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Petrography, Geochemistry and U-Pb Detrital Zircon Dating of the Clastic Phu Khat Formation in the Nakhon Thai Region, Thailand: Implications for Provenance and Geotectonic Setting

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ABSTRACT: The purpose of this paper is to determine the provenance and tectonic setting of the Phu Khat Formation and get a better understanding of the tectonic evolution of the Nakhon Thai region using the petrography and whole-rock geochemistry integrated with the U-Pb detrital zircon dating. The sandstone of the Late Cretaceous to Early Tertiary Phu Khat Formation is chiefly characterized by unsorted texture and highly unstable volcanic lithic fragments. The formation overlies unconformably on a high textural and mineral maturity of clastic sandstone of the Late Cretaceous Khao Ya Puk Formation. Geochemically, the tectonic setting discrimination (K_2O/Na_2O-SiO_2, Al_2O_3/SiO_2-Fe_2O_3+MgO, and Th-Sc-Zr/10) and the petrography indicate that the Phu Khat Formation was accumulated in a passive margin tectonic setting which is the same as the Khao Ya Puk Formation but with a different depositional environment. The plots of geochemical provenance discrimination (La/Th-Hf, Th/Sc-Zr/Sc, Eu anomaly Eu/Eu* 0.42 to 0.74) and the petrography reveal that the provenance of the Khao Ya Puk Formation is mainly recycled sedimentary rocks while the Phu Khat Formation consists primarily of recycled sedimentary rocks associated with minor felsic volcanic rocks from the old continental island arc of the uplifted either western or eastern continental terranes or both. However, the U-Pb detrital zircon dating indicates a unique provenance of the Phu Khat Formation from the terrane west of the Nakhon Thai region where the volcanic continental arc is active predominantly in the Middle to Late Triassic. The results indicate that while the Phu Khat Formation was accumulated in Nakhon Thai region, the western terrane was uplifted by reactivation of the pre-existing structure probably since the Maastrichtian time to be the source area of sediments. Meanwhile, the eastern terrane (mainly Loei-Phetchabun fold belt) had not been uplifted probably until, the accumulation of the Phu Khat Formation terminated. Subsequently, the whole region began to uplift forming a high mountainous area since the Ypresian time when the Greater India collided with the Eurasia.

KEY WORDS: Phu Khat Formation, provenance, U-Pb detrital zircon dating, geochemistry, petrography.

0 INTRODUCTION

The modal petrography has long been utilized in clastic sandstones to determine their provenance and sediment recycling (e.g., Dickinson, 1985; Dickinson and Suczek, 1979). Moreover, the use of this method in conjunction with the whole-rock geochemistry has been proved to be a powerful tool to evaluate tectonic setting of the deposit (e.g., Hara et al., 2012; Yang et al., 2012). However, the petrographic and whole-rock geochemistry study may lack unique signature of a specific location or terrane when the source areas of the clastic sandstone lie within an area of broadly uniform geology (Carter and Bristow, 2003). To overcome this problem the detrital zircon age dating of representative samples is required in order to constrain the location of the source areas by identifying the main crust-forming events (Carter and Bristow, 2003). Moreover, this method has also shown that the tectonic evolution and/or genesis of the rock between two formations can be revealed (Lee et al., 2012).

The clastic Phu Khat Formation in the Nakhon Thai

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region is the topmost unit of the red bed sandstone sequences (mainly Khorat Group and overlying salt formation) in the Indochina Block (Heggemann, 1994; Heggemann et al., 1994). It was interpreted to have been derived from both western and eastern thrust fault blocks as the result of the Himalayan orogeny in the Latest Cretaceous–Early Tertiary with an ambiguous contact with the underlying rocks (Heggemann, 1994). However, the interpretations of the previous study (e.g., Assavapatchara and Raksasakulwong, 2010; Meesook et al., 2002; Heggemann et al., 1994; Kosuwan, 1990) are principally based on surface mapping without detailed study of their provenance and tectonic setting. The purpose of this paper is, therefore, to determine the provenance and tectonic setting of the Phu Khat Formation using the petrographic and whole-rock geochemistry study integrated with the U-Pb detrital zircon dating. The results of this study will provide a better understanding of the tectonic evolution of the Nakhon Thai region and will subsequently constrain the genesis and depositional age of the Phu Khat Formation.

1 GEOLOGICAL SETTINGS

It is widely accepted that Thailand is divided into four tectonic zones, i.e., the Sibumasu Block, the Inthanon zone, the Sukhothai zone and the Indochina Block, respectively, from west to east (Fig. 1a). The Indochina Block and the Sibumasu Block are two main continental blocks that were originally derived from the Gondwana in the Devonian and the Permian, respectively (Metcalfe, 2013, 2011; Sone and Metcalfe, 2008; Ueno and Hisada, 2001). After a long time of northward drifting, the Sibumasu Block collided and amalgamated with the Indochina Block in the southern Eurasia margin by closing of the Paleo-Tethys in western Thailand during the Triassic (Sone and Metcalfe, 2008; Feng et al, 2005; Chonglakmani, 2002; Ueno and Hisada, 2001). The Inthanon and the Sukhothai zones were interpreted as an accretionary complex resulted from closure of the Paleo-Tethys and a remnant of Permo–Triassic island arc induced by subduction of the Paleo-Tethys, respectively (Sone and Metcalfe, 2008).

The Nan-Uttaradit suture zone has been interpreted as a remnant of a closed back arc basin (Nan Back Arc Basin) (Sone and Metcalfe, 2008; Ueno and Hisada, 2001) or small ocean (Yang et al., 2008), divided between the Sukhothai zone and the Indochina Block. It is a narrow ophiolite zone which comprises the Carboniferous to Permian Pha Som metamorphic complex and the Permo–Triassic Pak Pat volcanic rocks (Singharajwarapan and Berry, 2000; Barr and MacDonald, 1987). The Nan Back Arc Basin may close and amalgamate with the Indochina Block in the Permian–Triassic (Sone and Metcalfe, 2008; Chonglakmani, 2002). The Loei-Phetchabun fold belt is formed as a high mountain range in western part of the Indochina Block. It comprises the succession of Paleozoic to Early Mesozoic sedimentary rocks and the igneous rocks of a long age range from the Silurian to the Tertiary (Kamvong et al., 2014; Salam et al., 2014; Zaw et al., 2014; Ueno and Charoentitirat, 2011; Khositanont, 2008; Intasopa, 1993).

The Nakhon Thai region is located between two tectonic terranes, the composite Nan-Uttaradit suture zone and Sukhothai zone to the west and the Loei-Phetchabun fold belt and Indochina Block to the east (Fig. 1a). Geographically the Nakhon Thai region is dominated by a series of parallel mountain chain which comprises the sequences of Late Jurassic to Cretaceous non-marine red beds of mainly the Khorat Group and younger units (Racey, 2009; Racey et al., 1996). These strata form a broad NE-SW trending synclinorium situated on western part of the Indochina Block. The Khorat Group and younger units (the Maha Sarakham and the Khao Ya Puk or the Phu Tok formations) are believed to extend westward and northward to the Nakhon Thai region of the North-Central Thailand and the Sayabouri Basin of Laos, respectively (Morley, 2012; Booth and Sattayarak, 2011; Chonglakmani et al., 2010; Heggermann et al., 1994). The Nakhon Thai Basin was formed subsequently by the uplifted Nan-Uttaradit suture zone to the west and the Loei-Phetchabun fold belt to the east during the Tertiary Himalayan orogeny (Booth and Sattayarak, 2011; Racey et al., 1997).

As shown in the geologic map (Fig. 1b) of the Department of Mineral Resource (1999) the red beds of the Khorat Group are well represented in both the Nakhon Thai region and the Khorat Plateau. The Khorat Group in the Khorat Plateau is overlain unconformably by the succession of Mid-Cretaceous rock salt of the Maha Sarakham Formation and the aeolian sandstone of the Late Cretaceous Phu Tok Formation (Fig. 2a) (Racey, 2009; Lovatt Smith et al., 1996; Sattayarak and Polachan, 1990). However in the Nakhon Thai region, the Khao Ya Puk Formation is proposed for the aeolian sandstone unit, although it is lithostratigraphically identical with the Phu Tok Formation (Sha et al., 2012; Meesook, 2011). So, the uppermost formations in the Nakhon Thai region are composed of the Khao Ya Puk and the overlying Phu Khat formations while on the Khorat Plateau only the Phu Tok Formation has been reported (Meesook et al., 2002).

2 STRATIGRAPHY AND SAMPLING

The clastic rocks of the Phu Khat Formation in this study are situated in the Nakhon Thai region, North-Central Thailand (Fig. 1b). The rocks are composed entirely of non-marine clastic rock which is interpreted to have been deposited in an alluvial fan by the braided stream (Fig. 2b) (Nulay et al., 2014; Meesook et al., 2002; Heggamann, 1994). They overlie unconformably on the aeolian sandstone of the Khao Ya Puk Formation. The present study of these two formations is carried out in order to explain their genesis. The study profile of the upper Khao Ya Puk Formation and the whole sequence of the Phu Khat Formation are shown in Fig. 2b.

The Khao Ya Puk Formation belongs to the Upper Cretaceous succession which is stratigraphically correlated with the Phu Tok Formation in the Khorat Plateau (Meesook et al., 2002; Lovatt Smith et al., 1996). It is composed of three main parts (Fig. 2b). The lower part is characterized by the fine-gained sediment which comprises reddish brown siltstone and mudstone with even parallel lamination. Gypsum dissemination is frequently observed at bottom of the lower part. The middle part comprises cross-bedded sandstone showing channel structure. Desiccation cracks are observed in the interbedded shale. They are very large about 10–20 cm wide and

30–40 cm deep. Generally, these cracks were filled with reddish brown medium- to coarse-grained sandstone. These features may suggest that they were formed by the ephemeral fluvial stream in semi-arid to arid paleoclimate. The upper part comprises chiefly resistant thick-bedded sandstone which is usually exposed as the steep escarpment. It is characterized by very thick cross-bedded sets with high angle foresets (29º to 33º) and is very well sorted grains. The thin-bedded sandstone usually shows coarsening upward sequence. All of these features suggest that the upper part of the Khao Ya Puk Formation may be formed by wind in a desert paleoclimate (Meesook, 2011; Hasegawa et al., 2010).

