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Tectonic setting of late Cambrian to early Ordovician meta-tuffs in Kanchanaburi Province, Western Thailand

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Abstract

Meta-tuffs are mapped as a Silurian-Devonian unit in Kanchanaburi Province, Western Thailand. These rocks were discovered and described for the first time in 1976 and mentioned in the 1:250,000 Suphanburi geologic map sheet (ND47-7). The detailed petrography and geochemistry of these rocks are still unclear and insufficient. Petrographically, the meta-tuffs can be named as a meta-quartz-K-feldspar crystal tuff and meta-lithic tuff. They are made up of pyroclasts (volcanic rock, quartz, K-feldspar, devitrified glass) and epiclasts (granitic and meta-sedimentary rocks) embedded in a very fine-grained matrix. The whole-rock composition shows enrichment in SiO_2 and K_2O and a strong depletion in CaO and Na_2O which is related to alteration and low-grade metamorphism. The meta-tuffs are divided into two groups based on immobile element classification. Group 1 rocks can be classified as dacitic-rhyolitic rocks which belong to the calc-alkaline series. Group 2 rocks are considered to be transitional rocks. Their chondrite-normalized patterns of both groups display light REE enrichment with nearly flat heavy REE and a negative Eu anomaly, typical for calc-alkaline volcanic rocks. Moreover, these meta-tuffs obviously show a negative Nb-Ta anomaly in the primitive mantle immobile-normalized spider diagram suggested volcanic arc environment. Both REE patterns and spider diagrams are coincident with the tectonic discrimination diagrams, which confirm that these meta-tuffs were formed in a volcanic arc environment. The zircon U-Pb dating of the meta-tuffs yield ages of 498.4+2.40/-3.0 Ma and 482.7+3.6/-1.0 Ma. These meta-tuffs are basement of Sibumasu Terrane. They were formed during the late Cambrian-early Ordovician possibly related to the closure of a proposed Proto-Tethys ocean along the margin of Gondwana.

Keywords: Late Cambrian-early Ordovician tuff, Proto-Tethys ocean, Sibumasu Terrane, Silurian--Devonian unit, Volcanic arc

1. Introduction

The pre-Cenozoic extrusive rocks of Thailand have been divided into four volcanic belts (Barr and Macdonald, 1991; Barr and Charusiri, 2011). However, there are occurrences of poorly investigated meta-tuffs in western Thailand. In particular, the Kanchanaburi study area, the mapped Silurian--Devonian meta-tuffs first time appeared in the 1:250,000 Suphan Buri geologic map sheet and the report (in Thai) in 1976 and 1980 respectively (Bunopas, 1976, 1980). No detailed petrography and geochemistry have been previously published. The 'Silurian-Devonian unit' in Kanchanaburi, is the Bo Phloi Formation which has a type section at Khao Yai-Ka, and consists of quartzite, shale, chert, tuff, tuffaceous sandstone, tuffaceous shale, phyllite, and thin crystalline limestone (Bunopas, 1981). "*Tentaculites* cf. *elegans*" has been reported from Khao Ka in the upper part of the Bo Phloi Formation which is probably Lower Devonian, while the unfossiliferous lower part is probably Silurian (Bunopas and Bunjitradulya, 1975). Although the formation is considered to be a result of an active margin from westward dipping subduction beneath the Shan-Thai related to a possible back-arc environment based primarily on regional stratigraphy and relative age (Bunopas, 1981; Bunopas and Vella, 1978), reliable data insufficient. The purposes of this study are to analyze the geochemical composition and classify the tephra as well as to evaluate the tectonic setting of these pyroclastic rocks in Kanchanaburi Province, Thailand.

