Structure of Phu Phan Range in the Khorat Plateau: Its Apatite Fission Track Ages and Geological Syntheses

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Abstract

Phu Phan area in northeastern Thailand has been selected for apatite fission track (AFT) geochronological analyses. Geological transects have been made over the region. Non-marine Mesozoic continental sediments only 4 formations have been encountered in the study area. Structurally, the rocks have been deformed and series of anticlinal structures have been encountered with their fold axes mostly trend in the northwest – southeast direction. The major fold has been displaced by a few of short left-lateral strike slip faults whose trend is in the northeast – southwest direction. Samples of the Khorat Group rocks were identified and collected for AFT analyses. The AFT result along with those of the previous studies reveals an interesting scenario. Three age ranges have been recognized viz., 78 to 60 Ma, 55 to 42 Ma, and about 37 Ma, the oldest range is a very mild event. The first episode corresponds to the movement along the northeast – southwest strike slip fault which may have been in turn caused a compressive stress within the Khorat. Two successive basins within the Khorat region may have been developed. The second episode indicates an extensive exhumation (uplift and erosion) which perhaps took place for the whole Khorat region, becoming a Khorat Plateau. The final episode is marked by the minor movement along the strike slip fault which slightly displaced the main structure of the Phu Phan area. The AFT results from this current and previous studies advocate an average exhumation rate of the Phu Phan Mountain range to be *ca.* 0.0139 mm/yr.

Keywords: Apatite fission track dating, Sandstone, Khorat Group, Exhumation, Phu Phan Ranges

1. Introduction

Khorat Plateau is an area which was affected from the tectonic events that created many folding structures and faults and exhumed later in Cretaceous and Cenozoic. Phu Phan Mountain Range which is located in the north-center of Khorat Plateau contains plentiful folding like anticlinal and synclinal structure. Besides, the area has exhumation histories after many uplift events. An apatite fission-track (AFT) study has been carried out to provide an insight into the timing and mechanism that drove basin formation during the Tertiary

Apatite fission track (AFT) dating is a method of the low-temperature thermo-chronology that has been widely used for constraining low-temperature thermal histories. This technique used for understanding thermal history of the area which was affected from tectonism using the spontaneous tracks decay of U-238 in apatite to date the time of rock cooling below the closure temperature (Gleadow et al. 1986).

Carter et al. (1995) is the first person who started investigating the thermal history of sandstone on Khorat Plateau by using apatite and zircon fission track. His ZFT study revealed the maximum age of possibly stratigraphic age of Phra Wihan Formation which ranged from 125 to 160 Ma. However, his AFT study is still going on. After that, Racey et al. (1997) and Upton (1999) continued studying the AFT in Khorat Group sandstone, mainly in Huai Hin Lat, Nam Phong, Phu Kradung, Phra Wihan, Sao Khua, Phu Phan, and Khok Kraut Formation, and some of the granite on the western edge of Khorat Plateau and north-western part of Phu Phan Mountain Range.

The location of study area covers on Phu Phan Mountain Range where the Khorat Plateau, Northeastern Thailand is located. The study area is approximately 500 km northeast of Bangkok, the capital city of Thailand (Figure 1). The sampling sites are displayed on Figure 2 and grid reference with some of description in Table 1. In addition to their location relative to the Phu Phan Mountain, fieldwork sited were also selected based on their rock type, elevation and folded structure (Figure 2).

2. Geological Background

2.1 Regional Physiography

The Phu Pan Range is the long and narrow range almost in the middle portion of the Khorat Plateau and trends in the NW-SE direction. The range also extends to Savannakhet and Salavan in southern Lao PDR. Generally, it is a range of hills dividing the Khorat Plateau of the Esan region into two basins: the northern Sakhon Nakhon Basin, and the southern Khorat Basin. The Phu Phan Mountains rise above the Plateau and are not prominent. They straddle most of the provinces of northern and eastern Isan, including Khon Kaen, Nong Bua Lamphu, Udon Thani, Sakon Nakhon, Nakhon Phanom, Kalasin, Roi Et, Maha Sarakham, Mukdahan, Amnat Charoen, and Ubon Ratchathani Province. The highest elevation of the Phu Phan Range is the 641-m high summit known as Phu Lang Ka. It is located in Nakhon Phanom Province. Other important peaks are 624 m high Phu Mai Hia in Mukdahan Province and the 563-m high summit known as Phu Langka Nuea in Nakhon Phanom Province.