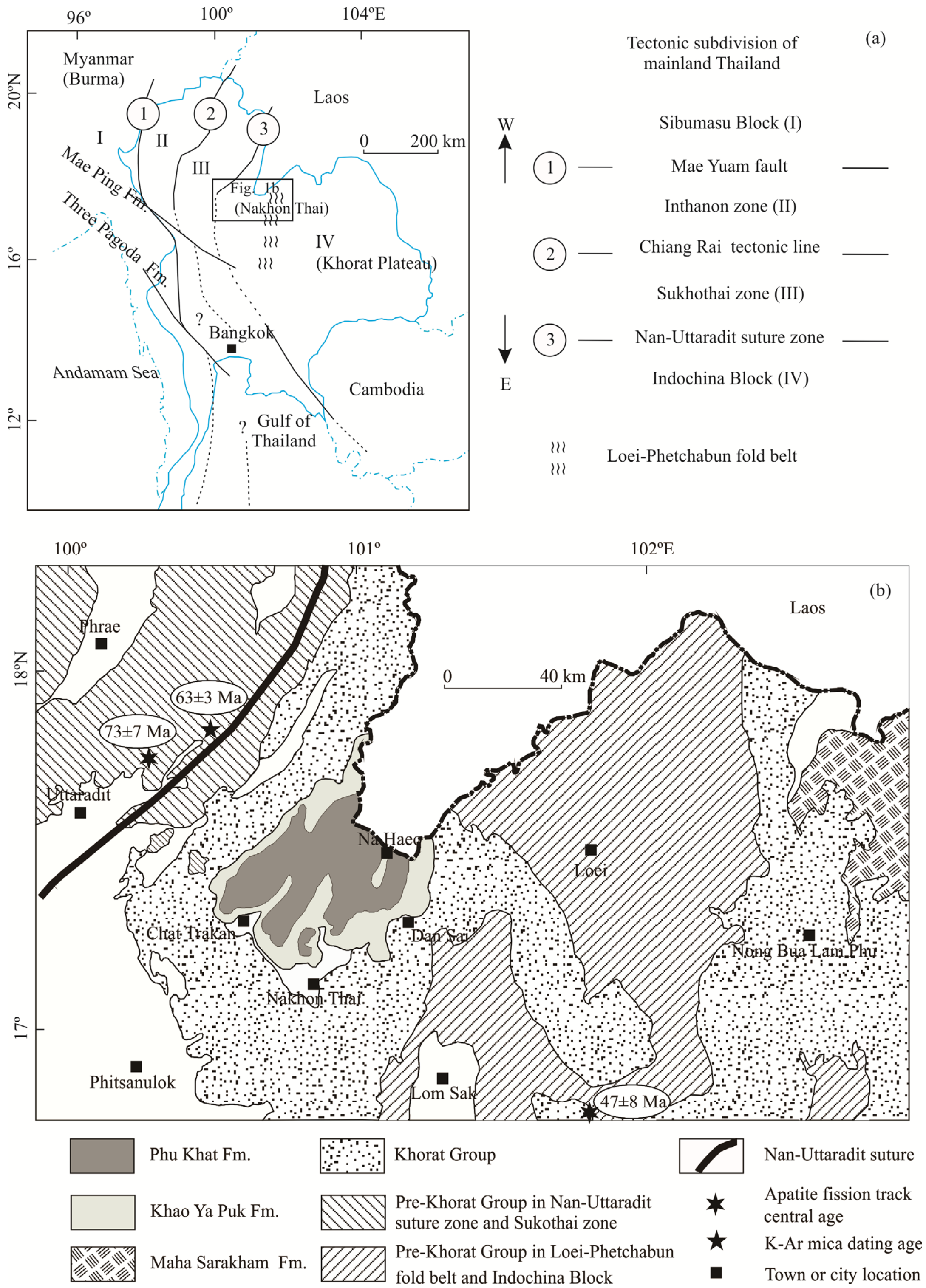

Figure 1. (a) Geotectonic subdivision map of Thailand (after Ueno and Hisada 2001; Barr and MacDonald, 1991). (b) Simplified geological map of the Nakhon Thai region (see Fig. 1a for map location). The map is based on the geological map of Thailand (1 : 2 500 000) published by Department of Mineral Resources (1999). Apatite fission track age is after Racey et al. (1997) and Upton (1999). The K-Ar mica dating age is after Ahrendt et al. (1993). Fm. Formation.

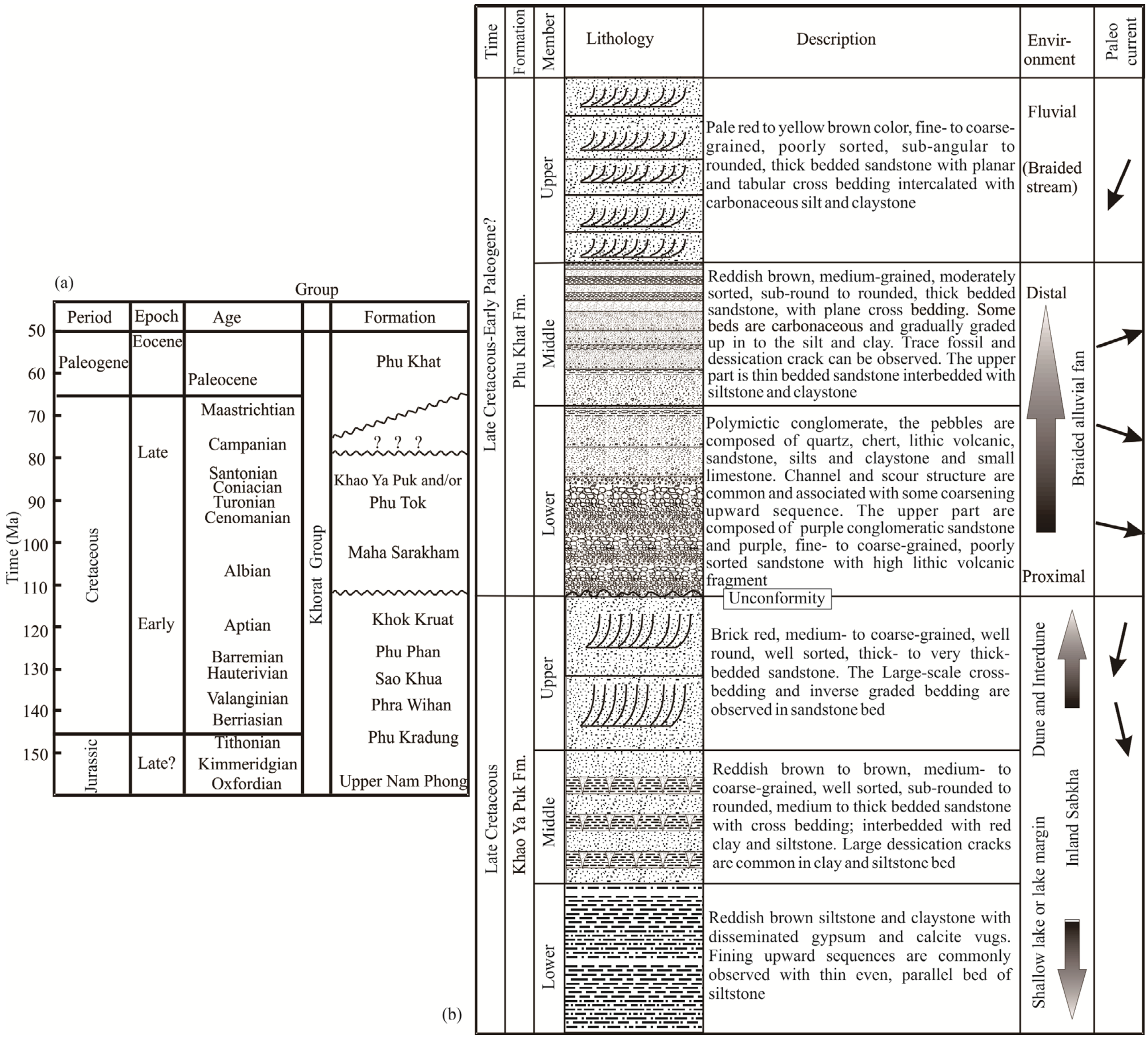

Figure 2. (a) Schematic stratigraphic column of the Nakhon Thai region since the Cretaceous (after Assavapatchara and Raksasakulwong, 2010; Racey, 2009; Racey et al.,1996). (b) Simplified lithostratigraphic column of the Phu Khat and the Khao Ya Puk Fms. in the Nakhon Thai region after Nulay et al., (2014) and Monjai (2006).

The Phu Khat Formation is predominantly characterized by water laid deposits. It can be subdivided into three parts. The lower part consists mainly of the proximal alluvial fan sequence (Nulay, 2014). It is composed predominantly of conglomerate, sandstone with high volcanic lithic fragment and some siltstone. The coarsening upward and fining upward sequences can be found through the section of the lower part. The middle part is characterized by the tabular geometry of reddish brown sandstone with high volcanic lithic fragment. It is horizontally stratified and graded upward into siltstone and mudstone. Based on its facies characteristic, the middle part of the Phu Khat Formation is interpreted to have been deposited by an ephemeral stream and poorly confined to unconfined flow of distal fan environment under semi-arid paleoclimate (Nulay, 2014). The upper part of the Phu Khat Formation is chiefly a sequence of braided fluvial sandstone. It is composed predominantly of thick-bedded sandstone with tabular cross-bedding intercalated with horizontal bedding. The bases of sandstone are commonly shown scour and lag pebbles. The presence of the fluvial braided stream deposit in the upper part of the Phu Khat Formation may imply that the environment gradually changes from semi-arid to semi-humid (Nulay, 2014.). The Phu Khat Formation is considered to be the Latest Cretaceous–Early Paleogene age based on the stratigraphic relation. The thickness of the measured section in the Nakhon Thai region is approximately 490 m (Nulay, 2014; Meesook et al., 2002; Heggemann, 1994). Seventy one samples were collected for analysis which comprises 51 samples from the three parts of the Phu Khat Formation and 20 from sandstone of the middle and the upper parts of the Khao Ya Puk Formation.

3 ANALYTICAL METHODS

3.1 Petrography

The thin sections of fresh sandstone samples were analyzed under the conventional microscope study. The Gazzi-Dickinson (Dickinson, 1985; Dickinson and Suczek, 1979) point counting method was used on 51 fine- to coarse-grained sandstone samples (15 of the Khao Ya Puk and 36 of the Phu Khat formations). In each thin section 300 grains on average of quartz, feldspar and rock fragment that are larger than 60 μm were point counted. The result was used for plotting the triangular discrimination diagram for provenance interpretation (Dickinson, 1985).

3.2 Bulk Geochemistry

The fresh rock samples of sand size were selected for analysis in order to reduce the variation of composition and to minimize secondary contamination due to weathering and alteration. The samples were cleaned, crushed and powdered in a tungsten-carbide mill to less than 60 μm in diameter. Fifteen samples consisting of 12 samples from the Phu Khat and 3 from the Khao Ya Puk formations were analyzed for bulk-rock geochemistry. Major, trace and rear earth elements (REE) were determined in all 15 samples. Major element analysis was conducted at the Bureau of Geological Analysis, Department of Mineral Resources (DMR, Thailand) on an Axios Advance X-ray fluorescence (XRF) spectrometer. For trace and rare earth elements, rock powders were first digested by $HF+HNO_3$ in Teflon bombs and then were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) using an Agilent 7500a at the Wuhan Supervision and Test Center for Mineral Resources of Ministry of Land and Resources (Wuhan, China). Analytical precision is generally better than 5% for most elements. All geochemical data are listed in Table 1.

3.3 U-Pb Detrital Zircon Dating

Three samples, each from the upper Khao Ya Puk (Up-Kyp), the lower Phu Khat (Low-Phk) and the middle Phu Khat (Mid-Phk) formations, were selected for the U-Pb dating. Zircons were separated using standard rock disaggregation and heavy mineral separation procedures, mounted in epoxy, and polished. Optical microscopy and cathodoluminescence (CL) images outline the morphology and internal structure of the grains. CL images were obtained on a JEOL JXA-8100 electron microprobe. All samples were analyzed by using laser ablation-ICPMS (LA-ICPMS). Two samples (Up-Kyp and Low-Phk) were conducted at the Department of Earth and Planetary Sciences Birkbeck, University of London (UK) and the other (Mid-Phk) was performed at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan. The $^{206}Pb/^{238}U$ ratio was used to determine the age <1 000 Ma and the $^{207}Pb/^{206}Pb$ ratio for the older age. The age distributions are displayed following the Kernel density plots (Vermeesch, 2012; Botev et al., 2010).

4 RESULTS

4.1 Petrography

4.1.1 Conglomerate of the Phu Khat Formation

The conglomerate beds are commonly present in the lower part of the Phu Khat Formation. Their composition and texture are varied. Pebbles and cobbles are generally rounded to sub-angular and are composed of quartz, chert, sandstone, volcanic clastic, mudstone, siltstone and few small limestone pebbles. Resistant pebbles consisting of quartz, chert and sandstone comprise 70% of the total clasts. Red chert clasts are common. The volcanic clast comprises 22% and the remainding 8% is mudstone and siltstone. The conglomerate beds can be classified as polymictic conglomerate. These polymictic conglomerates are matrix to clast supported. The clasts are ranging from 2–14 cm in size. The matrix is sandy to siltly and normally is purple to reddish purple in color. The conglomerate beds are 50 cm to 8 m thick and are generally intercalated with thin-bedded, purple and cross-stratified litharenite. They often show coarsening upward sequence and structureless frabric.