2. Geological background

Thailand is subdivided into four major tectonic zones, from west to east: Sibumasu Terrane, Inthanon Suture Zone, Sukhothai Terrane, and Indochina Terrane (Sone and Metcalfe, 2008). The Sibumasu Terrane and Inthanon Suture Zone dominate Western Thailand. The Inthanon Suture Zone is a large accretionary complex that formed with the closure of the Palaeo-Tethys Ocean in the Triassic (Barr and Macdonald, 1991; Ueno, 1999; Sone and Metcalfe, 2008). Suture zone rocks include Permian basaltic volcanics, Carboniferous-Permian limestones, Devonian--Triassic radiolarian cherts, Triassic S-type granitoids, and mylonitic/migmatitic gneisses (Sone and Metcalfe, 2008), with Sibumasu basement thrust slices in the western part of suture zone (Metcalfe, 2013). Sibumasu Terrane (or Shan Thai) composed of Precambrian metamorphic rocks (Tabsila Gneiss) with Paleozoic sedimentary rocks (Bunopas, 1981). The Silurian-Devonian Unit in Kanchanaburi area is situated at the boundary between the Sibumasu Terrane and Inthanon Suture Zone. By using U-Pb zircon dating, Jatupohnkhongchai et al. (2020) revealed that the mapped Silurian--Devonian meta-tuffs were emplaced in the late Cambrian-early Ordovician (ca. 498-482 Ma). As a result of their age and the lack of reported Cambro-Ordovician rocks in the Inthanon Suture Zone, these meta-tuffs belong in the Sibumasu basement.

The study area (Fig. 1) is located in Muang District, Kanchanaburi Province, and was mapped between 1968 to 1971 by the German Geological Mission in cooperation with the Department of Mineral Resources of Thailand. The following are the five periods that the study area can be divided according to its age into: 1) Cambrian Chao Nen Formation which consist of biotite-muscovite-quartz schistose hornfels, quartzo-biotite schistose hornfels, quartzo-feldsparthic-biotite -muscovite schistose hornfels, calc-silicate hornfels, quartz schist, quartzite (Nanorn, 2016); 2) Ordovician Tha Manao Limestone Formation which consists of metalimestone, slate, marble, feldspathic quartzite, calc-silicate, hornfel, tremolite marble hornfels (Nanorn, 2016; Panjamart, 2016); 3) Silurian-Devonian Bo Phloi formation which consists of feldspathic quartzite, meta argillaceous sandstone, and shale (Jatupohnkhongchai, 2018); 4) Triassic S-type granite (Nanorn, 2016); and 5) Quaternary old alluvial fan, colluvial, old and recent flood plain.

3. Methodology

Representative rock samples were collected during field observation for petrographic and geochemical analyses. The petrographic studies have been carried out at the Geoscience Program Mahidol University, Kanchanaburi Campus and Department of Geological Sciences, Faculty of Science, Chiang Mai University. The bulk geochemical analysis was determined using Bruker Pioneer S4 X-ray fluorescence (XRF) spectrometer for major elements at the NAWI Graz Geocenter--Institute of Earth Sciences (Petrology and Geochemistry), University of Graz, Austria. Samples were prepared to a glass bead using one gram of sample powder and seven grams of $Li_2B_4O_7$ flux. Loss on ignition (LOI) was determined by heating the powdered rock material to 1030 °C for one hour. A selected subset of five samples were analyzed for trace and rare earth elements by an Agilent 7700 quadrupole inductively mass spectrometer (ICP-MS) at the Institute of Chemistry--Analytical Chemistry, University of Graz, Austria. Sample powders (40-50 mg) were dissolved at the cleanroom facility of the NAWI Graz Geocenter.

For U-Pb zircon age dating, sample CHK11A and sample CHK27 were selected. A plastic gold pan was used to separate the heavy minerals from the light minerals after crushing and sieving about 1-2 kg of each sample. In the divided heavy minerals, zircons are maintained. The zircon grains were then hand-picked under a binocular microscope and mounted in epoxy resin. The zircon mount was polished until the