2.2 Regional Stratigraphy

Based upon the current lithological and stratigraphical investigations, the Phu Phan Mountain Range study area consists of 5 formations, from old to young, are Phu Kradung, Phra Wihan, Sao Khua, Phu Phan, and Khok Kruat Formations, respectively. Figure 3 shows the correlation of the litho-stratigraphical column between Khorat Group (Racey 2009, Department of Mineral Resources 2014) and Phu Phan Mountain from this study.

2.3 Regional Structures

Chuaviroj (1997) suggested 3 deformations of the Mesozoic rocks of the Khorat Plateau from Landsat TM5 imagery as briefly are: 1) N-S fold axes trends from the suturing of Shan Thai to Indochina. It is possibly Late Cretaceous in age. 2) NW-SE trend from the collision between India and Eurasia and produced the Phu Phan Range. and 3) Possibly NE-SW trend during the later stages of the Himalayan Orogeny. The Phu Phan Mountain Structural Domain is NW-SE trending and only the southeastern end is extended into Laos PDR at Savannakhet and Salavan province. The northeastern flank is followed the Mae Khong River. The basement of basin is formed as a half graben with boundary fault along Mae Khong River.

Table 1. Sample locations of sandstones**.**

Sample	Location	Elevation (m) [1]	Formation [2]	Stratigraphic age (Ma) [3]
PP01	16°48'18"N 103°57'53"E	239	Phu Kradung	Late Jurassic (163.5-145)
PP10	16°28'42"N 104°31'09"E	191	Phu Phan	Early Cretaceous (145-100.5)
PP15	16°11'41"N 104°51'35"E	217	Phu Phan	Early Cretaceous (145-100.5)
PP16	15°47'53"N 105°23'33"E	120	Phu Phan	Early Cretaceous (145-100.5)
PTT14	16°45'39"N 104°7'46"E	380	Phu Kradung	Late Jurassic (163.5-145)
PTT15	16°54'12"N 104°10'56"E	282	Phu Phan	Early Cretaceous (145-100.5)

Note: *1. Elevation based on GPS (Garmin) which accurate from an elevation pin at Phu Mu Forest Park, Mukdahan Province, Thailand (Veeravinantanakul, 2018); 2. Data based on Veeravinantanakul (2018); 3. Stratigraphic age based on Department of Mineral Resources (2014).*

