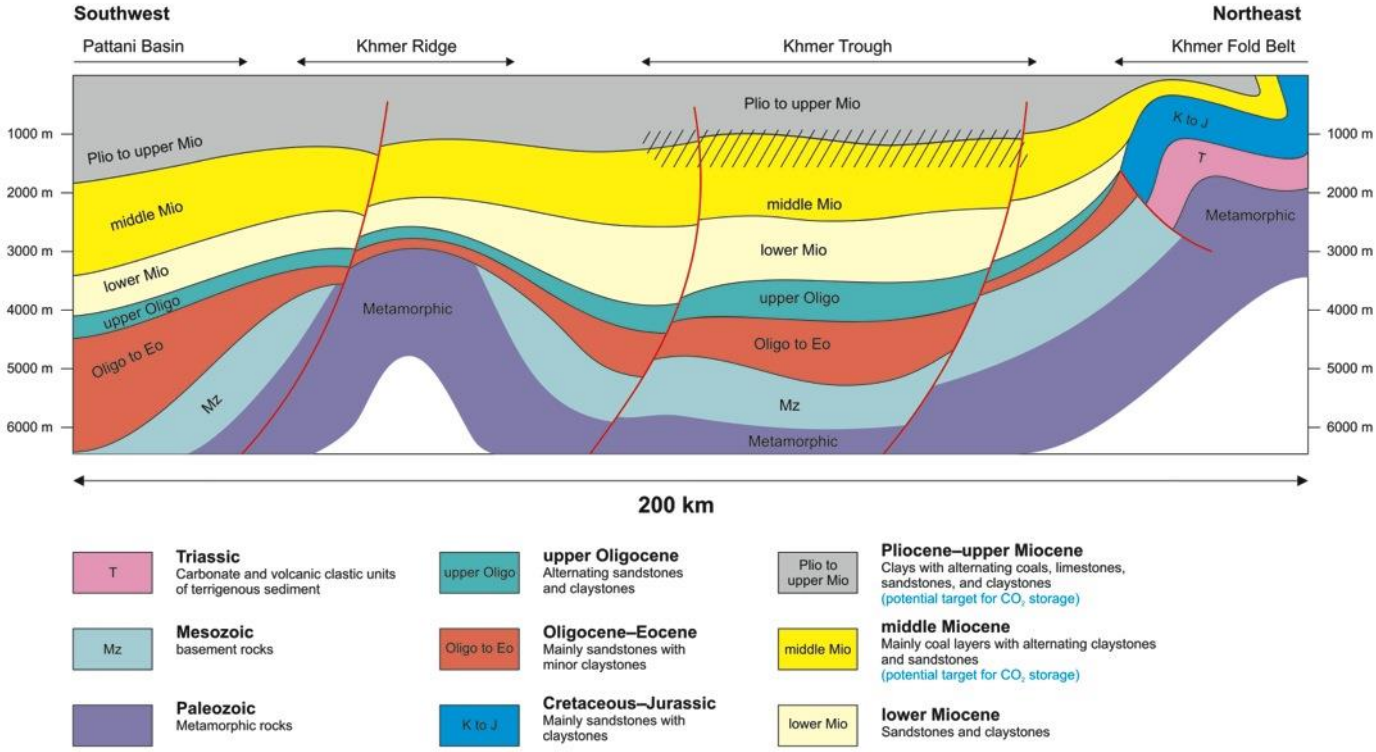

Fig. 3. Simplified geological cross-section of the offshore Cenozoic Khmer Basin (based on a CNPA internal technical report), showing potential reservoirs and cap rocks for CO_2 storage within the Khmer Trough. Suitable storage lithologies are located within the lower–middle Miocene successions. The hatched area indicates the primary injection target for CO_2 storage in aquifers.

5.2 Kampong Saom Basin

5.2.1 Geological setting and reservoir–seal systems

The Kampong Saom Basin is thought to be a foreland basin (Vysotsky et al., 1994; Fyhn et al., 2010) that formed in response to the Sundaland Accretion. This basin is about 100 km wide, and is flanked to the east by the Kampong Saom Fold Belt and to the west by the Khmer Fold Belt (Figs. 2 and 5). The Kampong Saom Basin extends north–south from the southern boundary of the Tonle Sap Basin to the central part of