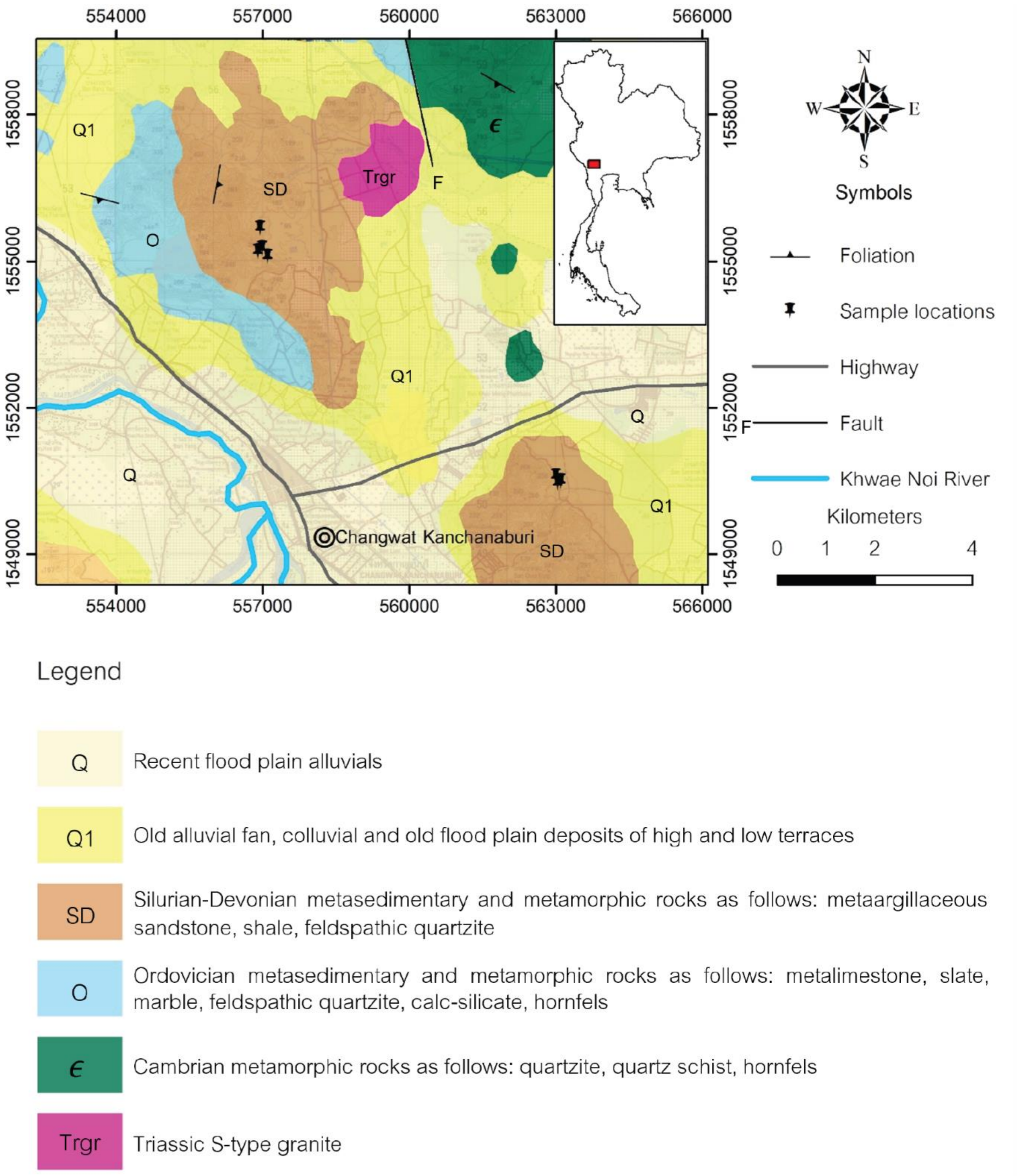

Fig. 1: Geological map of the study area and sample locations. (modified after Bunopas, 1976).

core of most of the grains was exposed. Zircon U-Pb isotopic analyses were measured using laser ablation-multi collector-inductively coupled plasma-mass spectrometryt (LA-MC--ICP-MS) at the Graz University of Technology cooperation within NAWI Graz Geocenter. The TuffZirc algorithm in the Isoplot program (Ludwig, 2008) was devised to reduce the possible effect of xenocrysts and Pb-loss in tuff zircon, and the results are displayed in Fig. 4.

4. Results

4.1 Field observation and petrography

The meta-tuffs were carefully collected from outcrops and float rocks along slope toe at Mueang District, Kanchanaburi Province. Field observation shows their outcrops are trending NW-SE direction. The elongated outcrop is around 15-20 meters high and extend more than 10 kilometers (Fig. 2a-c).

The meta-tuffs consist of various fragments which display lineation parallel to foliation (Fig. 2d). Some exposures of the meta-tuffs are weathered and altered to clay minerals and fine-grained white mica, showing a silky sheen to the foliation surface.

Fisher and Schmincke (1984) terminology for volcaniclastic particles is adapted here. Terms of volcaniclastic particles refer to the processes by which the fragments originate. The term pyroclast is commonly used to refer only to volcanic materials ejected from a volcanic vent. Epiclasts are lithic clasts and minerals released by ordinary weathering processes from pre-existing consolidated rocks, and volcanic epiclasts are clasts of older volcanic rocks derived from weathering and erosion. We use term pyroclast for all volcaniclastic particles, including volcanic epiclast, and use term epiclast for nonvolcanic particles. It is difficult to distinguish each type of clasts of the Cambrian-Ordovician tuff that have already metamorphosed and deformed.