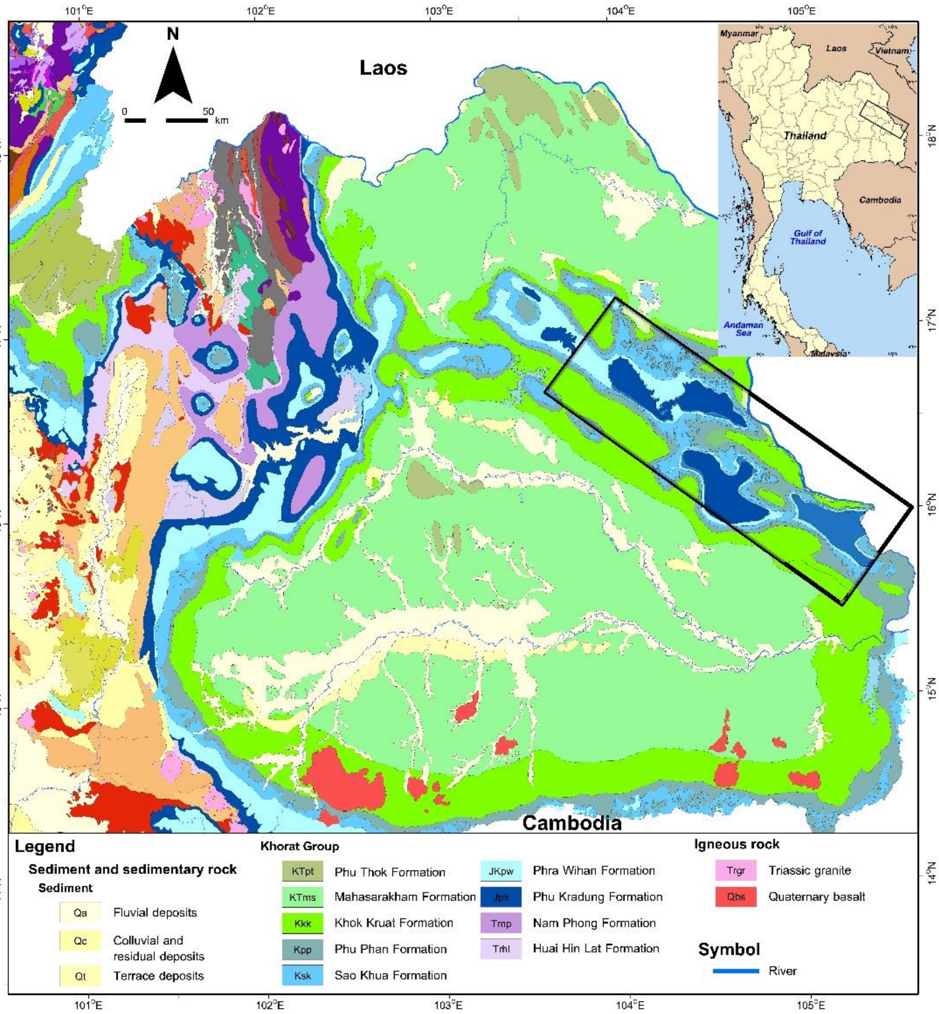

Figure 1. A simplified geological map of northeastern Thailand based on 1:250,000 geological map of Department of Mineral Resources (Department of Mineral Resources 2007). The black box is the study area in the Phu Phan Range (PPR).

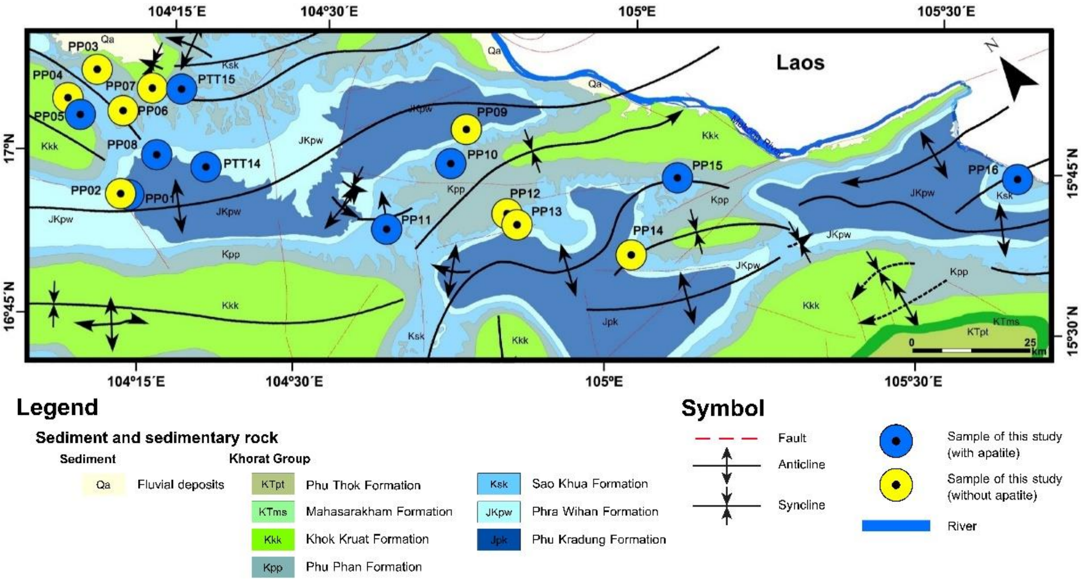

Figure 2. Geological map based on 1:250,000 map modified from Department of Mineral Resources (2007) and Veeravinantanakul (2018) showing sample locations of the study area (purple star is a sample containing apatite grains and yellow star is a sample without apatite grains).