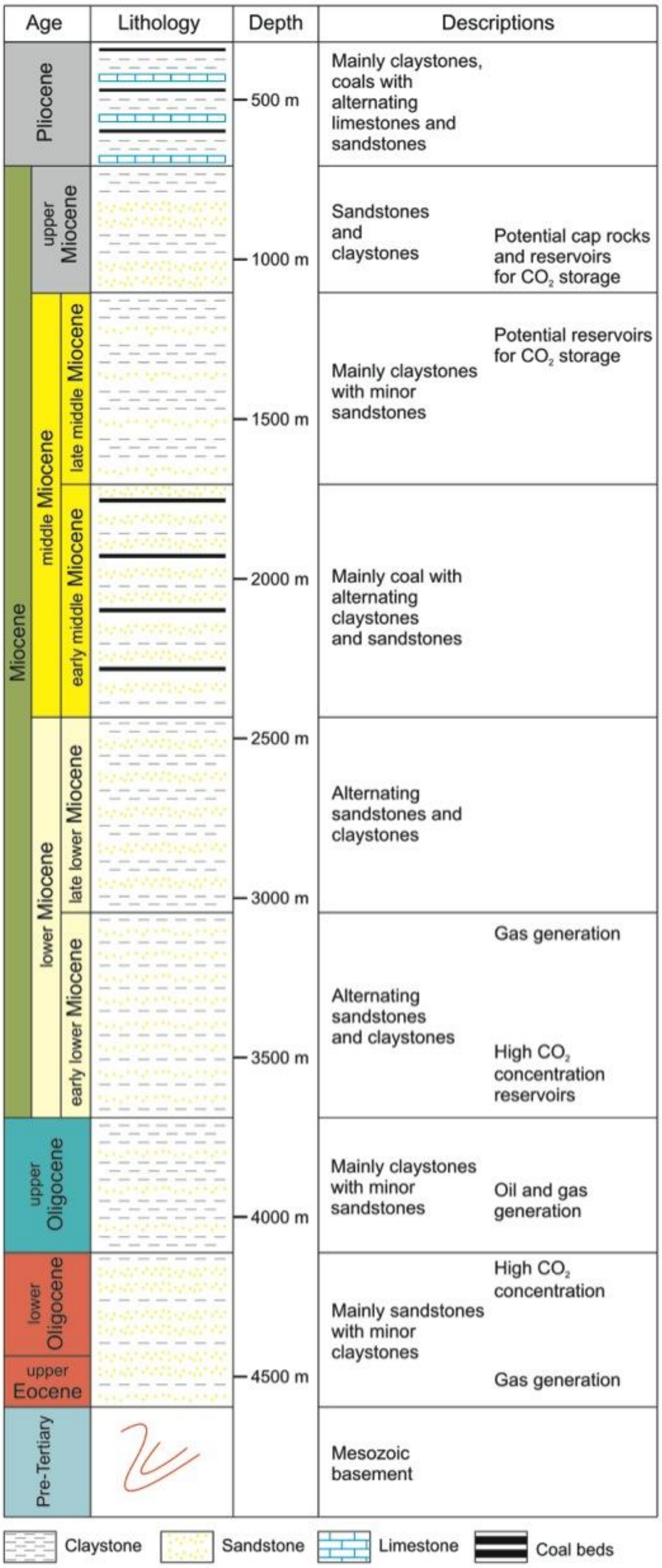

Fig. 4. Generalized stratigraphy of the Khmer Trough with CO_2 injection targets and potential cap rocks (based on Vysotsky et al., 1994; CNPA internal technical report). The stratigraphic positions of suitable storage reservoirs and associated cap rocks are given in the descriptions within the figure.

the Gulf of Thailand (Fig. 1 and 2; Fyhn et al., 2010), covering a total area of ~28,000 km^2 offshore and ~12,000 km^2 onshore. The Kampong Saom Trough, in the center of the basin, consists of deformed Paleozoic complex basement material and overlying Upper Triassic–Cretaceous orogenic complex sediments (Fig. 6). These Mesozoic sediments are dominated by terrigenous sandstones with widespread silt and clay horizons that were deposited during the development of the trough. Upper Jurassic–Cretaceous successions within the trough have just entered the main stage of oil generation (Vysotsky et al., 1994), suggesting that gas generation may already have taken place in this section. Gas and condensates may also have been generated within upper Carboniferous to Triassic successions (Fig. 6), although the most promising targets for hydrocarbon exploration are Upper Triassic to Middle Jurassic, and Upper Jurassic to Cretaceous sequences within the trough (Vysotsky et al., 1994; Fyhn et al., 2010).

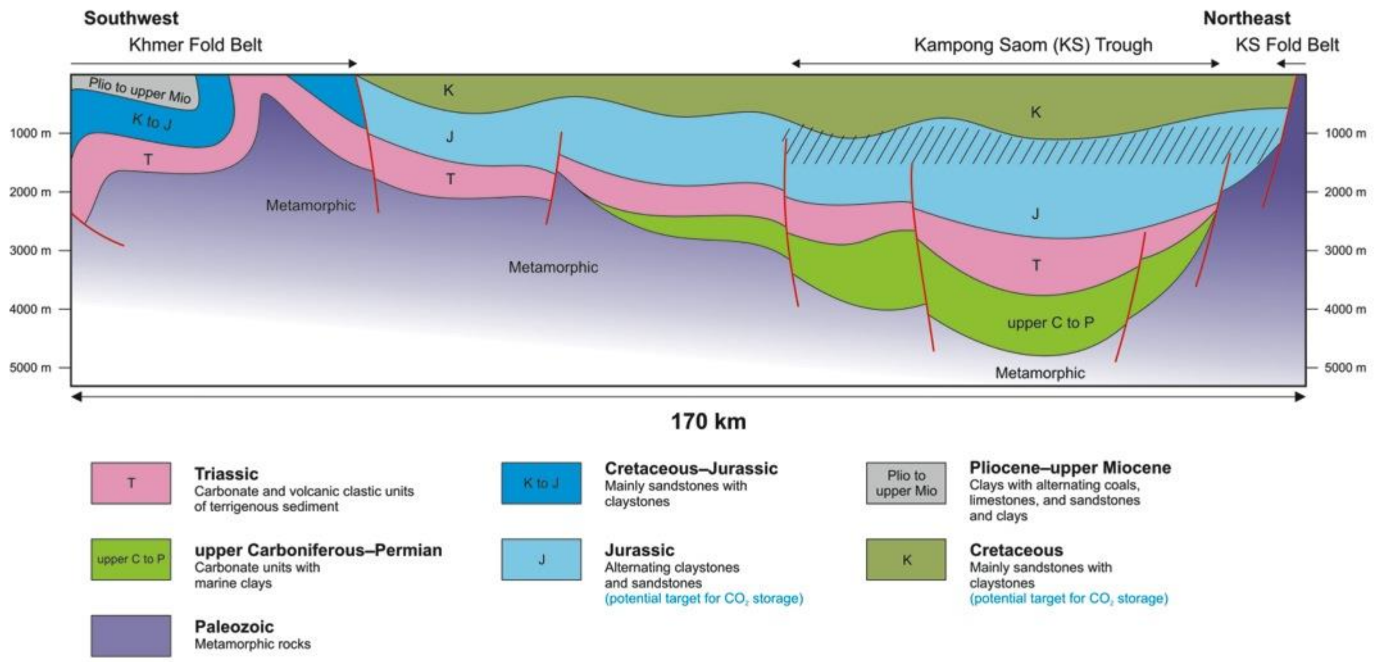

Fig. 5. Simplified geological cross-section of the Kampong Saom Basin (based on Vysotsky et al., 1994 and a CNPA internal technical report), showing potential formations for CO_2 storage located within the Kampong Saom Trough. Suitable formations are located within the uppermost Triassic–Middle Jurassic and Upper Jurassic successions. The hatched area indicates the primary injection target for CO_2 storage in aquifers.

5.2.2 CO_2 storage potential

The sedimentary succession within the Kampong Saom Trough ranges in age from late Paleozoic to Recent and is up to 5 km thick. A Carboniferous to Middle Triassic rift forms the basement of the basin, overlain by younger sedimentary cover that consists of Upper Triassic to Cretaceous Indosinian orogenic complexes. The basement successions are moderately faulted, but the overlying Upper Jurassic to Cretaceous successions have undergone minimal faulting (Vysotsky et al., 1994). Previous seismic activity is limited (Giardini et al., 1999) in both onshore and offshore areas, suggesting that the basin is relatively tectonically stable at present.