4.1.2 Sandstones of the Khao Ya Puk and the Phu Khat formations

The sandstones of Khao Ya Puk Formation are medium- to coarse-grained, moderately to well-sorted and consist of sub-rounded to rounded grains (Fig. 3a). They show a high textural and mineral maturity. The stable quartz detrital grain is significantly high with more than 80% on average. The unstable lithic fragment grains are normally less than 20% and the feldspar is rare the same as represented in the Phu Khat Formation.

The sandstones in the lower part of the Phu Khat Formation are fine- to very coarse-grained and poorly sorted and consist of angular to sub-rounded grains. The quartz clasts represent 58% of the rock on average. They are predominantly monocrystalline with about 3% of polycrystalline quartz. The lithic fragments comprise dominantly volcanic and some sedimentary rocks and represent 35% to 40% of the rock. The volcanic grains are mainly of intermediate type containing phenocrysts of plagioclase feldspar (Fig. 3b). Feldspar is quite rare representing 3% to 5%. The middle part of the Phu Khat Formation is characterized by fine- to medium-grained sandstone with moderately sorted, sub-angular to rounded grains (Fig. 3c). The quartz clasts containing 65% on average are slightly higher than the lower part. Monocrystalline quartz is still the main constituent with some polycrystalline quartz. The volcanic fragment is about 32% of the total lithic grains. Feldspar is still quite rare about 3% to 5% which is the same as the lower part. Sandstones of the upper Phu Khat Formation are petrographically identical to the lower part. They are fine- to coarse-grained, poorly to moderately sorted and consisting of angular to sub-round grains (Fig. 3d). Detrital quartz grain comprises about 56% and is mainly monocrystalline quartz. Unstable volcanic fragment is about 38% of the rock.

In summary, the Phu Khat Formation shows lower maturity than the Khao Ya Puk Formation. The un-sorted sediments of the Phu Khat Formation indicate that they were deposited not far from the source by the fluvial process (Nulay, 2014). The presence of very large pebbles of soft siltstone and mudstone in the conglomerate beds also substantiates this view. The occurrence of well rounded pebbles of resistant quartz and sandstone associated with non-resistant siltstone and mudstone was caused by a reworking process. The binary plot between ln(Q/F) and ln(Q/L) of Weltje (1994) also suggests that the source area of the Phu Khat Formation had been subjected to less chemical weathering and sorting process than the Khao Ya

Table 1 Geochemistry of sandstone of the Phu Khat and the Khao Ya Puk formations

Formation	Up-Phk		Mid-Phk		Low-Phk								Up-Kyp		Mid-Kyp
number	CK_M76-4	CK_M90-3	NH_B12	NH_B17	KM23B12	KM23B16	CK_M86-2	KM40B3	KM40B5	KM40B13	KM40B26	KM40B34	Kyp-1	Kyp-3	Kyp-2
Major elememts (wt.%)															
SiO_2	83.72	82.65	82.30	74.02	84.66	78.54	77.47	87.91	89.28	88.21	89.60	84.54	92.05	93.47	94.33
TiO_2	0.40	0.31	0.32	0.39	0.36	0.38	0.49	0.37	0.22	0.29	0.20	0.54	0.23	0.15	0.13
Al_2O_3	5.97	6.07	5.87	7.86	6.98	6.00	7.65	5.61	5.22	5.37	5.06	7.11	3.79	3.39	2.87
Fe_2O_3(t)	2.32	2.28	2.09	2.89	2.63	2.53	3.26	1.85	1.39	2.30	1.53	3.02	1.37	0.92	0.82
FeO	0.61	0.75	0.46	1.14	0.14	0.07	0.82	0.07	0.07	0.25	0.25	0.14	nil	nil	0.04
MnO	0.08	0.03	0.04	0.07	0.03	0.14	0.05	0.02	0.02	0.05	0.01	0.04	0.01	0.01	<0.01
MgO	0.84	0.84	0.89	1.01	0.68	0.73	1.14	0.53	0.38	0.50	0.37	0.63	0.21	0.16	0.19
CaO	1.59	2.30	2.68	5.08	0.35	4.64	3.11	0.06	0.04	0.05	0.03	0.07	0.07	0.03	0.03
Na_2O_3	0.88	0.61	0.72	1.20	0.77	0.68	0.91	0.36	<0.1	<0.1	<0.1	0.10	<0.1	<0.1	<0.1
K_2O	1.39	1.47	1.30	1.69	1.16	0.87	1.43	1.47	1.66	1.04	1.34	1.51	0.64	0.31	0.32
P_2O_5	0.07	0.03	0.06	0.09	0.06	0.05	0.04	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01
LOI	2.50	3.09	3.45	5.40	1.98	5.17	4.16	1.61	1.35	1.74	1.51	2.03	1.31	1.28	1.05
H_2O	0.12	0.09	0.14	0.16	0.22	0.14	0.15	0.07	0.22	0.28	0.20	0.20	0.20	0.16	0.15
Trace elements (ppm)															
Sc	4.97	4.58	4.82	5.81	6.66	5.96	7.64	4.22	3.10	4.89	3.03	6.86	2.65	3.64	1.96
Co	82.47	70.80	129.60	45.16	202.80	73.17	153.30	168.60	102.70	208.00	127.00	143.90	106.20	143.50	207.70
V	45.77	44.51	44.32	45.58	49.76	57.05	68.07	42.48	31.42	43.71	35.25	53.85	22.98	17.15	21.91
Rb	57.48	63.97	51.40	69.66	50.60	35.42	62.96	66.31	70.07	47.03	66.31	66.95	27.17	12.54	13.65
Zr	375.8	150.70	182.10	151.60	170.60	176.90	277.70	328.70	126.90	112.10	156.10	423.5	243.30	106.00	94.20
Nb	11.47	4.28	4.54	6.79	5.05	6.71	5.03	5.81	3.38	3.18	2.87	6.98	3.89	2.83	1.58
Hf	11.35	4.39	5.02	4.39	4.74	5.26	7.72	9.79	3.83	3.21	4.75	12.00	6.74	3.06	2.65
Ta	5.16	1.00	1.02	1.47	1.15	2.44	0.97	1.24	0.92	0.87	1.09	1.19	1.32	1.38	0.96
Pb	10.26	7.78	7.21	8.31	6.22	23.12	9.32	8.45	8.27	6.52	7.71	7.35	6.91	8.03	3.41
Th	11.73	6.16	6.18	8.13	12.83	7.13	7.24	8.11	5.32	4.56	5.85	8.61	5.80	4.16	3.52
U	2.37	1.22	1.27	1.73	1.88	1.89	1.75	1.44	1.01	1.05	1.13	1.77	1.01	0.71	0.59
Cr	43.83	37.39	32.41	49.83	36.28	38.81	52.80	33.19	20.45	33.87	26.41	44.47	19.02	11.21	9.55
Ba	296.95	182.30	200.45	238.85	191.95	380.65	161.55	241.70	248.65	183.90	230.50	206.70	165.40	131.65	31.20
Ni	18.95	14.55	18.24	16.25	25.62	17.46	22.83	17.94	13.65	18.61	12.51	22.75	7.13	7.61	9.43
Sr	53.17	49.10	50.01	73.29	49.33	66.24	72.27	34.84	27.60	21.16	19.38	28.56	23.16	14.35	11.25
Th/Sc	2.36	1.35	1.28	1.40	1.93	1.20	0.95	1.92	1.72	0.93	1.93	1.25	2.19	1.14	1.79
Th/U	4.94	5.04	4.87	4.70	6.81	3.77	4.14	5.64	5.25	4.36	5.19	4.86	5.75	5.83	5.95
Zr/Sc	75.64	32.92	37.78	26.09	25.62	29.68	36.35	77.95	40.99	22.91	51.52	61.73	91.71	29.12	48.01
La/Th	2.04	2.55	2.66	2.56	2.37	2.59	2.70	2.30	2.35	3.18	2.32	2.89	2.33	3.24	2.77

Table 1 Continued

Formation	Up-Phk		Mid-Phk		Low-Phk								Up-Kyp		Mid-Kyp
number	CK_M76-4	CK_M90-3	NH_B12	NH_B17	KM23B12	KM23B16	CK_M86-2	KM40B3	KM40B5	KM40B13	KM40B26	KM40B34	Kyp-1	Kyp-3	Kyp-2
REE (ppm)															
La	23.98	15.69	16.44	20.82	30.37	18.46	19.54	18.69	12.51	14.52	13.59	24.89	13.52	13.51	9.75
Ce	46.15	28.12	30.36	35.80	56.28	32.78	34.85	34.43	22.25	26.83	23.35	51.33	21.72	25.40	17.08
Pr	5.50	3.47	3.73	4.88	6.68	4.06	4.41	4.75	2.74	3.22	3.28	5.81	2.58	4.39	2.01
Nd	20.06	13.03	13.84	18.80	23.47	14.92	16.4	18.17	9.88	12.06	12.62	21.58	8.35	18.71	6.75
Sm	3.98	2.55	2.79	3.68	4.10	2.99	3.24	3.74	2.02	2.27	2.54	4.03	1.53	4.63	1.20
Eu	0.73	0.53	0.55	0.79	0.51	0.62	0.66	0.74	0.47	0.48	0.58	0.79	0.28	1.05	0.21
Gd	3.61	2.17	2.27	3.29	3.00	2.55	2.75	2.99	1.77	1.98	2.36	3.43	1.30	4.43	1.14
Tb	0.57	0.38	0.37	0.55	0.44	0.45	0.44	0.48	0.30	0.31	0.38	0.55	0.19	0.71	0.19
Dy	3.45	2.19	2.22	3.15	2.43	2.56	2.67	2.66	1.77	1.81	2.09	3.21	1.24	4.16	1.12
Ho	0.70	0.43	0.42	0.65	0.49	0.52	0.52	0.49	0.35	0.35	0.41	0.64	0.26	0.81	0.23
Er	1.90	1.26	1.23	1.75	1.35	1.45	1.53	1.49	0.98	1.00	1.13	1.78	0.79	2.11	0.64
Tm	0.30	0.19	0.20	0.28	0.22	0.23	0.24	0.22	0.15	0.17	0.18	0.29	0.12	0.31	0.11
Yb	1.88	1.18	1.19	1.64	1.38	1.36	1.51	1.38	0.95	0.99	1.03	1.83	0.86	1.85	0.65
Lu	0.27	0.17	0.17	0.23	0.18	0.19	0.21	0.19	0.14	0.14	0.15	0.25	0.12	0.26	0.09
LaN/YbN	9.14	9.54	9.95	9.09	15.79	9.75	9.27	9.69	9.43	10.48	9.47	9.76	11.34	5.23	10.77
GdN/YbN	1.59	1.52	1.59	1.65	1.80	1.55	1.50	1.78	1.53	1.65	1.90	1.55	1.26	1.98	1.45
Eu/Eu*	0.58	0.68	0.64	0.68	0.42	0.67	0.66	0.65	0.74	0.68	0.72	0.63	0.59	0.70	0.53

Puk Formation (Fig. 4a). Based on this plot, it may imply that the provenance of the Phu Khat Formation probably was under high mechanical breakdown for supplying sediments to the depositional area. Comparing the three parts of the Phu Khat Formation, the middle part shows higher degree of sorting than the two others. However, these three parts are similar in petrographic composition and are probably derived from the same source. The different grades of sorting are due to the changing of transporting energy (Nulay, 2014.).