The hand specimens are commonly greyish-white and consist of crystals and lithic fragments. They can be named as a meta-quartz-K-feldspar crystal tuff and meta-lithic tuff, showing pyroclastic texture (Fig. 3). They are made up mainly of pyroclasts and mixed with epiclasts embedded in a very fine--grained matrix. The meta-quartz-K-feldspar crystal tuff consists of pyroclasts (quartz with small amount K-feldspars) (Fig. 3e, f), while the meta-lithic tuff comprises both pyroclasts (volcanic rock, quartz, K-feldspar, devitrified glass) (Fig. 3a, d) and epiclasts (granitic and meta-sedimentary rocks) (Fig. 3b, c). The quartz crystals reacted with the melt and show rounded edges or embayed outlines due to resorption. The matrix shows foliated texture, comprising quartz, feldspar, micas, clay minerals, and sericite.

4.2 U-Pb age results

Zircon grains are primarily colorless, with a few yellow grains, and have well-developed oscillatory zoning. They're prismatic, euhedral

Fig. 2: Outcrop photographs of meta-tuff (a) at Khao Yai (The woman is 155 cm height), (b) close up view of outcrop (a) (Hammer is 35 cm long), (c) at Khao Tong (The woman is 158 cm height). (d) Meta-tuff float rock sample at Khao Yai (Hammer head is 15 cm long).