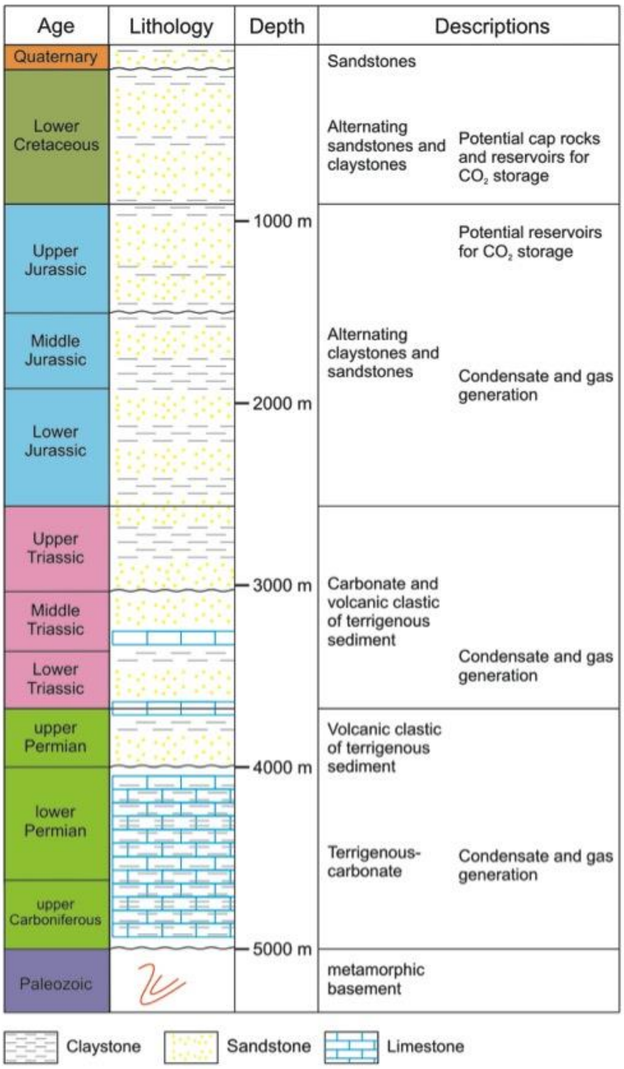

Fig. 6. Generalized stratigraphy of the Kampong Saom Trough (based on Vysotsky et al., 1994) showing CO_2 injection targets and potential cap rocks. The stratigraphic positions of suitable storage reservoirs and associated cap rocks are given in the descriptions within the figure.

This basin is interpreted to be immature but is currently undergoing hydrocarbon exploration. It is assumed that the majority of oil and gas reservoirs are trapped in structural closures formed within Upper Triassic to Middle Jurassic sandstones that are regionally intercalated with clay-rich lithologies, which act as seals for the hydrocarbon accumulations (Vysotsky et al., 1994). Resource estimates and the volumetric density of hydrocarbon within the basin (Vysotsky et al., 1994) indicate that the oil fields within the Kampong Saom Trough may be less economically significant than those within other basins, but these fields may be suitable for CO_2 storage after hydrocarbon depletion. Reservoir–seal pairs within the trough that may be suitable for CO_2 accumulation are plentiful within uppermost Triassic–Middle Jurassic and Upper Jurassic–lowermost Cretaceous successions (Fig. 5). In addition, the aquifer with the highest potential for CO_2 storage is most likely present within Upper Jurassic sediments (Figs. 5 and 6); this aquifer has an aggregate thickness of 450 m and a net sand thickness of about 20%.

The Upper Jurassic sediments in this trough are equivalent to, although named differently from, sediments along the southeast Thailand–western Cambodia border (Meesook, 2011; Meesook and Saengsrichan, 2011; Ridd et al., 2011; Ridd and Morley, 2011). This means that regionally, these aquifer intervals can be assumed to have an average porosity of ~10.8% (Canham et al., 1996; El Tabakh et al., 1999; Racey, 2011), indicating that they have fair CO_2 storage potential. The depth from the surface to the top of the reservoir varies from 900 to 1000 m, at which depths any stored CO_2 would be supercritical. Extrapolation of data from the Khmer and Tonle Sap basins suggests that the Kampong Saom Basin is a warm basin. The Kampong Saom Trough also contains Middle Jurassic and Cretaceous coals at depths of 250 and 2000 m (Vysotsky et al., 1994), although subjectively these coal layers should not be considered as potential sites for CO_2 storage.

5.3 Tonle Sap Basin

5.3.1 Geological setting and reservoir–seal systems

The foreland Tonle Sap Basin covers an onshore area of 23, 800 km^2 and, in central Cambodia, is bordered to the north by a regional orogenic uplift (Vysotsky et al., 1994) that is comparable to the transpression zone of the northwest–southeast-trending Mae Ping Fault Zone (Fig. 2; Fyhn et al., 2010), and farther to the north by the southernmost monocline of the Khorat Basin. The Tonle Sap Basin is bordered to the south by the onshore Kampong Saom Basin (Figs. 1 and 2). The basement of the Tonle Sap Basin is a complex Paleozoic graben that is dominated by metamorphic rocks. This graben may have developed between the late Carboniferous and the Middle Triassic, and is filled with sediments dominated by terrigenous sandstones and carbonates, with a total thickness of >1000 m. These horizons may have potential for both gas generation and hydrocarbon reservoirs. The overlying Upper Triassic to Middle Jurassic strata have an average thickness of 2000 m and have entered the oil window, indicating that these strata are a possible source rock for liquid hydrocarbons. Other suspected reservoirs and seals may also be present within Upper Jurassic–Lower Cretaceous intervals, which have a total thickness of ~2000 m; these intervals are collectively termed the Bokor Formation (Vysotsky et al., 1994; Fyhn et al., 2010).

5.3.2 CO_2 storage potential

The sedimentary fill within the central trough consists of more than 4 km of sediments that mirror the Kampong Saom sedimentary successions. The burial and hydrocarbon generation histories (Vysotsky et al., 1994) of the Tonle Sap and Kampong Saom basins are also similar. The syn-rift portion of the basin fill (i.e., upper Carboniferous to lower Permian and lower Permian to Middle Triassic sediments) within the Tonle Sap Trough has undergone intense and extensive faulting, leading to the development of many complex half-grabens. The intensity of faulting decreases within the post-rift Upper Triassic to Middle Jurassic sediments, and is least intensive in the overlying Upper Jurassic to Cretaceous sequences (Fig. 7). In addition, both left- and right-lateral faults (e.g., the Mae Ping Fault Zone) have been active during the Tertiary (Morley, 2002; Fyhn et al., 2010). However, the low magnitudes of more recent earthquakes suggest that this basin is tectonically stable (Giardini et al., 1999).