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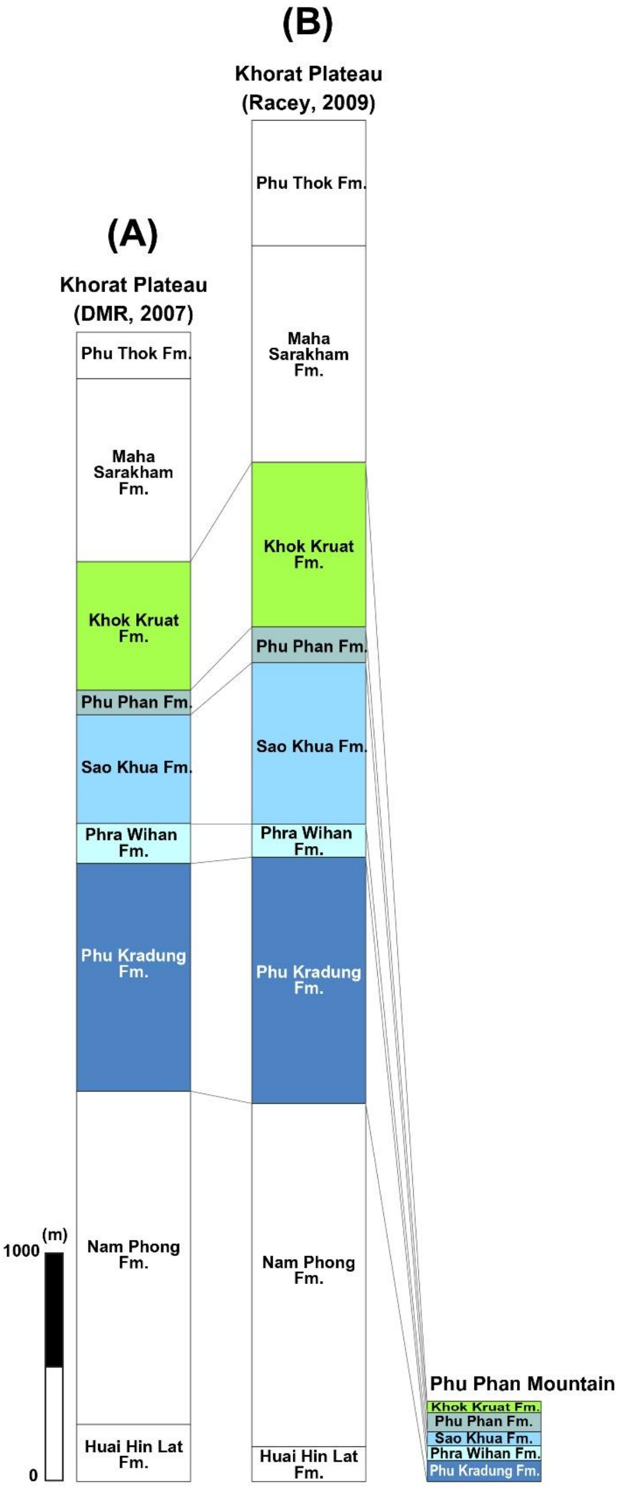

Figure 3. Composite lithostratigraphic column of the PPR study area in comparison with these of the Khorat Group by (A) Department of Mineral Resources (2014) and (B) Racey (2009).

3. Methodology

3.1 Mineral separation process and sample preparation

For apatite fission track dating, it is necessary to separate apatite from their host rocks using their characteristic properties of size, magnetism and density. The examination of petrographic thin sections is sometimes convenient to observe the presence of apatite in sample before starting the separation procedure (Tagami, et al. 1988). The mineral separation process mineral separation process contains mainly 5 steps that are crushing, sieving, panning, heavy liquid separation, and magnetic separation. After mineral separation processes are done, it is importantly to prepare the sample before AFT dating. For doing sample preparation, Tagami et al. (1988) proposed three necessary steps would be done before doing AFT analysis that are grinding with #1500 silicon carbide paper, polishing with 15 μm and 3 μm diamond paste and etching in 5 M HNO_3 at 20ºC for 20 seconds to expose the spontaneous fission tracks. These processes have been done at Kanazawa University.

3.2 Apatite fission track dating

The AFT ages of the samples are determined by counting the spontaneous tracks within an area. The measurement is carried out with the optical microscope (Eclipse E600, Nikon) at a magnification of 1000x (10x eye piece and 100 x objective lens magnifications). The software used for observing track is NIS-Elements Microscope Imaging Software.

For This study, the AFT dating carries out the LA-ICP-MS method (Donelick et al, 2005; Hasebe et al., 2004) to measure uranium concentration. The analysis has been done at Kanazawa University. The settings of laser are dimensions of the laser spot which is half a sphere obtained from the 20 μm laser spot size.

In case of detrital samples in sedimentary basins can have multiple source areas that can show a wide spread in AFT ages because of variations in apatite chemistry which may influence annealing behavior. Galbraith (2005) proposed a Poissonian distribution to test samples. If the sampled grains derived from a single source, a P(χ^2) test should contribute upper than 5% level (Yates 1934). In contrast, if grains of sample fail in test (lower than 5%), it would indicate that either the grains are from different populations (such as in detrital samples) or that the U distribution is inhomogeneous in a grain which can influence the track measurement (Galbraith 1981). However, apatite fission track (AFT) central ages in this study were carried out with IsoplotR program (Vermeesch, 2018) with zeta calibration was performed using repeated analysis on Durango apatite standard. More details on methodology can be found in Takami et al. (1988) and Veera-vinantanakul (2018).