4.2 Geochemistry

4.2.1 Major elements

The result of geochemical analysis of major elements of the studied samples is shown in Table 1. The classification of sandstones based on the chemical composition indicates that most of the Phu Khat Formation are litharenite and all the Khao Ya Puk Formation are sub-litharenite (Fig. 4b). Generally, all samples of the Phu Khat Formation contain a higher concentration of elements than the Khao Ya Puk Formation except the

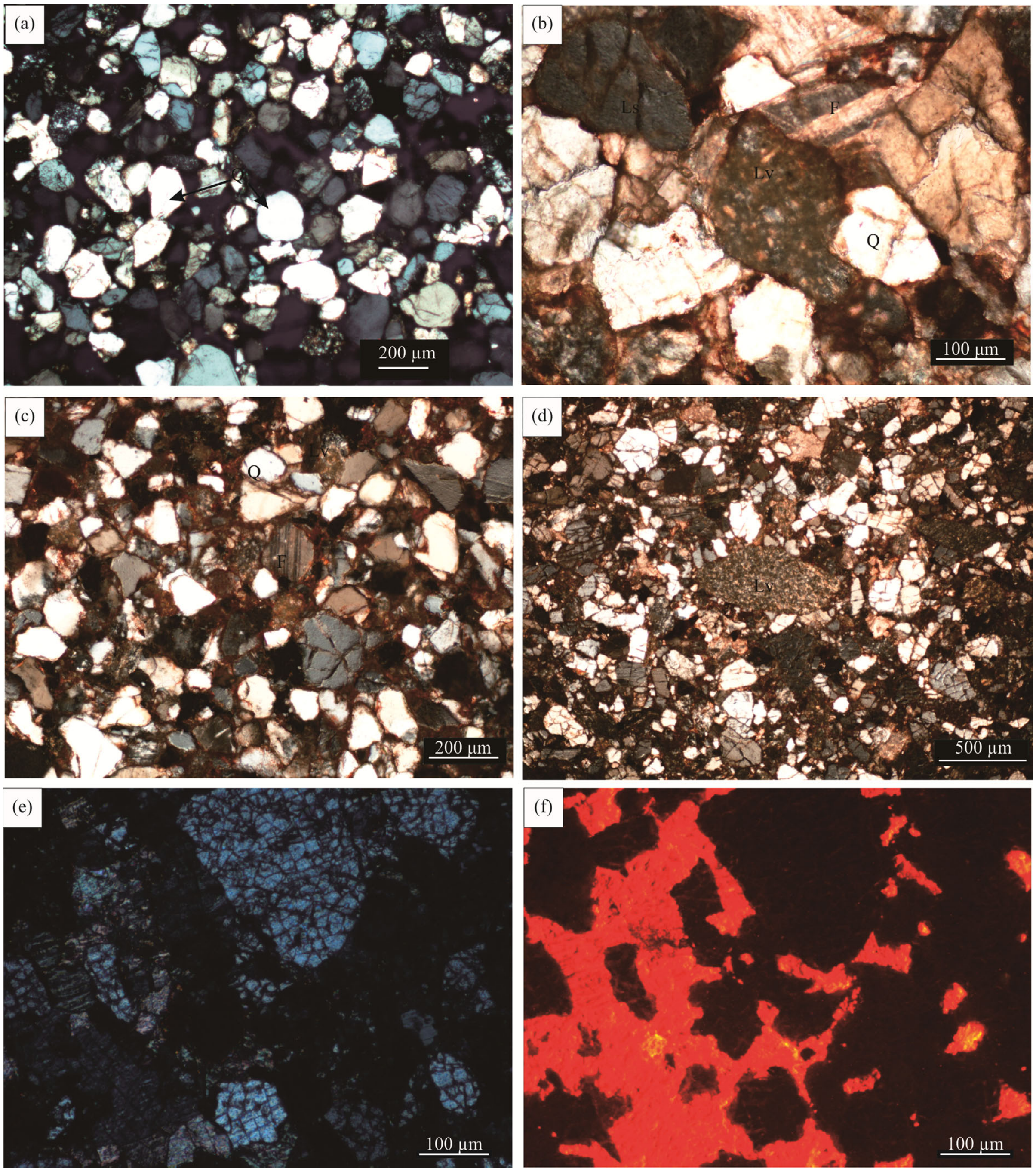

Figure 3. Photomicrographs of sandstones. (a) Well sorted sublitharenite of the upper Khao Ya Puk Fm.. (b) and (d) Poorly sorted litharenite of the lower Phu Khat Fm.. (c) Moderately sorted litharenite of the middle Phu Khat Fm.. (e) Calcareous sandstone of the lower Phu Khat Fm.. (f) Cathodoluminescence image of calcareous sandstone of (e). The pale red patch to the left indicates calcite cement around clastic grains. (a), (b), (c), (d) and (e) Photographs were under cross polarized. Q. Quartz; F. feldspar; Lv. volcanic lithic fragment; Ls. sedimentary lithic fragment.

SiO_2 concentration. The SiO_2 in the Khao Ya Puk Formation is higher than 90 wt.% whereas the Phu Khat Formation contains 70 wt.% to 80 wt.% on the average. TiO_2 (0.36 wt.%), Al_2O_3 (6 wt.%), Fe_2O_3 (2.3 wt.%), MgO (0.8 wt.%), Na_2O (0.6 wt.%) and K_2O (1.4 wt.%) are relatively high in the Phu Khat Formation compared with the Khao Ya Puk Formation. This is caused by an increase in unstable detrital grains particularly the volcanic rock fragments and a decrease in mineralogical maturity as evident in the less quartz content of the Phu Khat Formation in the petrographic study. The Fig. 4c illustrates the model of possible path of sediment in relation to weathering and sorting. It agrees well with the petrographic study in Fig. 4a which suggests that the Phu Khat Formation shows a low degree of chemical weathering and sorting. It contrasts with the Khao Ya Puk Formation that was experienced a high degree of sorting.

The mean values of the major elements of the Khao Ya Puk sandstone and the Phu Khat sandstone normalized to Post-Archean Australian shale (PAAS) are illustrated in Fig. 5a. The CaO content is depleted in the Khao Ya Puk Formation whereas it is enriched in the Phu Khat Formation. The

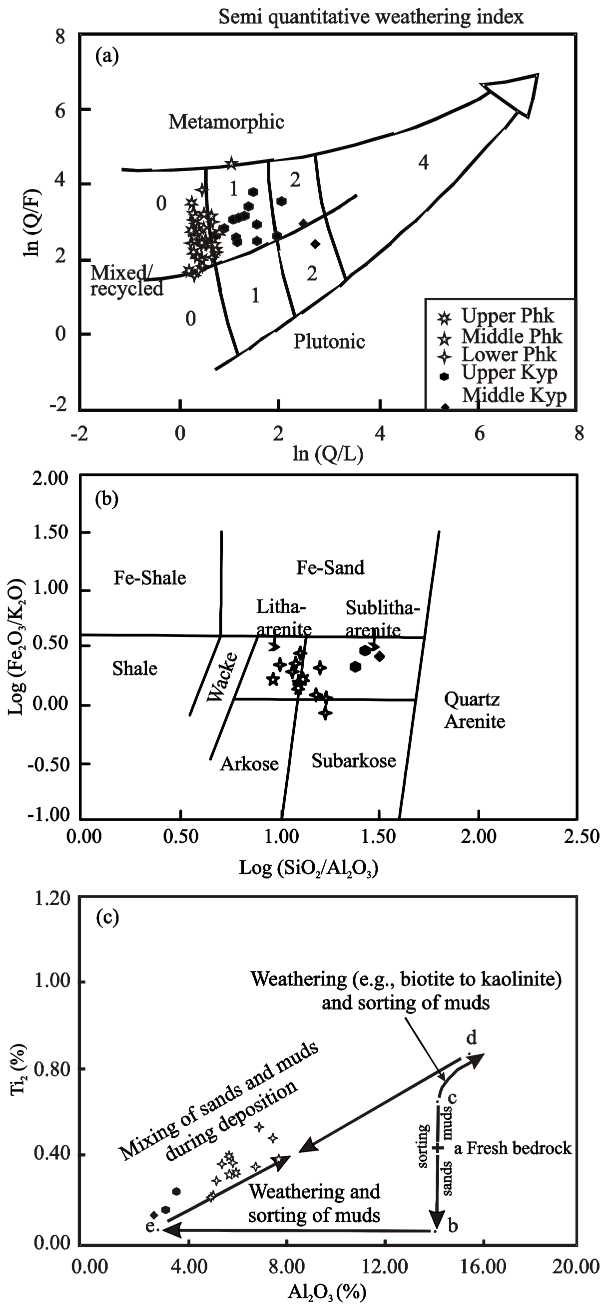

Figure 4. (a) The semi quantitative weathering index plot of Weltje (1994). (b) Sandstone classification of the Phu Khat and the Khao Ya Puk Fms. based on chemical composition (after Herron, 1988). (c) Bivariate plot of Al_2O_3 against TiO_2 diagram showing possible weathering and sorting paths for sandstone of the Khao Ya Puk and the Phu Khat Fms. (after Young and Nesbitt, 1998). Upper Phk. upper Phu Khat Fm.; Middle Phk. middle Phu Khat Fm.; Lower Phk. lower Phu Khat Fm.; Upper Kyp. upper Khao Ya Puk Fm.; Middle Kyp. middle Khao Ya Puk Fm..

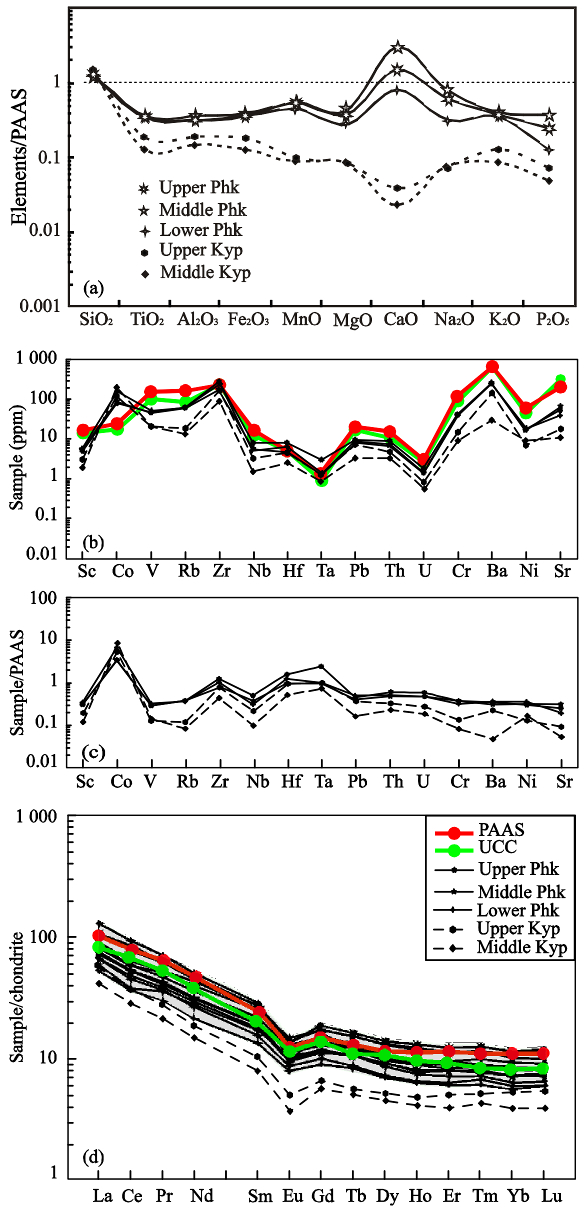

Figure 5. Major and REE patterns of the sandstones of the Phu Khat and the Khao Ya Puk Fms.. (a) Major elements normalized against Post-Archean Australian shale (PAAS) (Taylor and McLennan, 1985). (b) Concentrations of trace elements relative with PAAS and upper continental crust (UCC) (Rudnick and Gao, 2003). (c) Trace elements normalized against PAAS. (d) REE normalized against chondrite (Sun and McDonough, 1989). For symbol see Fig. 4.

enrichment of the CaO in the Phu Khat Formation is probably due to the diagenetic secondary calcite cement as shown in the microscopic petrography (Figs. 3e and 3f). The depletion of CaO in the Khao Ya Puk Formation may reflect either lacking of CaO from their provenance or a reduction during the sorting process or both (Bhatia, 1983). This assumption is amplified by bivariate plot of TiO_2 vs. Al_2O_3 of Young and Nesbitt (1998) (Fig. 4c). It clearly indicates the low chemical weathering and short transportation of the Phu Khat Formation and the long history of transportation and/or high degree of weathering in the source area of the Khao Ya Puk Formation.