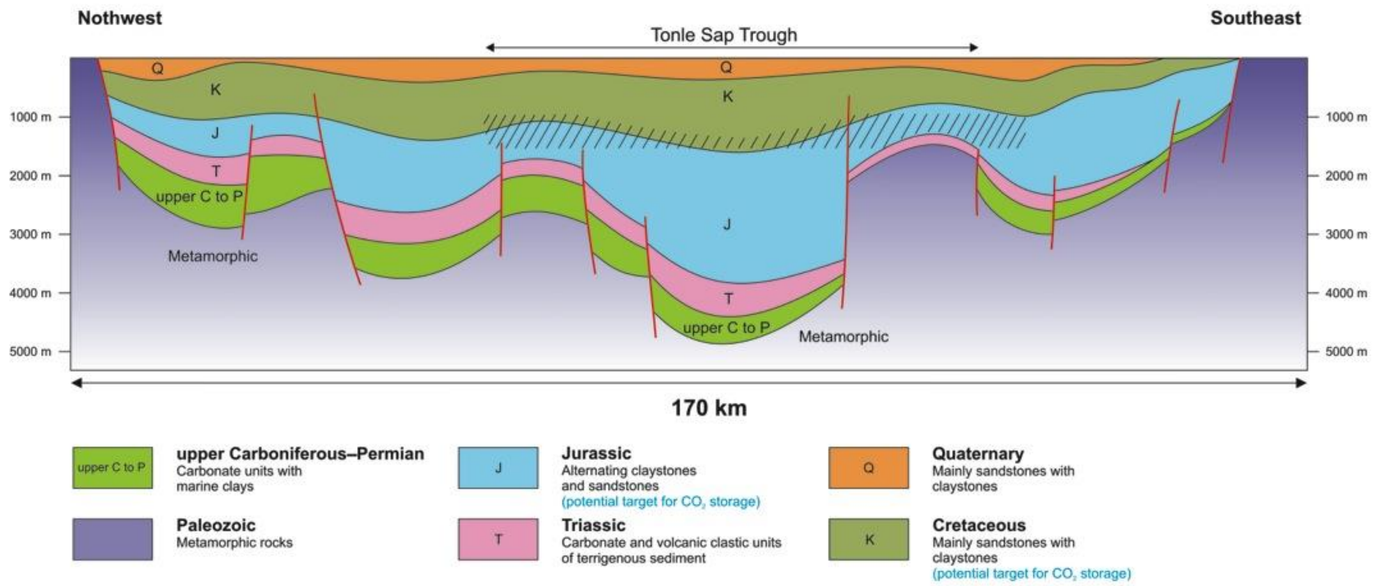

Fig. 7. Simplified geological cross-section of the Tonle Sap Basin (based on Vysotsky et al., 1994), showing potential targets for CO_2 storage within the Tonle Sap Trough. Suitable formations are located within the Jurassic and lowermost Cretaceous successions. The hatched area indicates the primary injection target for CO_2 storage in aquifers.

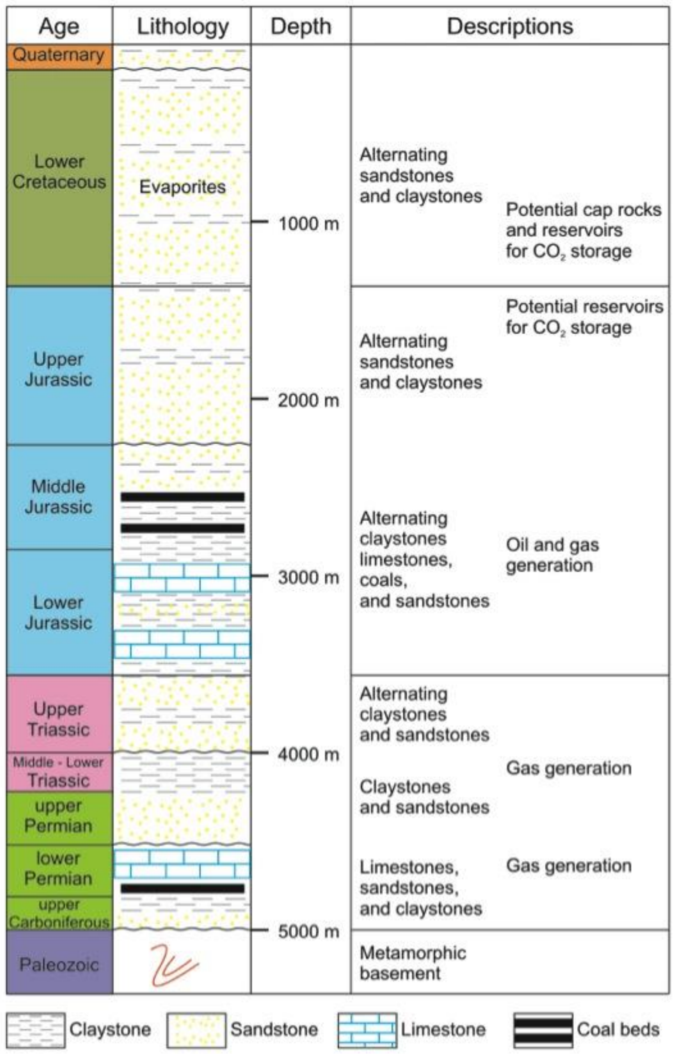

Fig. 8. Generalized stratigraphy of the Tonle Sap Trough (based on Vysotsky et al., 1994) showing CO_2 injection targets and associated cap rocks. The stratigraphic positions of suitable storage reservoirs and their associated cap rocks are given in the descriptions within the figure.

The Tonle Sap basin has also been subjected to hydrocarbon exploration, with oil and gas reservoirs being identified in Jurassic sedimentary sequences that have postdepletion CO_2 storage potential. The basin also contains deep saline aquifers within uppermost Jurassic–lowermost Cretaceous sediments that contain numerous volcanogenic clastic sediments; these are good-quality reservoir formations, and have an aggregate thickness of 500 m. The reservoir intervals have an average porosity of 10% (locally >20%) and an assumed net value of 20%, indicating good CO_2 storage potential. These reservoirs are sealed by Lower Cretaceous evaporites and claystones, both of which would make good cap rocks for CO_2 storage (Figs. 7 and 8). The geothermal gradient of the basin is 35°C/km (Vysotsky et al., 1994), meaning that this is a cold basin in terms of the geothermal effects on CO_2 storage (Bachu, 2003). The Tonle Sap Trough also contains Carboniferous–Permian and Upper Triassic–Middle Jurassic coals, with the Middle Jurassic coals being predominantly bituminous, although none of these beds has CO_2 storage potential.