4. Results on apatite fission track dating

4.1 Data accuracy

Durango apatite is used as standard sample of this study, yields pooled AFT age analysis as 35.6±2 Ma, where analyses from 2 pieces of large apatite crystals were crushed. The total number of track is 268 tracks in the counted area is 155,600 μm^2. AFT ages from pooled age comparing with reference age (Green 1985) at Kanazawa University laboratory. The pooled age is older than reference age from Green (1985) about 4.2 Ma (13.2%).

4.2 Results

Among these, 4 samples which contain apatite were not analyzed due to the samples contain less amount of apatite grains, so the detail data are not here in included. Therefore, AFT dating analysis was undertaken on 6 samples.

4.2.1 Phu Kradung Formation

Two samples of the Phu Phan Mountain Range study are selected for apatite fission track dating, they are sample nos. PTT14 and PP01 (Table 3). The age dispersion value for sample PTT14 is 7.9% with $P(\chi^2)$ of about 6.2%, suggesting a single population of apatite grain ages (Table 3). The apatite grains yield the AFT age derived from 36 apatite crystals analysed, Central FT age calculation to be *ca.* 77.6±4.7 Ma (Figure 5 Left). Moreover, sample no. PP01 is 0.094 of the χ^2 test with the age dispersion of 15%, verified that central FT age calculation to be 72.8±7.1 Ma, obtained from 14 apatite grains. Mean track length distribution given by sample PTT14 is about 12.84±0.7 µm (15 confined tracks) with attached standard deviation of 2.71 µm (Table 3). The track length distribution graph of sample PTT14 (Figure 5 right) conform with slow cooling from apatite partial annealing zone (APAZ). Confined tracks are not found in sample no. PP01 during the course of analysis. More details can be found in Veeravinantanakul (2018).

4.2.2 Phu Phan Formation

Four samples have been selected from the Phu Phan Formation including sample nos. PP10, PP15, PP16, and PTT15 (Table 3). AFT age obtained from 13 apatite grains sandstone (no. PP10) with value of $P(\chi^2)$ less than 1 and age dispersion of 29%. The result of analysis gives the central age of 62.6±6 Ma. Based on the radial plot of single grain age shown in two age groups can be visualized; i.e., the older is about 91.3±8.9 Ma (n=5) and the younger group is about 49.7±3 Ma (n=8). The other sandstone samples are those of nos. PP15, PP16, and PTT15, shows χ^2 test of 0.0000053 (PP15), 0.061 (PP16), and 0.072 (PTT15) with contributed age dispersion of about 26%, 1.7%, and 15%, respectively. Nevertheless, sandstone sample no. PTT15 may be possible is likely to be composed of 2 age components but the two young plots are obscure because number of tracks counted is small. The samples yield the AFT age from central age to be 50.2±3.6 Ma for sample PP15, 45.8±1.3 Ma for sample PP16, 60.8±6.7 Ma for sample PTT15. Their results were analyzed from 25 (PP15), 7 (PP16), and 5 (PTT15) apatite crystals. Confined track lengths are relatively low in sample no. PP16 (n=2) with a mean of 0.11±0.13 µm and standard deviation of about 0.18. The result is not clearly to be in any model. The other samples have not found confined track in the measurement. More details can be found in Veeravinan-tanakul (2018).

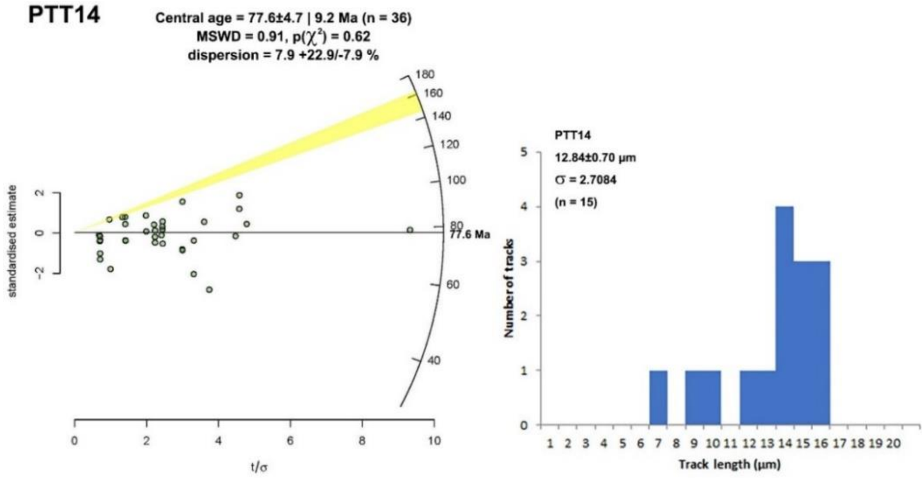

Figure 5. (Top) Radial plots from IsoPlotR program (Vermeesch 2018) illustrating the relationship between apatite single grain ages and (Bottom) the histogram showing track length distribution of the sample PTT14 assigned to the Phu Kradung Formation, Phu Phan Mountain Range. Sample no. PTT14 contain apatite with the track length 12.84±0.7 and the S.D. of 2.7084.