4.2.2 Trace and rare earth elements (REE)

The concentrations of trace elements are shown in Table 1 and plotted in Fig. 5b. The trace elements normalized against PAAS are shown in Fig. 5c. Both the Khao Ya Puk and the Phu Khat formations display similar trace element trends which are comparable to the PAAS and upper continental crust (UCC) values. However, the Phu Khat Formation shows relatively high concentration of trace elements comparing to the Khao Ya Puk Formation. The significant higher values are Sc, V, Rb, Cr, Ni, and Sr elements as shown in Table 1. The average of Sc=5, V=50 ppm, Rb=60 ppm, Cr=40 ppm, Ni=20 ppm and Sr=45 ppm is found in the Phu Khat Formation, while the Khao Ya Puk Formation shows Sc=2 ppm, V=20 ppm, Rb=20 ppm, Cr=13 ppm, Ni=8 ppm, and Sr=16 ppm. These higher values are caused by the presence of volcanic grains and the less textural and chemical maturity of the Phu Khat Formation (Bhatia, 1985). The Khao Ya Puk Formation shows the uniform Th/U and Th/Sc ratios which are higher than 5 and 1, respectively indicating the upper continental and/or recycled provenance (McLennan et al., 1993). While the Phu Khat Formation yields a wide range of Th/U and Th/Sc ratios between 3.77 to 6.81, and 0.93 to 2.3, respectively, reflecting the variable provenance (McLennan et al., 1993).

Both the Khao Ya Puk and the Phu Khat formations have a similar chondrite-normalized REE trend as shown in Fig. 5d. They show parallel trend to both the PAAS and the UCC. The LREE enrichment and HREE depletion values as reflected by La_N/Yb_N and Gd_N/Yb_N are 10 to 15, and 1.26 to 1.80, respectively. They are also display significantly negative Eu anomalies (average Eu/Eu*=0.61 in the Khao Ya Puk and 0.42 to 0.74 in the Phu Khat formations). The total abundant of REE (La to Lu) is low (100 ppm and 50 ppm on the average in the Phu Khat and the Khao Ya Puk formations, respectively) comparing to the PAAS (184.77 ppm) and UCC (148.14 ppm). These lower values are caused by abundant detrital quartz which dilute the total REE values (Barth et al., 2000; Taylor and Mclennan, 1995) especially in the sub-litharenite of the upper Khao Ya Puk Formation. A slight difference between the Phu Khat and the upper Khao Ya Puk formations in the chondrite-normalized REE patterns is that the Phu Khat Formation pattern is close to PAAS and UCC but the upper Khao Ya Puk Formation is significantly lower as shown in Fig. 5d.

4.3 U-Pb Detrital Zircon Dating

The U-Pb detrital zircon dating was employed in this study in order to overcome the limitation of petrography and geochemistry for constraining the specific source terrane. Three representative samples, one from the upper Khao Ya Puk Formation (Up-Kyp) and other two from the lower (Low-Phk) and the middle Phu Khat Formation (Mid-Phk) were selected for analysis. The age distribution of the three samples is presented on the Kernel density plots with concordia diagram as shown in Fig. 6.

4.3.1 Upper Khao Ya Puk Formation (well sorted, large-scale cross-bedded sandstone)

The analysed sample was taken from the upper Khao Ya Puk Formation immediately below the contact with the overlying Phu Khat Formation. It is composed of medium- to coarse-grained, very well-sorted sandstone with high angle foresets of large-scale cross-bedding. The analysis of 133 detrital zircon grains shows that the upper Khao Ya Puk Formation contains six pervasive zircon cluster ages, i.e., 2 800 to 2 280 Ma (peak 2 462 Ma), 2 050 to 1 530 Ma (peak 1 831 Ma), 1 302 to 1 050 Ma (peak 1 184 Ma), 930 to 720 Ma (peak 821 Ma), 630 to 420 Ma (peak 546 Ma), and 300 to 160 Ma (peak 215 Ma). The dominant ages are the Meso-Proterozoic, the Neo-Proterozoic and the Phanerozoic. All zircons grains have Th/U ratios higher than 0.2 suggesting an igneous origin (Rubatto, 2002).

4.3.2 Lower Phu Khat Formation (poorly sorted sandstone intercalated in conglomerate beds)

The analysed sample was taken from sandstone of the lower Phu Khat Formation which is intercalated with polymictic conglomerate. The analysis of 107 detrital zircon grains shows different distribution of U-Pb age cluster from the underlying formation (Up-Kyp) (Fig. 6). Four major cluster ages are recognized, i.e., 2 800 to 2 280 Ma (peak 2 453 Ma), 2 050 to 1 530 Ma (peak 1 850 Ma), 1 200 to 900 Ma (peak 934 Ma), and 300 to 160 Ma (peak 230 Ma) with dominant age in the Phanerozoic. The Th/U ratios of all zircons are higher than 0.2 suggesting that most of them are from igneous origin.

4.3.3 Middle Phu Khat Formation (moderately sorted sandstone)

The analysed sample is from fine- to medium-grained sandstone of the middle Phu Khat Formation. The analysis of 66 zircon grains yields an age ranging from 2 667 to 112 Ma and can be classified into five cluster age groups of 2 667 to 2 350 Ma (peak 2 450 Ma), 2 050 to 1 530 Ma (peak 1 880 Ma), 1 200 to 900 Ma (peak 996 Ma), 640 to 370 Ma (peak 510 Ma), and 300 to 112 Ma (peak 240 Ma). The cluster age of the Mid-Phk is similar to the Low-Phk particularly the Precambrian, the Th/U>0.2 and the dominant age in the Phanerozoic. In general, most of the Phanerozoic or younger zircon ages are characterized by euhedral prismatic shape with oscillatory zoning internal structure. Based on these features and the Th/U>0.2, the zircons may be derived from the igneous rock and without prolonged transported process (Wu and Zheng, 2004).

5 DISCUSSION

5.1 Provenance of Sandstones

Two widely used methods for provenance discrimination in the petrographic study are the Qt-F-L and Qm-F-Lt triangular plots of Dikinson (1985) and Dikinson and Suczek (1979).

The plots of the Phu Khat and the Khao Ya Puk formations indicate that both were derived mostly from the recycled orogenic terrane (Fig. 7a). Dikinson and Suczek (1979) demonstrates that it could be formed either from the deformed and uplifted sequence of the collision orogens or the foreland fold and thrust belt. On the Qm-F-Lt plot, most of the Phu Khat Formation samples are in transitional between the quartzose recycled and the lithic recycled fields. Whereas the Khao Ya Puk samples are entirely fallen in the quartzose recycle (Fig. 7b). The result may suggest that sandstones of the two formations were fed by different sources. The Khao Ya Puk Formation which shows high quartzose recycle was derived mainly from polycyclic sedimentary sources since it shows both high textural and mineral maturity. Whereas the Phu Khat Formation was derived from mixed sedimentary and volcanic sources as evident in a high content of volcanic and lithic fragments. The well-rounded and high resistant pebbles associated with non-resistant siltstone and mudstone clasts in the conglomerate also suggest a low maturity.

Roser and Korsch (1988) presented the provenance discriminant function plot based on the major element component to distinguish four different lithologic types of the source area, i.e., mafic igneous, intermediate igneous, felsic igneous and recycled rocks. Roser and Korsch (1988) categorized the plot into two schemes. One is based on seven major elements (TiO_2, Al_2O_3, Fe_2O_3(t), MgO, CaO, Na_2O and K_2O) and the other on oxide/Al_2O_3 ratios (e.g., TiO_2/Al_2O_3, $Fe_2O_3(t)/Al_2O_3$, MgO/Al_2O_3, Na_2O/Al_2O_3, and K_2O/Al_2O_3). As suggested by Roser and Korsch (1988) the later scheme should be applied for the high CaO samples due to rich carbonate cement and/or bioclasts in sandstone. In this study the oxide/Al_2O_3 ratio scheme is used to distinguish provenance of sandstones in the Phu Khat Formation due to their high content of secondary calcite cement (Fig. 7c), but in the Khao Ya Puk Formation the other

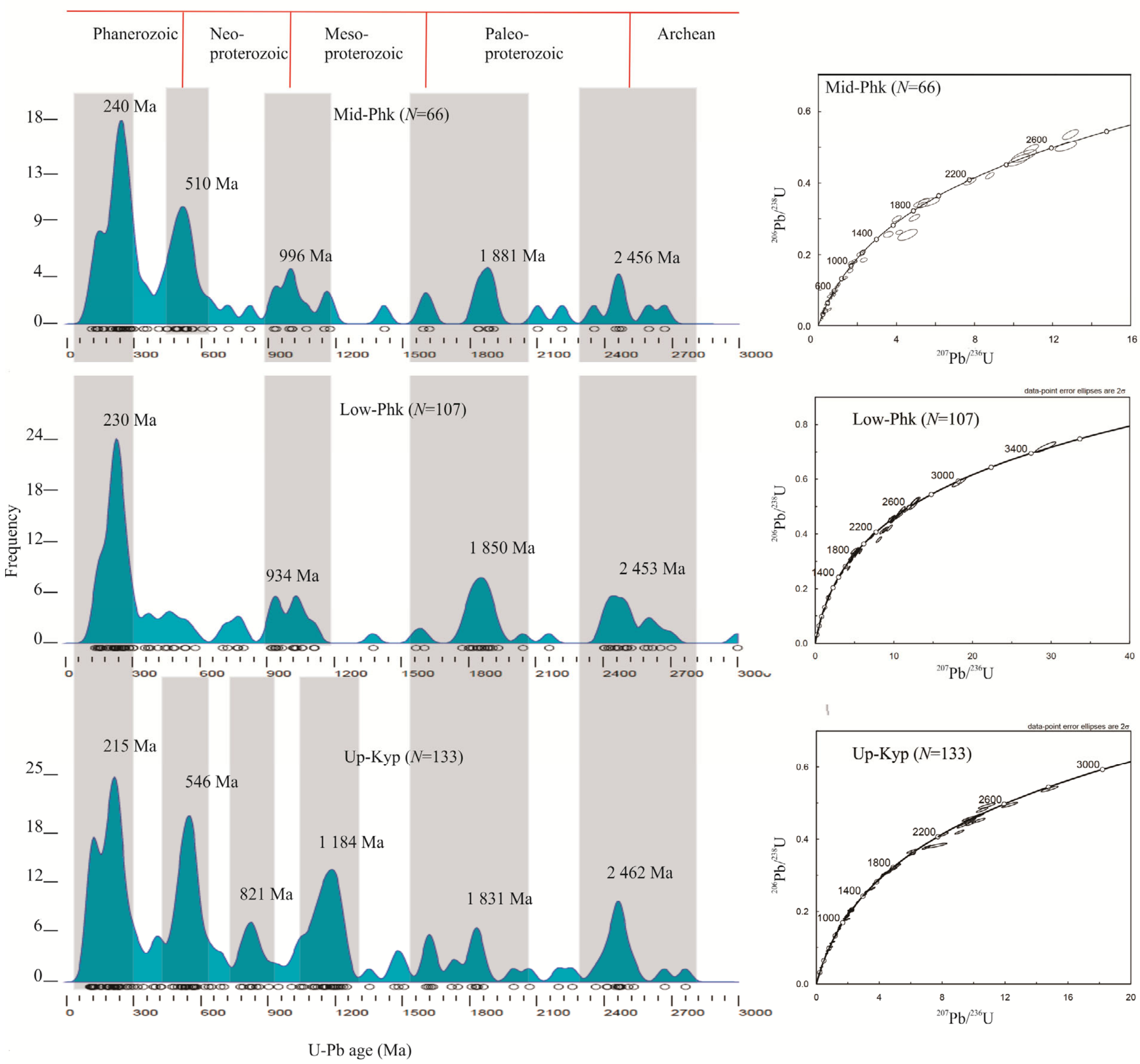

Figure 6. Kernel density plots with concordia diagram of detrital zircons from the sandstone of the upper Khao Ya Puk Fm. (Up-Kyp), the lower (Low-Phk) and the middle (Mid-Phk) Phu Khat Fm.. *N* is total number of analyzed grains. $^{206}Pb/^{238}U$ ages for zircons younger than 1 000 Ma, and $^{207}Pb/^{206}Pb$ ages for 1 000 Ma or older.