5.4 Khorat Basin

5.4.1 Geological setting and reservoir–seal systems

The southern monocline of the Thai Khorat Basin flanks the northern part of Cambodia and covers an area of 12,400 km^2 (Figs. 1 and 2). This foreland basin is thought to be associated with regional uplift comparable to the Mae Ping transpression zone (Fyhn et al., 2010). The uppermost part of the basin in Thailand consists of Upper Jurassic–Lower Cretaceous and Upper Cretaceous–lower Paleogene sediments (Racey et al., 1996; El Tabakh et al., 1999), dominated by sandstones of variable oil and gas reservoir quality and by nonreservoir mudstones and siltstones (Canham et al., 1996). In comparison, the majority of the upper Mesozoic section of the basin in Cambodia has been eroded as a result of minor basin inversion associated with the earliest stages of the Himalayan Orogeny (Racey et al., 1996), leaving scattered outcrops of Upper Jurassic–Lower Cretaceous sediments, in addition to older sediments that are considered to have formed during the Late Triassic–Middle Jurassic and Permian (Vysotsky et al., 1994). Sediment thickness modeling by Heine (2007) suggests that the depth to the base of the basin varies from 36 m at the southern margin to 500 m in northern Cambodia. The lower section of the basin, which contains Upper Triassic–Middle Jurassic and Permian sediments, may be prospective for gas accumulations, especially within Permian limestones (Vysotsky et al., 1994; Canham et al., 1996; Racey et al., 1996; El Tabakh et al., 1999).

5.4.2 CO_2 storage potential

The Khorat Basin in Cambodia extends from the northern Cambodia–Thailand border to the area north of the Tonle Sap Basin. This area is thought to be generally tectonically stable judging from recent seismicity (Morley, 2002) and from the current tectonic setting of the region (Giardini et al., 1999). Upper Triassic–Upper Jurassic sandstones and associated aquifers within the basin have a gross thickness of 300 m, and reservoir intervals within these units have an average porosity of 15% (Canham et al., 1996; El Tabakh et al., 1999). Very little is known about the productivity of Permian limestone gas reservoirs within this basin, although it is possible that these reservoirs may be suitable for storing CO_2 gas. However, the graben shallows significantly towards the southern margin of the basin, meaning that both Permian limestone and Upper Triassic–Upper Jurassic reservoirs occur at depths of <500 m, meaning that any CO_2 stored in these reservoirs may not be supercritical; thus, this setting provides limited opportunities for CO_2 storage.

5.5 Preah Basin

The Preah Basin is interpreted to be a Mesozoic foreland basin and covers an onshore area of 11,400 km^2 within an east–west-trending trough (Figs. 1 and 2). This basin consists of a Lower to Middle Triassic orogenic complex basement overlain by an Upper Triassic–Middle Jurassic sedimentary fill that may have entered the main stage of oil generation (Vysotsky et al., 1994). Sediment thickness modeling by Heine (2007) suggests that the depth to basement is ~317 m, meaning that this basin provides limited opportunities for CO_2 storage within hydrocarbon reservoirs, because such reservoirs would be too shallow.

5.6 Chhung Basin

The Chhung Basin is a foreland basin confined to a north–south-trending graben developed during the Indosinian Orogeny, and covers an onshore area of 2600 km^2 (Figs. 1 and 2). The basin is filled by Mesozoic (and possibly Cenozoic) sediments (Vysotsky et al., 1994). Sediment thickness modeling by Heine (2007) suggests that the depth to basement varies from 275 to 452 m; these shallow depths indicate that this basin provides limited opportunities for CO_2 storage.

5.7 Svaryrieng Basin

The Svaryrieng Basin, a foreland basin located in southeast Cambodia (Fig. 1), is filled by Mesozoic sediments and covers an onshore area of 6700 km^2 (Vysotsky et al., 1994). Sediment thickness modeling by Heine (2007) suggests that the depth to basement within the basin varies from 195 to 800 m, although Mesozoic reservoirs may not occur at sufficient depths to ensure the supercritical storage of CO_2, meaning that this basin provides limited opportunities for CO_2 storage.

6. Basin ranking

The criteria presented in Table 2 were classified in terms of containment, capacity, and feasibility; each of these key features was discussed in Section 5 for each of the basins outlined here, with screening results summarized in Table 3. It is important to note that the parameterization (F_i) described within equation (1) is a subjective method of transforming basin characteristics (in Table 3) into numerical values. The range of numerical values (function F_i) for the classes in a given criterion has an exponential form because subjectively these classes differ in importance. Importantly, the weighting of each criterion has been adjusted to reflect the immature oil-producing nature of Cambodia.

The original use of this approach is outlined by Bachu (2003), who focused on the mature oil-and gas-producing country of Canada, where the majority of basins have undergone technologically advanced exploration and are undergoing economical extraction using advanced hydrocarbon production infrastructure, although while also containing less important and underexplored basins that have both significant or no oil and gas potential. In addition, CO_2 sources in Canada are well known and well characterized. This means that the Canadian assessment weighted basin resource criteria, such as hydrocarbon potential, coal beds, and aquifers, lower than it weighted industry maturity, infrastructure, and CO_2 source criteria, all of which were weighted highly during the ranking process outlined in Bachu (2003). In addition, the Canadian climate (ranging from temperate to arctic) and the location of individual basins were also weighted highly, as Canada is a continental-size country that consists of both mainland and numerous islands that are isolated by sea. These differing weightings indicate the differing factors and difficulties involved in CCS implementation in offshore and continental settings.

In comparison, the on- and offshore hydrocarbon potential and exploration information compiled by Vysotsky et al. (1994) and by the CNPA provide primary data that can be used to evaluate the CO_2 storage suitability of Mesozoic and Cenozoic sedimentary basins in Cambodia. The approach used in the present study weighted basin resources (i.e., hydrocarbon potential, aquifers, and coal beds) and storage capacity (i.e., basin size and geothermal regime) criteria highly, with the weightings for each criterion being reassigned appropriately. In addition, containment factors, namely location and tectonic regime, faulting intensity within reservoirs, and depth of the basin, are also important criteria that help determine whether CO_2 can be safely stored (i.e., under supercritical conditions). Furthermore, the fact that the oil and gas industry in Cambodia is somewhat immature and is still focused on exploration means that technological and feasibility criteria are less important in this case.

The parameterization and normalization procedure of Equation (1) was used to produce a normalized score for each criterion outlined above (reported in Table 3), and Equation (2) was used to sum the normalized scores using the associated weightings to calculate the final ranking of sedimentary basins in Cambodia. In addition, to further understand the suitability of individual basins, normalized totals were allocated to containment (30%), storage capacity (40%), and feasibility suitability (30%) groups, with these percentage values being determined by summing the weighted values of the criteria within each group. The total scores (suitability) were classified into three categories according to CO_2 storage suitability (Table 4): very good (0.73), good (0.66–0.60), and poor (0.29–0.18).