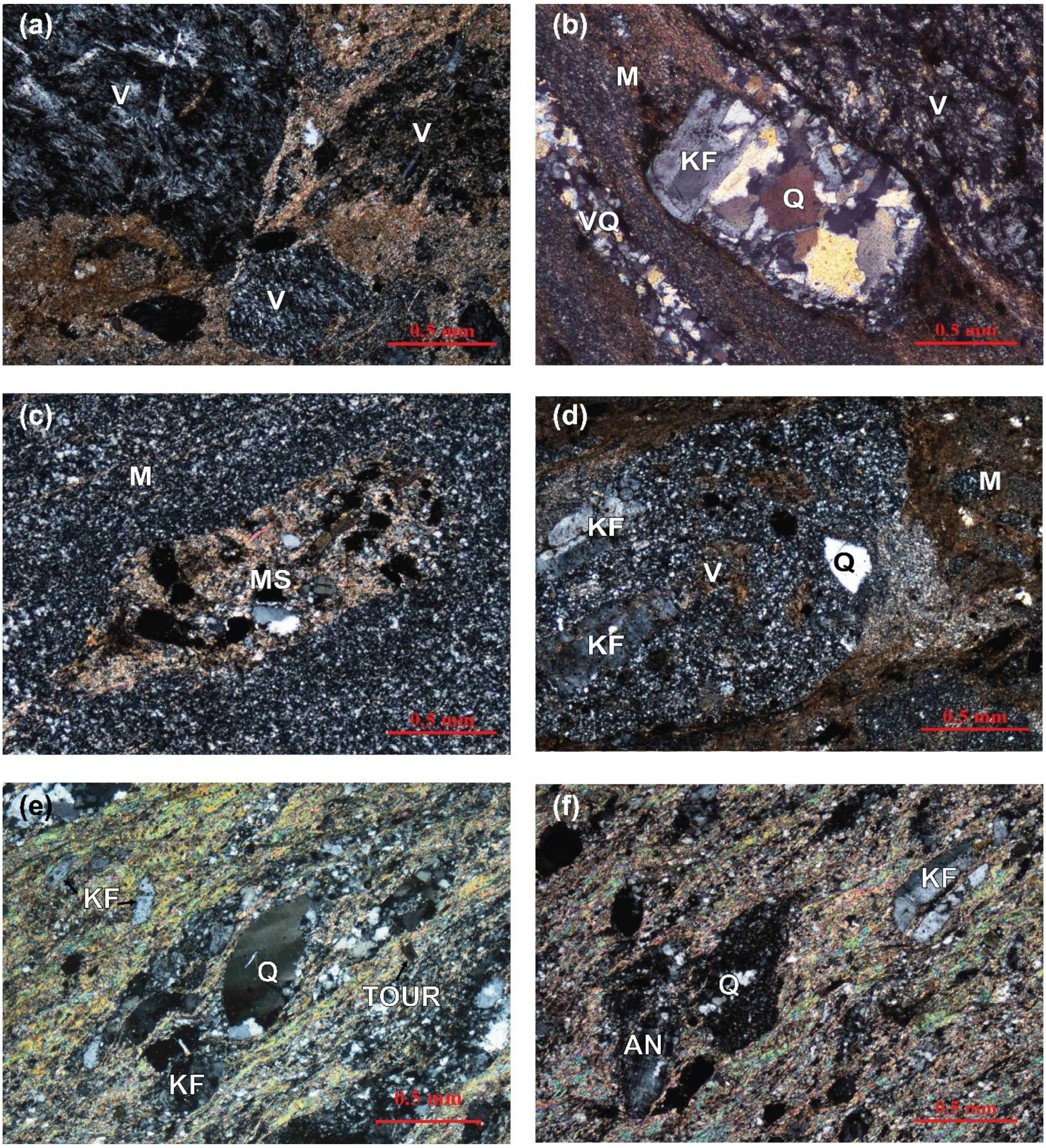

Fig. 3: Photomicrograph of meta-tuffs showing (a) pyroclast of volcanic rock containing plagioclase laths, (b) epiclast of granitic rock comprising K-feldspar and quartz, (c) epiclast of meta-sedimentary rock, (d) pyroclast of volcanic rock comprising K-feldspar and quartz, (e) pyroclasts of quartz and K-feldspar, (f) pyroclasts of quartz, K-feldspar, and anorthoclase. V=volcanic rock, M=matrix, KF=K-feldspar, Q=quartz, MS= meta-sedimentary rocks, AN=anorthoclase, Q= quartz, VQ=vein quartz, TOUR=tourmaline.

to subhedral, and come in the form of elongated grains. Based on 17 and 21 zircon grains, the Tuffzirc ages for the meta-lithic tuffs in the mapped Silurian--Devonian unit, Bo Phloi Formation are 498.4+2.40/-3.0 Ma and 482.7+3.6/-1.0 Ma, respectively (Fig. 4 and Table 1).

4.3 Major and trace elements

The geochemical data of the meta-tuffs are presented in Table 2. The whole-rock composition shows enrichments in SiO_2 and K_2O and a strong depletion in CaO and Na_2O which is related to alteration and low-grade metamorphism. They can be classified as trachyandesite,

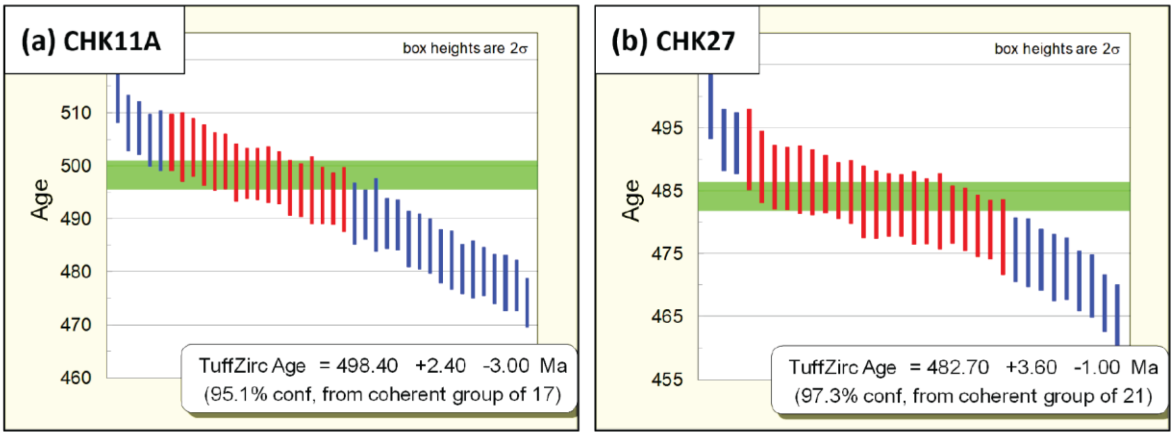

Fig. 4: TuffZirc Age calculation for meta-lithic tuffs a) CHK11A and b) CHK27. (After Jatupohnkhongchai et al., 2020).