Table 3. Summary of obtained AFT dating results from samples of the Khorat Group in Phu Phan Mountain Range.

Sample No.	P(χ^2)	Disp (%)	AFT age (Ma)	Number of Grains	P1±1σ (Ma)	P2±1σ (Ma)	MTL±SD (μm)	nl
Phu Phan Fm.								
PP10	0.000025	29	62.6±6	13	49.7±3	91.3±8.9	-	-
PP15	0.0000053	26	50.2±3.6	25	-	-	-	-
PP16	0.061	1.7	45.8±1.3	7	-	-	10.11±0.18	2
PTT15	0.072	15	60.8±6.7	5	-	-	-	-
Phu Kradung Fm.								
PP01	0.094	15	72.8±7.1	14	-	-	-	-
PTT14	0.62	7.9	77.6±4.7	36	-	-	12.84±2.7	15

Note: P (χ^2) *is the chi-squared probability that the dated grains belong to a single statistical population (samples fail this test if P(χ^2) < 0.05);* ***Disp*** *gives the percentage of single-grain age dispersion;* ***nl*** *is the number of measured confined tracks;* ***MTL*** *is the average confined track length in μm with σ standard deviation.*

5. Discussion

5.1 AFT-age grouping

The sample locations and the AFT age dating results of Racey, Duddy et al. (1997) and Upton (1999) included this study central AFT age are show in Figure 6.

From the AFT age results on the Phu Phan Range from this study and previous studies, the total average AFT age is 53 Ma with the total standard deviation of 11.8. However, the AFT ages of sandstones from the Phu Phan Range fall into 3 groups by using standard deviation are 78 - 60 Ma, 55 - 42 Ma, and 37 Ma (Figure 7).

5.2 Rates of exhumation

In the AFT age (Ma) versus sample elevation (m) plot (Figure 8) shows a trend with increasing AFT ages with elevation of the Phu Phan Range by AFT age versus elevation of sample point plot from the results of Racey et al. (1997), Upton (1999), and this study. The graph depicts a positive-trending linear that give rise to almost consistent uplift rate, viz 0.0192 mm/yr, 0.0112 mm/yr, and 0.0113 mm/yr. It can be stated that on average, the rate of uplift is about 0.01 mm/year. The maximum uplift rate of the PPR study area is 0.019.