The Khmer Basin is an excellent candidate for CO_2 storage, because it is tectonically stable and has a small amount of faulting within reservoir formations. This basin has a large and mature hydrocarbon field and extensive infrastructure, meaning that the basin has high scores for both capacity and feasibility. The offshore Kampong Saom Basin is also an excellent candidate for CO_2 storage, although this basin has a reduced storage capacity and feasibility, primarily because it contains only a medium-ranked hydrocarbon resource, has a lack of infrastructure, and is an immature oil field. The Tonle Sap Basin shows the best potential for onshore CO_2 storage of all of the onshore basins studied here. This basin has a moderately faulted reservoir formation but is relatively well sealed and stable, meaning that containment within the basin is suited to CO_2 storage. Although the Tonle Sap Basin has only a small hydrocarbon resource, it has a high capacity for CO_2 storage, primarily because the basin is cold and has a low geothermal gradient. However, a lack of infrastructure and CO_2 point sources significantly downgrade the suitability and feasibility of this basin for CO_2 storage. The remaining basins, such as the Khorat, Chhung, Preah, and Svaryrieng basins, have no potential for CO_2 storage as they are small and unexplored, have limited potential reservoir–seal systems, and are generally too shallow to ensure safe CO_2 accumulation. In summary, the most suitable basin for geological CO_2 storage is the Khmer Basin, followed by the offshore Kampong Saom and onshore Tonle Sap basins, with other basins being generally unsuitable for CO_2 storage (Table 4; Fig. 9).

Table 4
Ranking of Cambodian basins in terms of containment, capacity, and feasibility for CO_2 geological storage (see Fig. 9 for the geographic distribution of the suitable basins).

Basins	**Containment (30%)**	**Capacity (40%)**	**Feasibility (30%)**	**Suitability (100%)**	**Rank**
Khmer	1.00	0.58	0.68	0.73 (very good)	1
(Offshore) Kampong Saom	1.00	0.51	0.53	0.66 (good)	2
Tonle Sap	0.76	0.69	0.37	0.61 (good)	3
Preah	0.27	0.27	0.34	0.29 (poor)	4
Khorat	0.27	0.05	0.34	0.20 (poor)	5
Svaryrieng	0.27	0.05	0.34	0.20 (poor)	5
Chhung	0.27	0.00	0.34	0.18 (poor)	7

7. CO_2 storage capacity

After basin screening and ranking, a basin-wide assessment of the available pore volume within existing hydrocarbon reserves and aquifers of suitable basins (namely the Khmer, offshore Kampong Saom, and Tonle Sap basins) was undertaken to determine their possible CO_2 storage capacity. The main sources of information for hydrocarbon reservoirs within these basins were Vysotsky et al. (1994) and exploration reports provided by the CNPA. The hydrocarbon reserve and aquifer volumes were converted to the volume of CO_2 that a basin is capable of storing. Table 5 presents the results of CO_2 storage capacity calculations for both hydrocarbon reservoirs and aquifers in Cambodian basins.

7.1 Oil reservoirs

A preliminary evaluation (Vysotsky et al., 1994) estimated that the total hydrocarbon resource within Cambodia is around one billion tons of oil equivalent, yielding a volume of 1.165 billion m^3, with recoverable hydrocarbons estimated to total 0.6–0.8 billion tons of oil equivalent. The average original volumetric density of hydrocarbons within both offshore and onshore areas can be combined with the thickness and surface area of sedimentary basins (Vysotsky et al., 1994) to yield an estimate of hydrocarbon reserves, with the onshore Tonle Sap Basin containing 35% of the total hydrocarbon reserves, the offshore Kampong Saom Basin containing 20%, and the offshore Khmer Basin 45%. Using Equation (3), the assumed CO_2 storage efficiency of 7% (representing the fraction of OOIP accessible to CO_2; Holt et al., 1995) yields an estimated storage capacity for the Khmer Basin oil fields of 2 Mt CO_2. In comparison, the offshore Kampong Saom Basin has an estimated storage capacity of 1 Mt CO_2, and the Tonle Sap Basin has 2 Mt CO_2. This indicates that existing oil reserves in Cambodia have the potential to store ~5 Mt mass equivalent of CO_2 (Table 5).

7.2 Aquifers

The assessment of aquifer reservoirs also incorporates safety (E_s) and storage efficiency (E_e) factors as in Equation (4). Here, it was assumed that aquifers provide clastic reservoirs and transmit CO_2-bearing waters by acting as heterogeneous porous media. Previous research (e.g., Koide et al., 1992; Van Der Meer et al., 1992, 1993; Bachu et al., 1994; Hendriks et al., 2004; Haszeldine, 2006; Höller and Viebahn, 2011; US DOE-NETL, 2012) indicates that storage efficiency factors for aquifers are ~2% (E_e). This E_e value was used in the present assessment because a more detailed analysis could not be undertaken given the current state of knowledge of the basins concerned. The safety factor, E_s, was derived from a minimum economic requirement, assuming that only 1% of the aquifer volume will be used (based on Koide et al., 1992; Bachu et al., 1994; Hendriks et al., 2004; Haszeldine, 2006; Höller and Viebahn, 2011). This allows the volume of offshore aquifers within the Khmer Basin to be calculated as equivalent to a CO_2 storage capacity of 22 Mt, with the offshore Kampong Saom Basin having a storage capacity of around 33 Mt CO_2, and an additional 30 Mt of CO_2 storage potentially available within the onshore Tonle Sap Basin. In total, the CO_2 storage capacity of aquifers in Cambodia is ~85 Mt (Table 5).

Table 5
Theoretical CO_2 storage capacity (Mt CO_2) using low-case storage efficiency in both hydrocarbon reservoirs and aquifers (structural traps) in the Cambodian subsurface.