Table 1: Summary of zircon U-Pb ages for meta-tuffs formerly assigned as Silurian-Devonian.

Formation: Bo Phloi Formation Formerly inferred age: Silurian-Devonian Sample	CHK11A (Group 2)	CHK27 (Group 1)
Zircon U-Pb data		
Number of all data (n)	39	33
Number of coherent data (n)	17	21
TuffZirc Age (Ma)	498.4+2.40/-3.0	482.7+3.6/-1.0

dacite and rhyolite in Zr/Ti-Nb/Y diagram (Fig. 5) (Pearce, 1996) which belong to the alkaline and calc-alkaline series. Chondrite--normalized REE patterns of these rocks display light REE enrichment with nearly flat heavy REE with the negative Eu anomalies, typical for calc--alkaline volcanic rocks (Fig. 6). Moreover, the REE patterns also show slightly to strongly negative Ce anomalies. The meta-tuffs obviously show negative Nb-Ta anomalies in their primitive mantle-normalized spider diagrams, which indicate magmatic arc signature (Fig. 7). Most samples fall in the volcanic arc granites field in the granite discrimination diagrams (Fig. 8) (Pearce, 1984). The Th-Hf-Ta, Th-Zr-Nb, and Th-Hf-Zr discrimination diagrams likewise show that all of the meta-tuffs fall in the calc-alkaline basalt field (Fig. 9) (Wood, 1980).

5. Discussion and Conclusion

Petrographically, the meta-tuffs from Kanchanaburi can be named as a meta-quartz--K-feldspar crystal tuff and meta- lithic tuff. They are made up of pyroclasts (volcanic rock, quartz, K-feldspar, devitrified glass) and epiclasts (granitic and meta-sedimentary rocks) embedded in a very fine-grained matrix. The matrix shows foliated texture and comprises quartz, feldspar, clay minerals, micas, and sericite, that is probably reflecting the influence of low-grade metamorphism. Geochemically, the meta-tuffs can divide into two groups. Group 1 rocks can be classified as dacite-rhyolite which belong to calc-alkaline series. Group 2 rocks are considered to be transitional rocks because there is a contrast between the classification diagram and REE pattern indicating alkaline rocks and calc--alkaline rocks, respectively. The discri-mination diagram for basalts and silicic lavas also indicates that both groups are calc-alkaline affinity. The REE patterns of group 1 and 2 rocks display negative Eu anomalies that may denote the removal of plagioclase from a felsic melt by crystal fractionation or the partial melting of rock in which plagioclase is retained

Table 2. Major oxide and trace element compositions of the meta-tuffs.