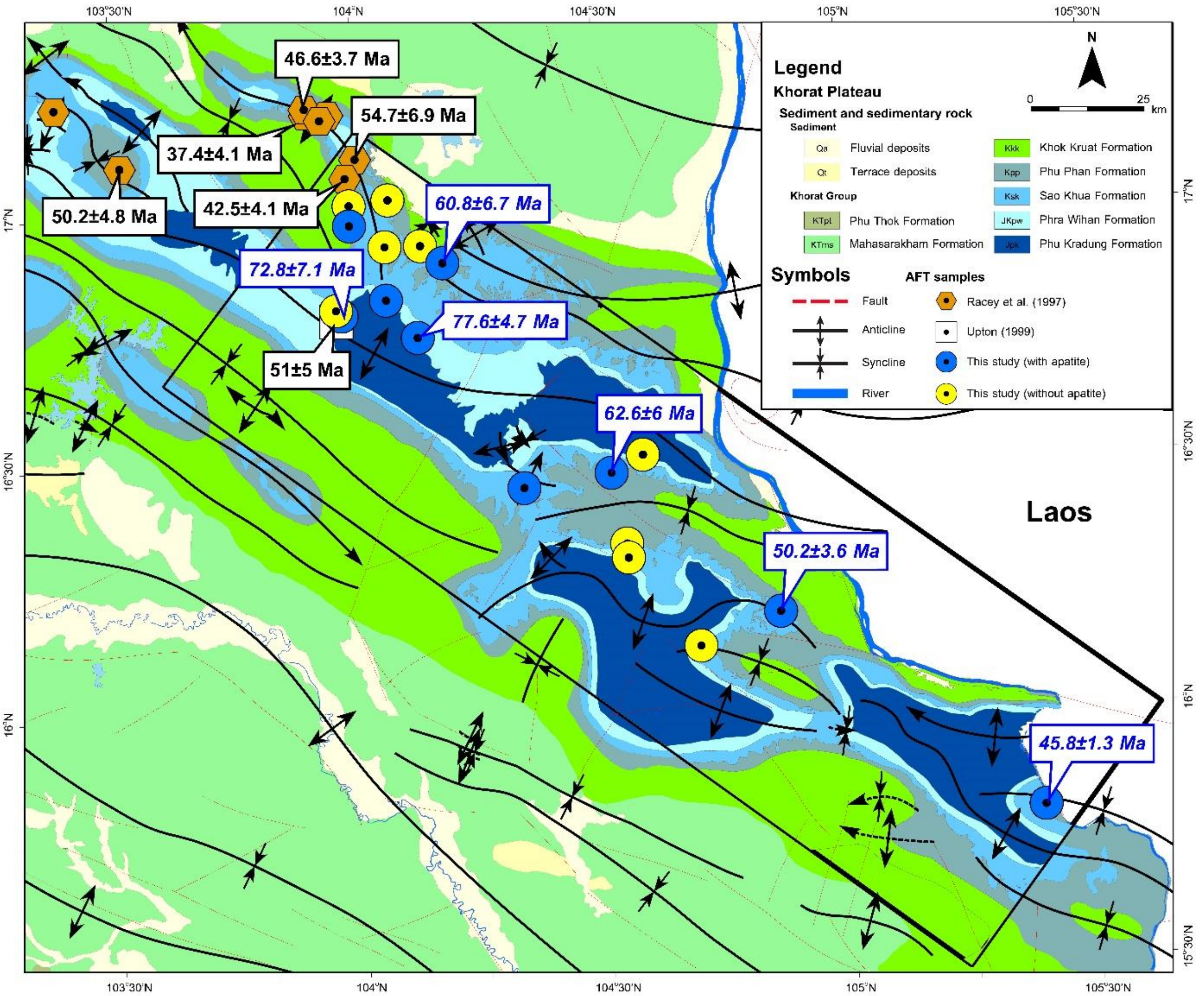

Figure 6. Geological map showing series of broad deformation structure with the major NW-SE trend based on Department of Mineral Resources (2007) and Veeravinantanakul (2018) with sample locations with AFT age results by Racey et al. (1997), Upton (1999), and this study.

6. Conclusion

This study provides the 3 events affected by tectonism in Khorat Plateau from apatite fission track dating method. Based on the current AFT and previous geochronological work, the following conclusions can be drawn as follows:

1. 78 - 60 Ma: corresponds to the NE-SE strike-slip fault movement in the Khorat.

2. 55 - 42 Ma: developed 2 basins in Khorat region that formed a Phu Phan mountain by an extensive exhumation (uplift and erosion). And the whole Khorat region became Khorat Plateau.

3. about 37 Ma: derived from the minor movement along the strike slip fault which slightly displaced the main structure of the Phu Phan area.

Tectonic uplift of Phu Phan Mountain Range has occurred since very Late Cretaceous/Early Paleogene times at an average rate of 0.0192 mm/yr. However, during Paleogene, the rate of uplift became lower, between 0.0112 mm/yr and 0.0113 mm/yr.