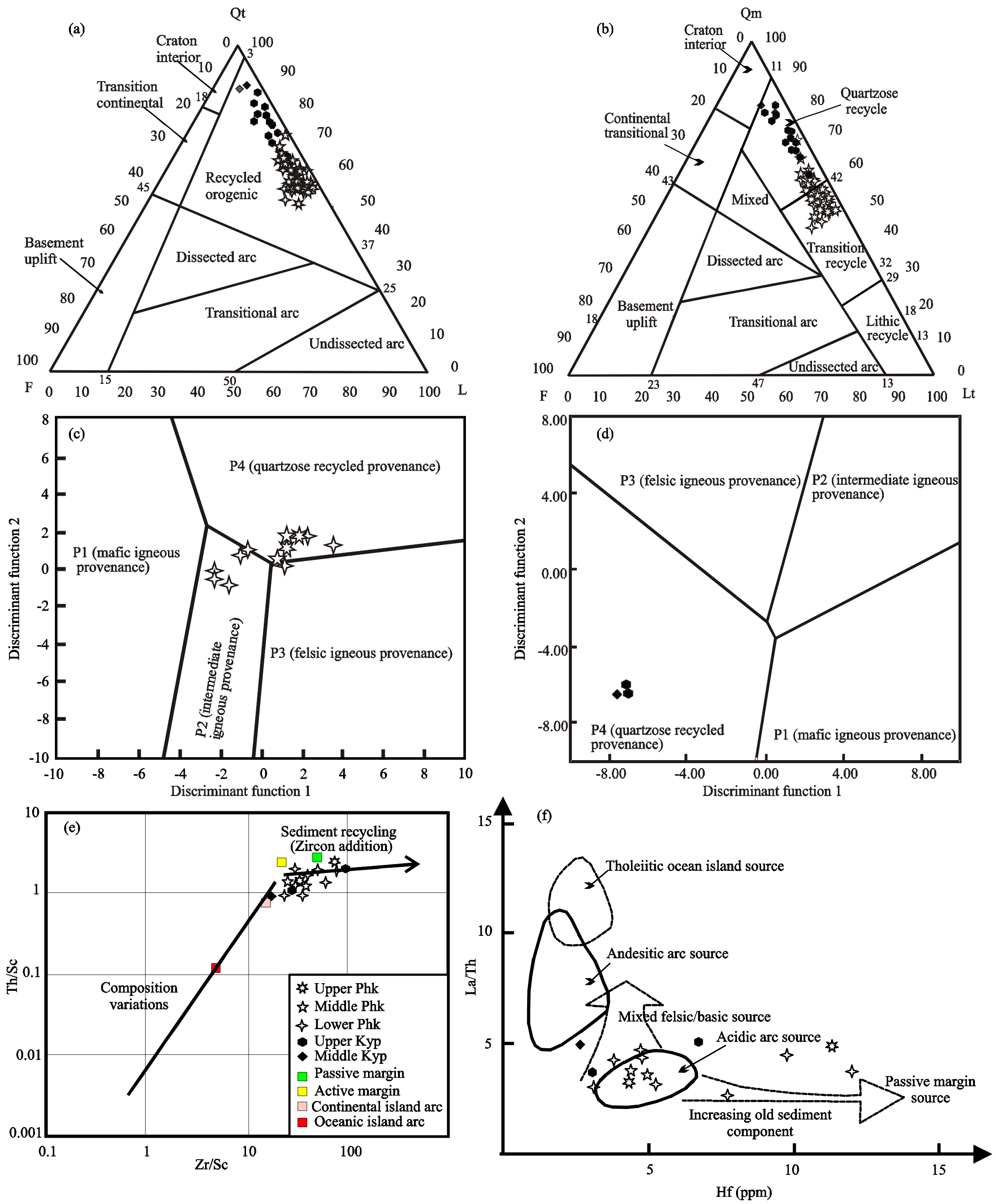

Figure 7. (a) and (b) Qt-F-L and Qm-F-Lt diagrams for distinguishing provenance of the sandstones from the Phu Khat and the Khao Ya Puk Fms. after Dickinson (1985). Qt. total quartz grains (mono- and polycrystalline quartz); Qm. monocrystalline quartz; F. felspar grains (plagioclase and K-felspar); L. lithic fragments; Lt. lithic fragments and polycrystalline quartz. (c) and (d) Major elements discriminant diagrams for provenance types. (c) The Phu Khat Fm. containing high secondary CaO contents. (d) The Khao Ya Puk Fm. with normal CaO contents (after Roser and Korsch, 1988). (e) and (f) Trace elements discriminant diagrams for provenance types. (e) Plot of Th/Sc versus Zr/Sc for variation of provenance after McLennan et al. (1993). The variation values of passive margin, active margin, continental island arc and oceanic island arc after Bhatia (1985). (f) Source and composition discrimination of sandstones using La/Th ratio and Hf abundance (Floyd and Leveridge, 1987). For symbol see Fig. 4.

discriminant function is applied. Half of the samples of the Phu Khat Formation are fallen in the quartzose sedimentary recycle and the rest are in the intermediate igneous field. All of samples of the Khao Ya Puk Formation fall in the quartzose recycled field (Fig. 7d). The result is comparable to those of the petrographic study which indicates that the bulk composition of the Phu Khat sandstone was derived from volcanic and quartzose sedimentary sources.

The plot of trace elements Th/Sc against Zr/Sc was proposed by McLennan et al. (1993) to outline the potential source of sediment. The Th/Sc is a good indicator of chemical differentiation process in igneous rock whereas Zr/Sc is useful index of zircon enrichment in the sedimentary recycling process (Fig. 7e) (McLennan et al., 1993). The Phu Khat Formation is characterized by a wide range of Zr/Sc ratios whereas Th/Sc is more uniform. Some samples of the Phu Khat Formation are close to the felsic volcanic rock and some are related to the sedimentary recycled process. This may suggest that the provenance of the Phu Khat Formation was mainly from the felsic volcanic rocks with minor sedimentary recycled source. It is also supported by the variation of the Eu/Eu* anomalies (0.42 to 0.74) of the Phu Khat Formation. Some samples show negative Eu/Eu* value in the range of the PAAS (0.64) which suggests the contribution of sedimentary source. But the others are higher than the PAAS indicating that they were derived from the volcanic source (Bhatia, 1985). The La/Th against Hf plot introduced by Floyd and Leveridge (1987) also supports this interpretation. The Phu Khat Formation sample is fallen in the field of acidic arc with some mixed felsic and basic sources. However, the recycled passive margin could also be the source as shown in Fig. 7f.

In order to indicate a specific age of the source terrane of the sandstone, the U-Pb zircon dating was conducted in three samples, one from the upper Khao Ya Puk Formation and the other two from the lower and middle Phu Khat Formation. The results show that all three samples provide a wide range of zircon age from the Precambrian to Mesozoic age but most are concentrated in the Mesozoic. The presence of the Precambrian zircon age in the Phu Khat Formation may relate directly to the Precambrian formation within the source area, or to recycling of the younger rocks. In this study the recycled process is preferable as no exposed Precambrian rocks in the adjacent area are known according to the U-Pb zircon dating data (Hansen and Wemmer, 2011; Clift et al., 2006; Lepvrier et al., 2004; Carter and Bristow, 2003; Dunning et al., 1995). One notable difference between the Phu Khat Formation and the upper Khao Ya Puk Formation is the difference in the Precambrian zircon age distribution (Fig. 6). We believe that the difference of the provenance ages of the two formations may imply the presence of a tectonic event or a major erosional event subsequent to the deposition of the Khao Ya Puk Formation. This interpretation is supported by the line of evidences in the field including (1) lack of structural dipping in the Phu Khat Formation while the underlying formation show an higher dipping angle (2) the abrupt facies change from the aeolian sandstone of the Khao Ya Puk Formation to the polymictic conglomerate of the alluvial fan environment of the Phu Khat Formation (Nulay, 2014). However, as stated by Huber et al. (2002, 1995) this abrupt facies change may be also caused by the global climate change during the Cretaceous. Huber et al. claimed that global climate changed from a warm greenhouse state during the Late Albian through Late Cenomanian to a hot greenhouse phase during the Latest Cenomanian through Early Campanian, then to cool greenhouse conditions during the Mid-Campanian through Maastrichtian. So that the abrupt facies change may be caused by the climate change which is required further studies to clarify.

The results of geochemical and petrographic studies of the Phu Khat Formation indicate that it was derived from the felsic volcanic and sedimentary rocks. It is possible from those terranes west and east of the NaKhon Thai region where both the terranes also contain volcanic and sedimentary rocks. So in order to indicate unique terrane, the cluster of zircon age is determined and compared with the zircon age of possible volcanic source terranes. The cluster of zircon age in the Phanerozoic of the Phu Khat Formation (Fig. 8) may relate directly to the exposed rocks of the source terrane. Additionally, the presence of euhedral prismatic shape and oscillatory zoning internal structure of zircon grains in this cluster may reflect the first cycle sediments of an igneous origin. So this zircon age cluster will relate directly to the provenance. The age distributions on the Kernel density plots of the Phu Khat samples since the Cambrian are shown in Fig. 8. They can specify the precise source location of the Phu Khat Formation.

The zircon age distribution of the Phu Khat Formation is characterized by the presence of age cluster in the Late Ordovician and the peak of dominant zircon age in the Late Triassic which are closely related with the igneous activity of the western terrane as shown in Figs. 8 and 9. The Late Ordovician volcanic activity which was present in the western terrane was not detected in the eastern terrane. The volcanic activity of the western terrane was dominant in the Middle to the Late Triassic (Qian et al., 2013; Srichan et al., 2009, 2008; Khositanont, 2008; Barr et al., 2006, 2000) but in the Late Permian to Middle Triassic in the eastern terrane (Kamvong et al., 2014; Salam et al, 2014; Zaw et al., 2014; Feng et al., 2009; Khositanont, 2008; Intasopa, 1993). The presence of widespread Late Triassic to Jurassic volcanic rock (ms_2 of Drumm et al., 1993) in northern Thailand is also consistent with the interpretation. Moreover, the paleocurrent pattern and lithofacies occurrence are also supported the interpretation that the provenance of Phu Khat was in the western terrane. Paleocurrrent obtained from cross-bedding in sandstone are most from west to east which is consistent with the lithofacie occurrence (Nulay, 2014). In the western part of Nakhon Thai region, the Phu Khat Formation are characterized chiefly by matrix to clast supported conglomerate of the proximal fan facies while in the eastern part of the region the Phu Khat Formation are characterized chiefly by tabular geometry of reddish brown sandstone of distal fan Facies. From all of these evidences in the field together with the zircon dating data in the laboratory, it can be concluded that the provenance of the Phu Khat Formation was in the western terrane. However, Heggemann (1994) concluded that the provenance of the Phu Khat Formation was from both the western and the eastern terranes based on the imbrication of pebbles in outcrop. Nevertheless, the pebble imbrications in the complex Nakhon Thai region may be formed by tectonic rotation. The outcrop (Km 35 Road No1268) mentioned by Heggemann (1994) was revisited by the authors but the possible source from the eastern terrane could not be confirmed. Based on the available evidence so far, it can be suggested that the main provenance of the Phu Khat Formation was the felsic volcanic associated with the polycyclic sedimentary rocks from the terrane west of the Nakhon Thai region.