Storage options / **Basins**	**Khmer Basin**	**Kampong Saom Basin**	**Tonle Sap Basin**
Hydrocarbon reservoirs	2	1	2
Aquifers	22	33	30
Total storage capacity	90		

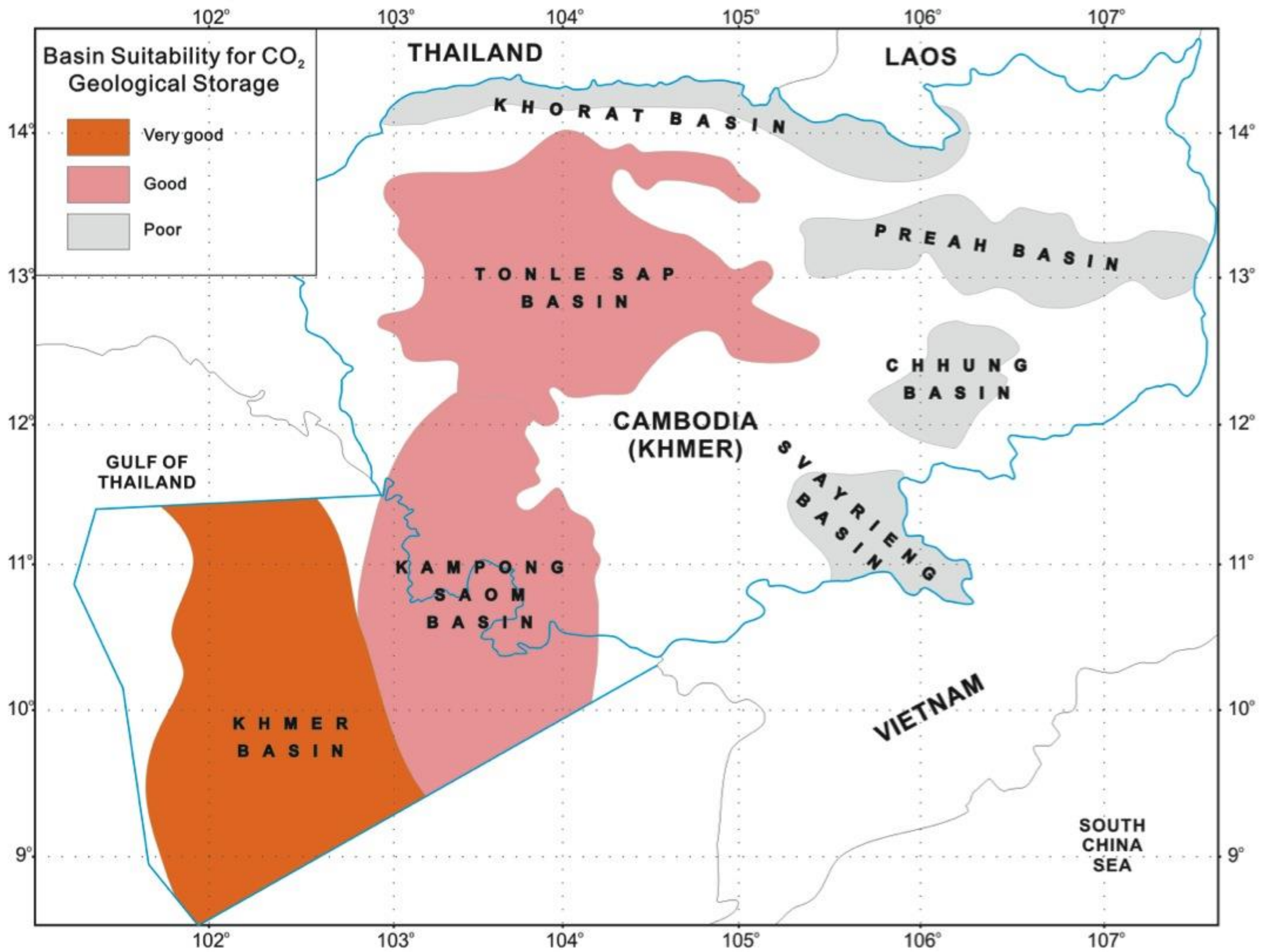

Fig. 9. Map showing the location of Cambodian basins and their suitability for CO_2 storage. See also Tables 4 and 5 for rankings of basin suitability and estimates of storage capacity, respectively.

8. Discussion

The primary objective of this study was to modify the basin screening and ranking (Bachu 2003) and basin-wide CO_2 storage estimation methods used in previous studies (Bachu et al., 1994; Hendriks et al., 2004; Bachu et al., 2007; CSLF, 2008; US DOE-NETL, 2012) to make them more suitable for application to Cambodia as an immature oil-producing country. The adjustments outlined above enabled Mesozoic and Cenozoic basins to be screened and ranked based on their suitability for geological CO_2 storage (Table 4; Fig. 9). This was followed by a preliminary estimation of the CO_2 storage capacity of each of the suitable basins identified during this study (Table 5). The second objective was to estimate CO_2 emissions from the major point sources that were described in Section 2 (about 43.1 Mt per year and 82 Gm^3 in place; Fig. 1), and place them to become nationally-perspective matched storage capacity. By definition, the matched storage capacity is the capacity that is obtained by matching the high-output stationary CO_2 sources with storage capacity of suitable geological storage basins (based on Bachu et al., 2007). Emissions data show that CO_2 will be emitted largely from future natural gas reservoirs located in the offshore Khmer Basin. As these reservoirs have potential to store commercial quantities of natural gas, the amount of recovered CO_2

(82 billion m^3 in place) will be able to be captured and safely disposed of by injection back into reservoir formations (Bachu, 2003; Gibson-Poole et al., 2008). Moreover, these reservoirs could offer CO_2 storage additional to this total after depletion, by assuming that the low hydrodynamic pressure occupying the pore space could be efficiently displaced with injected CO_2 (Bachu and Shaw, 2003, 2005; US DOE-NETL, 2012). This result indicates that after depletion, these commercial gas reservoirs (offshore Khmer Basin) may have the potential to store a significant amount of the CO_2 emissions generated by future major point sources including power plants and natural gas extraction.

The screening and ranking exercise indicates that the offshore Khmer Basin is the most suitable basin for CO_2 geological storage, followed by the Kampong Saom and Tonle Sap basins, with the Khorat, Preah, Chhung, and Svaryrieng basins being judged as entirely unsuitable for geological CO_2 storage (Table 4; Fig. 9). The Tonle Sap Basin is the best onshore setting for the implementation of CCS, and the implementation of oil and gas production in onshore Cambodia would also upgrade the capacity and suitability of onshore basins. This means that the Tonle Sap Basin may become the best option for CO_2 storage in Cambodia, before the Khmer and Kampong Saom basins can be utilized.

The subsurface geology of Cambodia is currently tectonically stable, and geological cross-sections (Figs 3, 5, and 7) indicate that although the basement of the majority of basins is relatively intensely faulted, only moderate or low amounts of faulting are present within shallower geological successions, such as the Upper Triassic–Cretaceous successions of the Mesozoic Kampong Saom and Tonle Sap basins, and the Miocene succession of the Cenozoic Khmer Basin, all of which have large pore volumes and could potentially be used for both aquifer and hydrocarbon reservoir CO_2 storage. Given the importance of these basins, regional extrapolation and estimation of basin-wide storage capacity was undertaken for these successions. The derived storage capacities are given in Table 5. It should be noted that this initial assessment of storage capacity does not use reservoir models and simulation studies to estimate the storage efficiencies of CO_2 in the pore spaces. Rather, the values for storage efficiency used in this study were taken from previous research, as discussed below.