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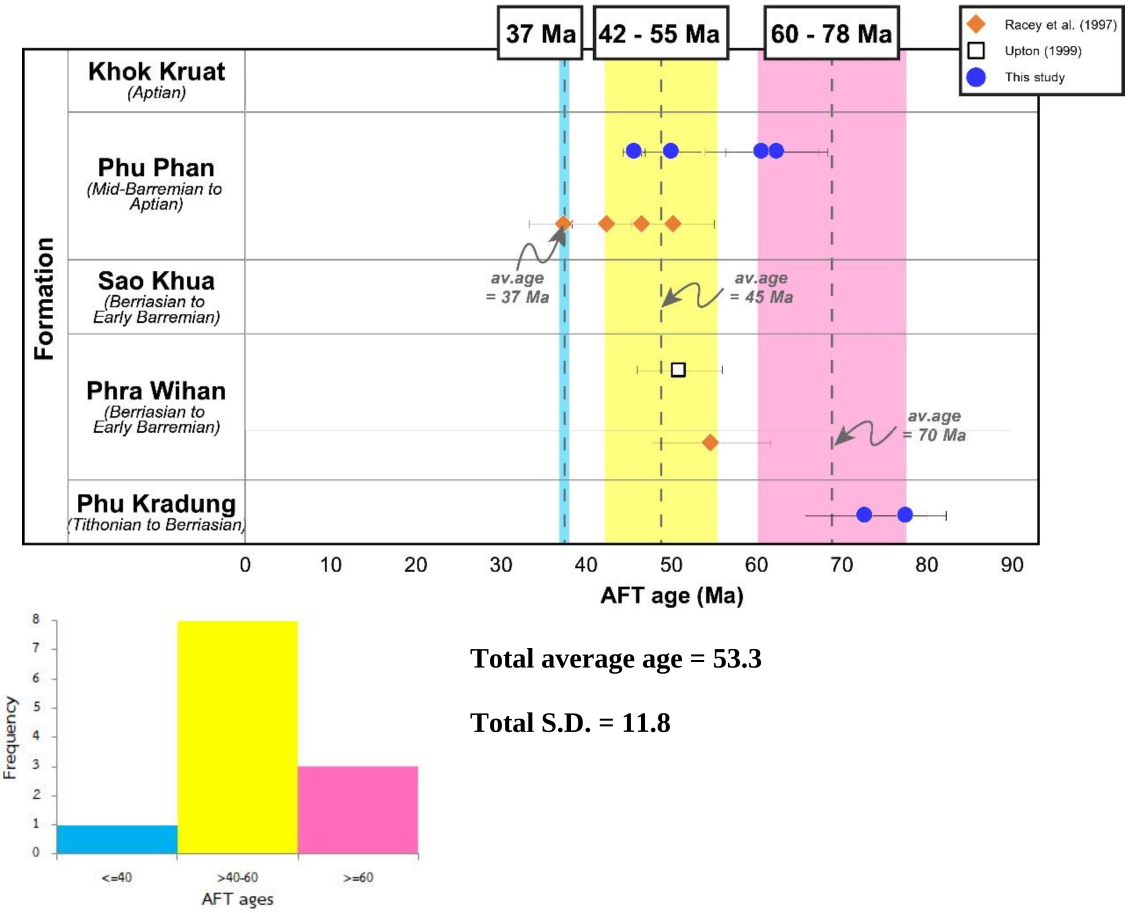

Figure 7. (top) Three AFT age groups of the sandstones of the Khorat Group in the Phu Phan Mountain Range from previous study (Racey et al. 1997, Upton 1999) included this study. Dash line showing average ages deduced from age-grouping of the result. (bottom-left) A histogram shows the number of AFT age on the Khorat Plateau in each age range with total average age = 53.3 and total S.D. = 11.8.

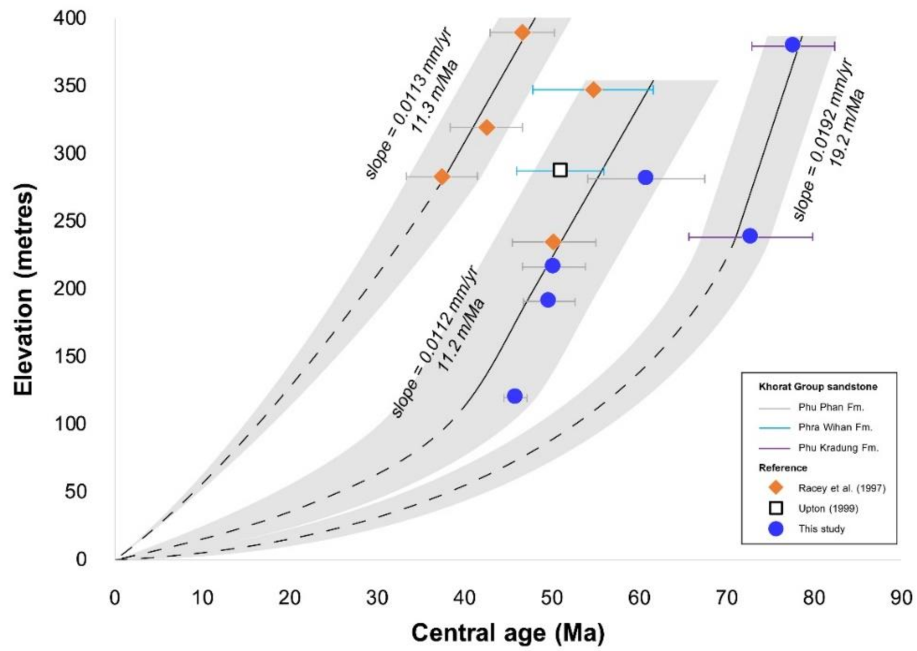

Figure 8. Apatite fission track age versus elevation plots for the Phu Phan Mountain Range from previous studies (Racey et al. 1997, Upton 1999) and this study.

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