5.2 Tectonic Setting

In order to gain more understanding of tectonic setting of the sedimentary deposits, the major elements together with the trace elements are used by various studies (e.g., Hara et al., 2012; Yang et al., 2012; Bhatia and Crook, 1986). The combination of geochemical and petrographic analysis have proved to be a powerful tool for determination of tectonic setting (Roser and Korsch, 1986). The tectonic discrimination diagram of Roser and Korsch (1986) using K_2O/Na_2O ratio against SiO_2 content was applied in this study. Moreover, the discriminant function plot of 11 major elements and bivariate plot of immobile elements of Bhatia (1983) are also used. In this study the TiO_2 and Al_2O_3/SiO_2 ratios are used to plot bivariation against (Fe_2O_3+MgO) because they show high correlation coefficient (0.9 and 0.84), whereas (K_2O/Na_2O) and Al_2O_3/(CaO+Na_2O) were omitted owing to their low correlation coefficient with Fe_2O_3+MgO (-0.29 and -0.53). Figure 10b shows the result of K_2O/Na_2O ratio against SiO_2 plot. It indicates that most samples fell in the passive margin field. The result is in agreement with the discriminant function plot of Bhatia (1983) and Al_2O_3/SiO_2 bivariate plot (Figs. 10a and 10d). However, a slight difference is shown in the bivariate plot of TiO_2 against (Fe_2O_3+MgO) which indicates that the Phu Khat Formation is in the overlapping field between the passive margin and the active continental margin (Fig. 10c).

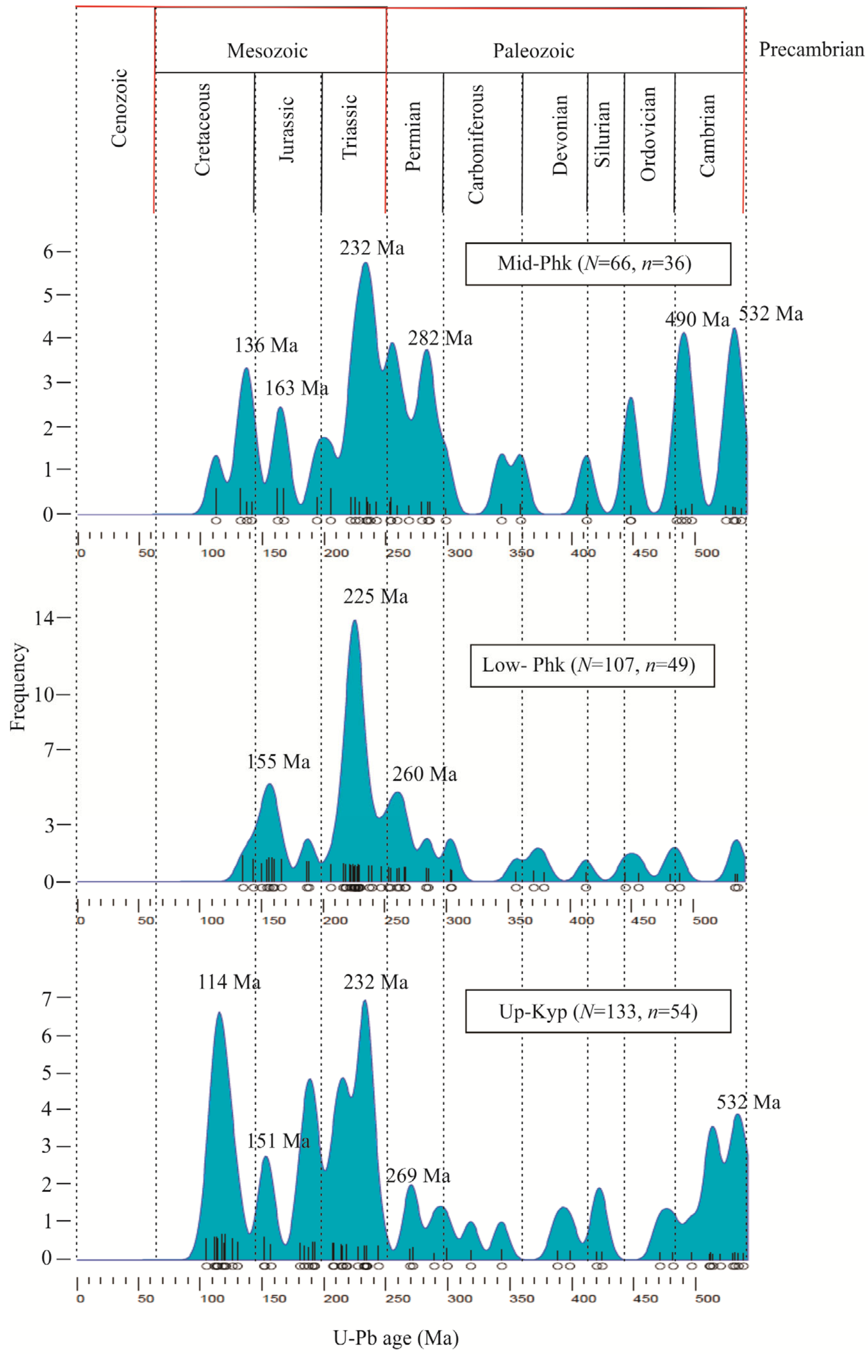

Figure 8. The post-Cambrian age distributions of detrital zircons from sandstone of the upper Khao Ya Puk Fm. (Up-Kyp) and the lower (Low-Phk) and the middle (Mid-Phk) Phu Khat Fm. *N* is total number of analyzed grains and *n* is number of post-Cambrian age grains.

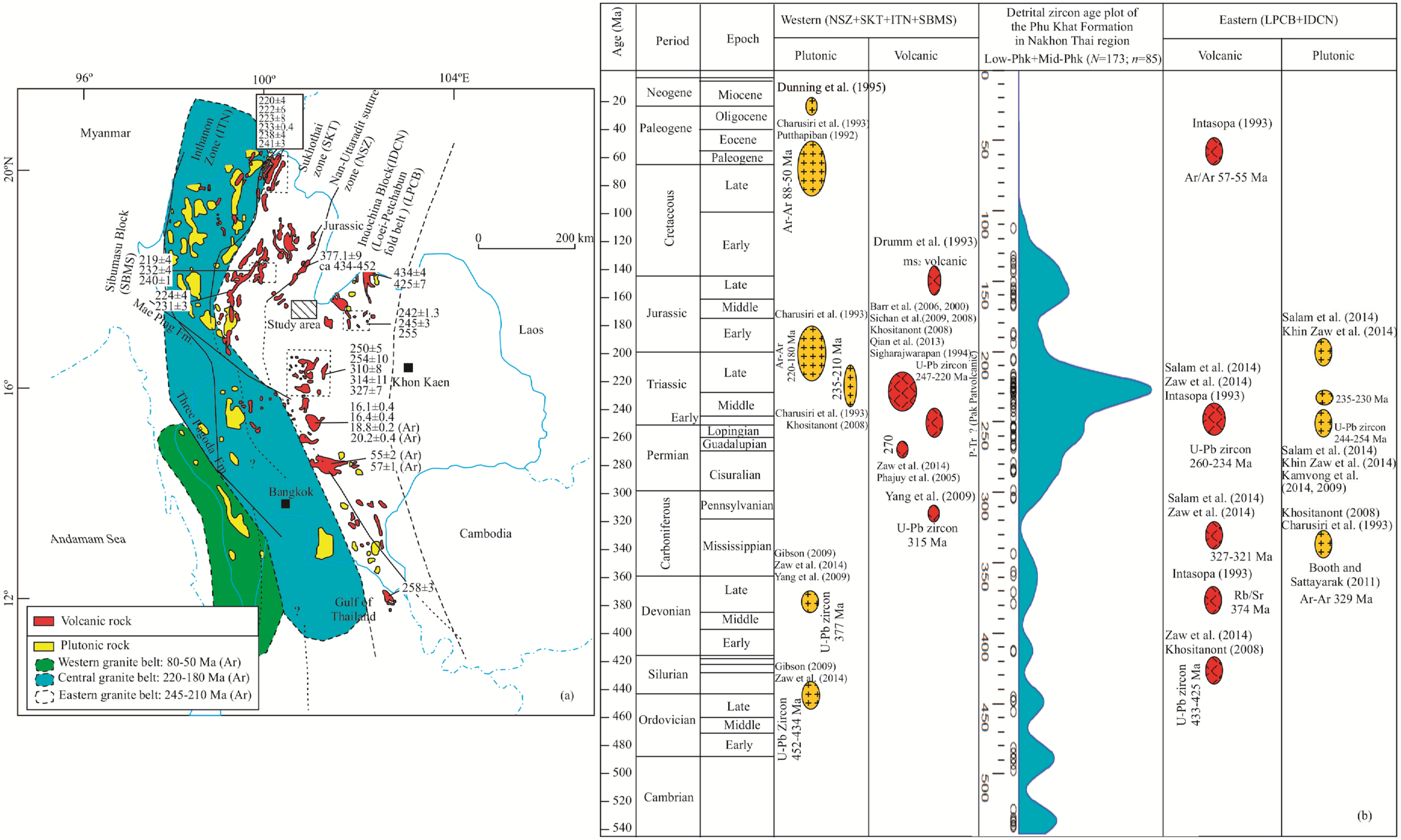

Figure 9. Potential sources of detrital zircon for the Phu Khat Fm.. (a) Distribution of igneous rocks which are the possible sources for the Phu Khat Fm., with age after Barr and Charusiri (2011), Barr et al. (2006, 2000), Charusiri et al. (1993), Drumm et al. (1993), Intasopa (1993), Kamvong et al. (2014), Zaw et al. (2014), Khositanont (2008), Putthapiban (1992), Qian et al. (2013), Salam et al. (2014), Srichan et al. (2009, 2008), and references therein. Ages were almost determined by the U-Pb zircon method except those indicated by (Ar) which are Ar-Ar ages. (b) The zircon ages distribution of the Phu Khat Formation compared with those of igneous activity in the western and the eastern terranes of the Nakhon Thai region. *N* is a total number of analyzed grains and *n* is total number of zircon grains with ages since the Cambrian.