In the case of aquifers, a generalized value of E_e of 2% was adopted in this study, a value that reflects reservoir variables and displacement efficiency factors derived from numerous reservoir simulations undertaken in previous studies. Considering only E_e (in Equation 4; for hydrodynamic traps), this value of 2% would dramatically increase estimates of storage capacity (as given in Table 5) from 22 Mt to 2 Gt for the Khmer Basin, from 33 Mt to 3 Gt for the Kampong Saom Basin, and from 30 Mt to 3 Gt for the Tonle Sap Basin. However, for safety reasons (E_s), values of only 1% of these capacities were included in the calculation because of the requirement that the CO_2 should be safely contained only within structural traps, and therefore the values of total storage capacity are low-case estimates. However, high-case estimates can be obtained in parallel with basin-wide estimates (IEA, 2009; US DOE-NETL, 2012). Although value of E_e could be increased from the 2% value, it is limited to ~6% for clastic reservoirs (IEA, 2009), a value that is applicable to the Kampong Saom and Tonle Sap basins. In this high-case estimate, the value of E_e of 6%

was used in the estimation of the storage capacity of hydrodynamic trap associated with structural traps, meaning that the CO_2 is safely stored in the basins in a state of hydrodynamic equilibrium (IEA, 2009; US DOE-NETL, 2012). In the case of the Khmer Basin, the values of net area, net thickness, and net porosity are directly known from CNPA exploration reports, and thus specific E_e values for displacement efficiency ranging from 7.4% to 24% (where 24% is used for high-case estimate) are suitable for the Khmer Basin (US DOE-NETL, 2012). Therefore, estimates for the CO_2 storage capacity of aquifers range from 22 Mt to 26 Gt in the Khmer Basin, from 33 Mt to 10 Gt in the Kampong Saom Basin, and from 30 Mt to 9 Gt in the Tonle Sap Basin.

In the case of oil reservoirs, the intensity of faulting is moderate in reservoir formations (Vysotsky et al., 1994), and production tests from offshore oil and gas fields (data obtained from CNPA) show that these reservoirs may have no supported aquifer either during or after depletion. Thus, the CO_2 storage volume is limited to being a function of the volume of recoverable oil, the volume factor of the formation, and the volume of irreducible fluids resulting from the initial reservoir conditions (IEA, 2009). Therefore, the mass-balance equation for oil reservoirs proposed by Bachu et al. (2007), Equation (1), is appropriate for this situation (IEA, 2009). Considering only these reservoir characteristics, the translation of recoverable oil to CO_2 mass would become 100%, and on this basis the estimates for CO_2 storage capacity in oil reservoirs are calculated to be 21 Mt in the Khmer Basin, 9 Mt in the Kampong Saom Basin, and 17 Mt in the Tonle Sap Basin. The storage efficiency factor reflects the displacement efficiency and the characteristics of the oil reservoir (i.e., CO_2 mobility and buoyancy, and reservoir heterogeneity) under consideration. However, the estimation of the storage efficiency of oil reservoirs is very complicated and beyond the scope of the present investigation. Bachu and Shaw (2003) assume an effective storage coefficient (*Ce*) of 0.5 for favorable conditions of mobility, buoyancy, heterogeneity, and water saturation. Using this storage efficiency factor (*Ce* = 0.5) increases the total storage capacities given in Table 5, which range from 2 to 15 Mt for the Khmer Basin, 1 to 7 Mt for the Kampong Saom Basin, and 2 to 12 Mt for the Tonle Sap Basin. Bachu and Shaw (2003) further suggest that the storage efficiency factor can be estimated based on experience of CO_2–EOR, and has an estimated range of 7%–21% (representing the fraction of OOIP accessible to CO_2; Holt et al., 1995). Prior to flooding with CO_2, water is introduced to the oil reservoir to keep the pressure stable during primary recovery (Bachu et al., 2007), which means that a depleted reservoir can behave in a similar fashion to an aquifer reservoir (IEA, 2009). Therefore, the value of storage efficiency of the oil reservoir will approach that of an aquifer in such a situation. Considering only displacement efficiency factors, because the producing oil volume is known, a value range of 7.4%–24% is considered (US DOE-NETL, 2012). Therefore, it can be concluded that a value range for C_e of 7%–20% is appropriate to use for the case of Cambodia as a country inexperienced in EOR. Therefore, estimates for the CO_2 storage capacity of oil reservoirs range from 2 to 6 Mt in the Khmer Basin, from 1 to 3 Mt in the Kampong Saom Basin, and from 2 to 5 Mt in the Tonle Sap Basin.

Overall, the above analysis indicates that Cambodia as a whole has a best-case preliminary estimate of ~45 Gt of CO_2 that could be stored, most of which would be in aquifers as hydrodynamic traps.

9. Conclusion

This study provides the first assessment of the prospective matched CO_2 storage capacity of the main sedimentary basins of Cambodia. It identifies the offshore Khmer Basin as the most promising option for CO_2 storage, followed in suitability by the offshore Kampong Saom Basin and the onshore Tonle Sap Basin. The suitability of the containment and capacity of these basins suggests that the safe storage of CO_2 in aquifers should be possible, although the estimated storage capacity should be considered a preliminary value as only limited geological data are currently available. The initial assessments of storage suitability and capacity provided here (Tables 4 and 5; Fig. 9), combined with a high-case estimate, should help both exploration geologists and CCS experts to understand the suitability (in terms of containment, storage capacity, and feasibility) of each of the basins discussed here for CO_2 storage. To conclude, this study identifies the Khmer, Kampong Saom, and Tonle Sap basins as having suitable CO_2 storage characteristics and these basins could provide a solution to the problem of reducing the future atmospheric emissions of point-sourced anthropogenic greenhouse gases.

These results are preliminary and reflect the scarcity of available hydrocarbon exploration information, and therefore the results may change with data and information gained from future exploration. The expansion of oil and gas exploration and development within the Khmer and Tonle Sap basins indicates that higher-quality geophysical and geological data should be available in the near future. Such data could be used for more detailed evaluations of reservoirs (from basin- to site-scale assessments) and for improved estimates of storage capacity, thereby improving the reliability of the initial results reported here.

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