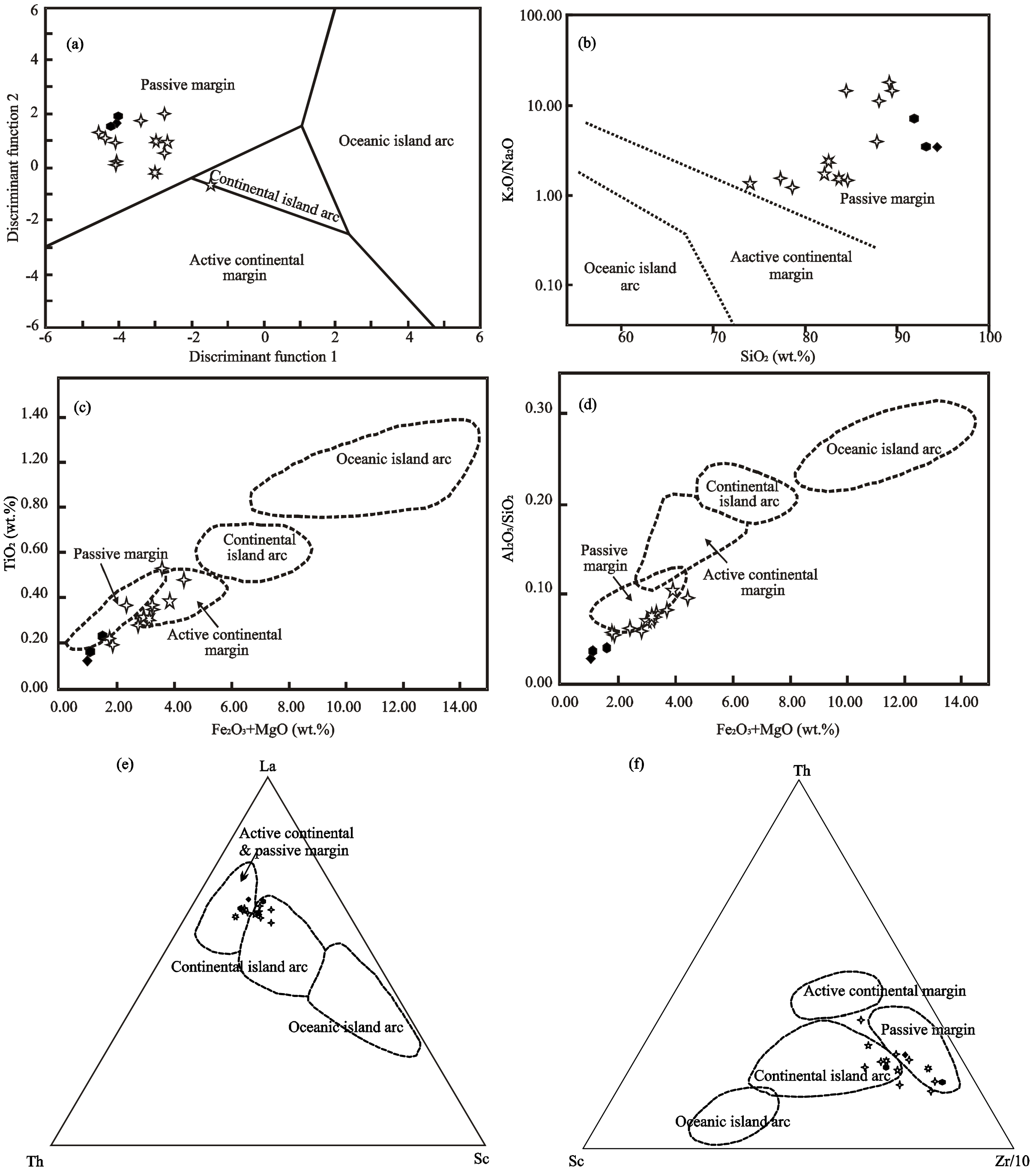

Figure 10. Geochemical composition plot for determination of tectonic setting. (a) Discriminant function plot of Bhatia (1983). (b) SiO_2 versus K_2O/Na_2O discrimination plot of Roser and Korsch (1986). (c) and (d) Plots of TiO_2, Al_2O_3/SiO_2 versus Fe_2O_3+MgO (after Bhatia, 1983) (Fe_2O_3 represents total iron). (e) and (f) Trace element plots La-Th-Sc and Th-Sc-Zr/10 of sandstone for tectonic setting discrimination (after Bathai and Crook, 1986). For symbol see Fig. 4.

The La-Th-Sc and Th-Sc-Zr/10 diagrams were presented by Bhatia and Crook (1986) as a useful tool to distinguish the sandstones derived from different tectonic settings and provenance fields. According to the La-Th-Sc plot, half of the Phu Khat Formation samples were in the field of continental island arc and the other half in the field of active continental and passive margins (Fig. 10e). In order to distinguish between active continental and passive margins, the Th-Sc-Zr/10 was employed. Figure 10f clearly indicates that the Phu Khat Formation samples were in the continental island arc and the passive margins. This result shows slight difference from the discrimination of the major element which indicates that the Phu Khat Formation is entirely deposited in the passive margin tectonic setting. This different distribution of the samples in different discrimination diagram may reflect a complex nature of tectonic setting for the Phu Khat Formation. However, the result of petrographic analysis has confirmed for the passive margin (high Qt; low F) rather than the continental island arc (low Qt; high F) as it shows high quartzoes (Qt_{60}) with low feldspar content (F_5) that is evident for the passive margin tectonic setting (Dikinson and Suczek, 1979; Schwab, 1975; Crook, 1974). Moreover, the REE chondite-normalized pattern of the Phu

Khat Formation also supported the passive margin tectonic setting. It is evident by high enrichment of LREE over HREE with pronounced negative Eu anomaly (Fig. 5d) which is contrasted with continental island arc setting that show slight enrichment of LREE over HREE with an absence or small negative Eu anomaly (Bhatia, 1985). The alternative possible explanation for the present of continental island arc setting in discrimination of trace element in this study is that it is reflected the tectonic setting of the old provenance terranes rather than the tectonic setting during the deposition of young sediment (e.g., Wang et al., 2014). The U-Pb detrital zircon dating of the Phu Khat Formation is dominated in the Triassic which is older than the depositional age of the Phu Khat Formation (the Late Cretaceous–Early Paleogene). So it may indicate that the tectonic settings derived from the plot of La-Th-Sc-Zr/10 in this study represent the tectonic setting of the old provenance terrane. It agrees with the study of Qian et al. (2013) and Barr et al. (2006, 2000) who claimed that the Triassic volcanic belt in west of the Nakhon Thai region is dominated by the continental island arc. In summary, based on the petrographic and geochemical analysis associated with the U-Pb detrital zircon age, the Phu Khat Formation is, therefore, considered to have been accumulated in the passive continental margin where the provenance is from the sedimentary rocks of recycled orogen together with felsic volcanic rocks from the old continental island arc in the western terrane.

5.3 Implication for Tectonic Evolution and Age Constraint

Since the Triassic, the Indochina Block and the Sukhothai zone had been joined together as a single continent by the closure of the Nan-Uttaradit back arc basin (Chonglakmani, 2002). In the Late Triassic the Indochina Block experienced an extensional phase which created the half garben basins with deposition of the fluvio-lacustrine Huai Hin Lat Formation (Chonglakmani and Sattayarak, 1978). While in the Sukhothai zone the Triassic Lampang Group was deposited in a marine environment (Chonglakmani, 2011). After the deposition of the Triassic sequence the continental red bed has blanketed the Indochina Block and the Sukhothai zone while western Thailand was still covered by the marine sediments in the Jurassic (Meesook and Seangseechan, 2011). The continental red bed is dominated in the Cretaceous (Racey, 2009) and is known as the Khorat Group in the Khorat Plateau or the Indochina Block. The Khorat Group extends beyond the Indochina Block to the Sukhothai zone through the Nakhon Thai region (part of the Loei-Phetchabun fold belt) and to the central plain (Morley, 2012). The Khorat Group deposited until the Mid-Cretaceous with the total thickness of more than 3 500 m (Racey et al., 1996). The inversion took place in the Mid-Cretaceous after the end of the Khorat Group accumulation (Racey, 2009; Lovatt Smith et al., 1996). The inversion in the Mid-Cretaceous was probably due to the arc collision around the western subduction margin of continental west Burma (Barber and Crow, 2009; Hall et al., 2009). The inversion in the Mid-Cretaceous led to the deposition of rock salt layers of the Maha Sarakham Formation under the hyper saline land-lock lake basin of an arid condition (Meesook, 2000; Racey et al., 1996). The basin was subsequently covered by the Phu Tok Formation in the Late Cretaceous under the desert environment (Meesook, 2011; Hasekawa et al, 2010). In the Late Cretaceous to Early Paleogene the Southeast Asian region including Thailand was subjected to a strong deformation due to collision of the Greater India with the Eurasia (Morley, 2012). The result of the apatite fission track study of the Khorat Group shows that the Khorat Group was subjected to two stages of cooling history (Upton, 1999; Racey et al., 1997). The first stage was during 65 and 45 Ma and the second between 35 and 25 Ma. Racey et al. (1997) concluded that the cooling stages were related to the folding and thrusting of the fold belt and the uplift of the Phu Phan range in the Khorat Plateau. To the west of the Nakhon Thai region, Singharajwarapan and Berry (2000) recognised the Phu Khon Kaen thrust fault that brought the sequences of the pre-Khorat Group in the Nan-Uttaradit suture zone to overlie the Khorat Group. Ahrendt et al. (1993) studied the K-Ar dating of mica in metamorphic rocks along this fault zone and concluded that the last deformational event was dated back to the Late Cretaceous (63 Ma). It is consistent with the apatite fission track data of Upton (1999) which indicates that the central age of the apatite fission track sample nearby the fault zone is the Late Cretaceous (≈73 Ma).

The Phu Khat Formation was accumulated in the Late Cretaceous to Early Paleogene in the Nakhon Thai region which is located between the Nan-Uttaradit suture zone and the Loei-Phetchabun fold belt. The main source of sediments can be derived from both terranes. However, the paleocurrent pattern, lithofacies occurrences and whole-rock geochemical data in conjunction with the U-Pb detrital zircon age dating reveal that the provenance of the Phu Khat Formation is mainly from the western terrane. The terrane west of the Nakhon Thai region was uplifted by folding and thrusting while the terrane on the east was still quiescent. This event may relate to the reactivation of pre-existing structure resulting from the renewed subduction of ocean crust along the Eurasian margin during the Late Cretaceous–Early Paleogene (Searle and Morley, 2011). The Nakhon Thai region, located at the front of thrust zone, is therefore the site of sediment accumulation eroded from the uplifted zone. It is represented by the alluvial fan facies of the lower Phu Khat Formation. This event might occur during 70 to 63 Ma as indicated by K-Ar dating and the apatite fission tract central age in the western terrane (Upton, 1999; Ahrendt et al., 1993). The accumulation of the Phu Khat Formation would extend to the Early Paleogene. This interpretation is supported by the absence of source materials from the eastern terrane in the Phu Khat Formation. Morley (2012) and Racey et al. (1997) used the apatite fission track data to constrain the age of the up-lifting event in the Loei-Pethcabun fold belt and concluded that it was uplifted by reactivation of the pre-existing structure at the Early Paleogene (~50 Ma based on apatite central age) (Morley et al., 2011) when the Greater India Block amalgamated with the Eurasia Block (Zhu et al., 2005; Rowley, 1998). We believed that during this time the Nakhon Thai region would also uplift with the Loei-Pethcabun fold belt since the present elevation of these two regions are comparable. Consequently, the depositional age of the Phu Khat Formation can be considered as the Late Cretaceous (Maastrichtian) to not younger than the Early Paleogene (Ypresian).

6 CONCLUSIONS

The petrographic and geochemical signatures together with U-Pb detrital zircon age of the clastic Phu Khat Formation from the Nakhon Thai region provide important information about provenance, possible tectonic settings, the genesis and depositional age and geotectonic evolution.

(1) The sandstone of Phu Khat Formation is characterized by immature and unsorted textures with highly unstable volcanic lithic fragments. The rocks overlie unconformably on a high textural and mineral maturity of the clastic Khao Ya Puk Formation.

(2) The petrography and whole-rock geochemistry of the sandstones of the Late Cretaceous–Early Tertiary Phu Khat Formation in the Nakhon Thai region indicate major recycled sediments with minor felsic volcanic source which was accumulated in a passive margin tectonic setting. Whereas the underlying Khao Ya Puk Formation is mainly recycled sediments and deposited in a passive margin tectonic setting which is the same as the Phu Khat Formation but with a different depositional environment.

(3) The U-Pb detrital zircon dating indicates a unique provenance of the Phu Khat Formation from the terrane west of the Nakhon Thai region where the volcanic continental arc is active predominantly in the Middle to the Late Triassic. In addition, the different pattern of detrital zircon age between the Phu Khat and underlying Khao Ya Puk Formation confirms the unconformity between these two formations.

(4) Provenance analysis suggests that the Phu Khat Formation was accumulating in the Nakhon Thai region probably from the Maastrichtian to the Ypresian time as the result of the uplifted of folding and thrusting due to the renewed subduction of ocean crust along the Eurasian Block margin and subsequently terminated when the Greater India Block amalgamated with the Eurasia Block.

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