Sample Number	CHK07	CHK07I2	CHK09A	CHK11A	CHK27	CHK28	CHK30
Group	1	1	1	2	1	2	1
Lithology	mQKT	mLT	mLT	mLT	mLT	mLT	mLT
Major oxide (wt%)							
SiO_2	70.51	81.76	82.24	64.00	61.54	79.84	84.19
TiO_2	0.22	0.06	0.08	0.56	0.54	0.28	0.10
Al_2O_3	15.40	9.14	7.24	17.67	18.10	9.88	7.68
FeOt	3.37	1.11	0.77	4.93	6.71	1.94	1.92
MnO	0.00	0.00	0.00	0.01	0.00	0.00	0.00
MgO	0.92	0.13	0.10	0.66	0.91	0.34	0.07
CaO	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.06	b.d.l.	b.d.l.
K_2O	6.85	6.51	5.63	9.59	8.83	6.12	5.90
Na_2O	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
P_2O_5	0.03	0.02	0.01	0.05	0.08	0.03	0.01
LOI	2.14	0.52	0.45	1.72	2.18	0.99	0.34
Total	99.46	99.25	96.53	99.20	98.96	99.42	100.22
Trace (ppm)							
Ni	15.40	2.58	1.50	11.20	12.60	5.48	2.94
Rb	225	115	98	309	272	145	104
Sr	43	140	71	44	55	54	27
Y	32.20	35.80	14.20	19.90	34.30	11.10	22.60
Zr	207	60	52	273	286	150	67
Nb	14.40	11.60	7.28	19.80	20.70	11	10.10
Sn	4.36	4.17	2.17	3.53	3.98	2.35	3.32
Ba	379	2253	852	486	546	356	122
La	33.90	28.40	13.70	27.40	47.70	12.20	11.40
Ce	53.50	53.20	17.90	27.90	88.10	24.50	19.80
Nd	22.60	27.80	9.02	17.80	41.20	7.07	10.40
Sm	3.95	5.81	2.11	3.63	7.41	1.53	2.61
Eu	0.76	1.51	0.47	0.81	1.71	0.31	0.47
Gd	4.25	5.48	2.06	3.50	6.94	1.56	2.77
Tb	0.66	0.86	0.33	0.54	1.01	0.25	0.50
Dy	3.68	4.57	1.87	2.83	5.10	1.44	2.95
Ho	0.76	0.88	0.35	0.55	0.97	0.28	0.59
Er	2.32	2.59	1.13	1.80	2.95	0.97	1.85
Tm	0.33	0.38	0.19	0.29	0.45	0.18	0.29
Yb	1.93	2.37	1.20	1.95	3.08	1.24	1.88
Lu	0.26	0.34	0.16	0.28	0.51	0.18	0.26
Hf	5.84	2.13	1.70	6.12	6.27	3.29	2.21
Ta	1.40	1.21	0.82	1.52	1.59	0.84	1.07
Pb	6.30	4.98	6.07	6.95	5.73	6.21	7.71
Th	8.91	22.20	14.50	12.40	16.70	6.43	9.63
U	1.15	0.70	1.30	2.70	3.08	1.35	0.62
La_N/Sm_N	0.99	1.71	1.34	1.47	1.76	1.12	0.80
Sm_N/Yb_N	0.12	0.18	0.06	0.08	0.17	0.04	0.08
Eu/Eu*	0.26	0.26	0.24	0.24	0.25	0.23	0.25
Nb/Y	0.45	0.32	0.51	1.00	0.60	0.99	0.45
Zr/Ti	0.09	0.10	0.07	0.05	0.05	0.05	0.07

Explanation of abbreviations: mQKT=meta-quartz-K-feldspar crystal tuff; mLT=meta-lithic tuff; FeOt=FeO+Fe_2O_3; b.d.l.=below detection limit.

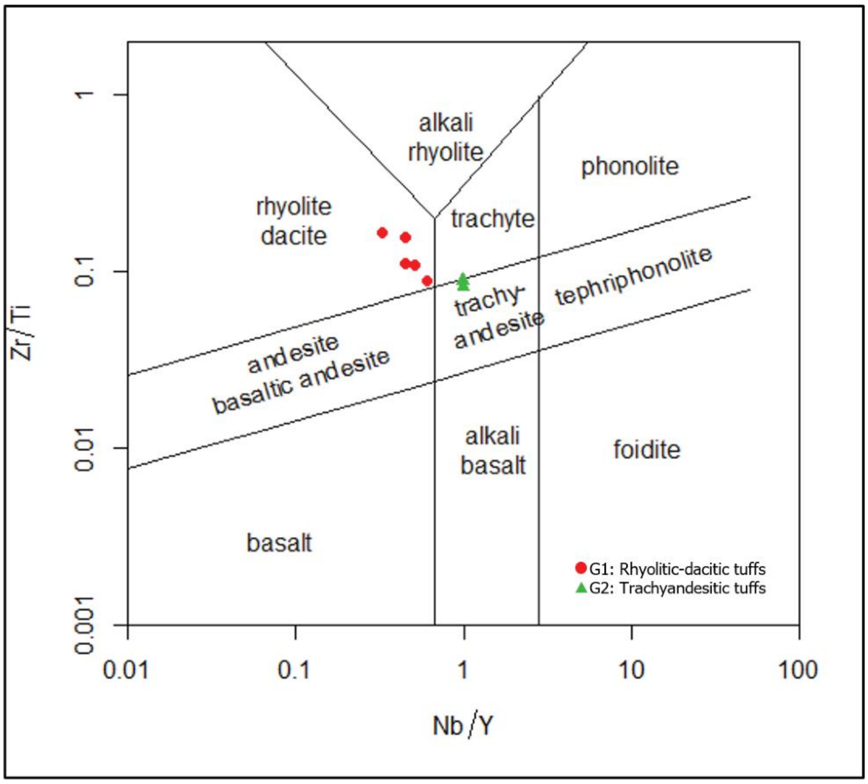

Fig. 5: The Nb/Y vs. Zr/Ti diagram for meta-tuffs (Pearce, 1996; Janoušek, 2006).

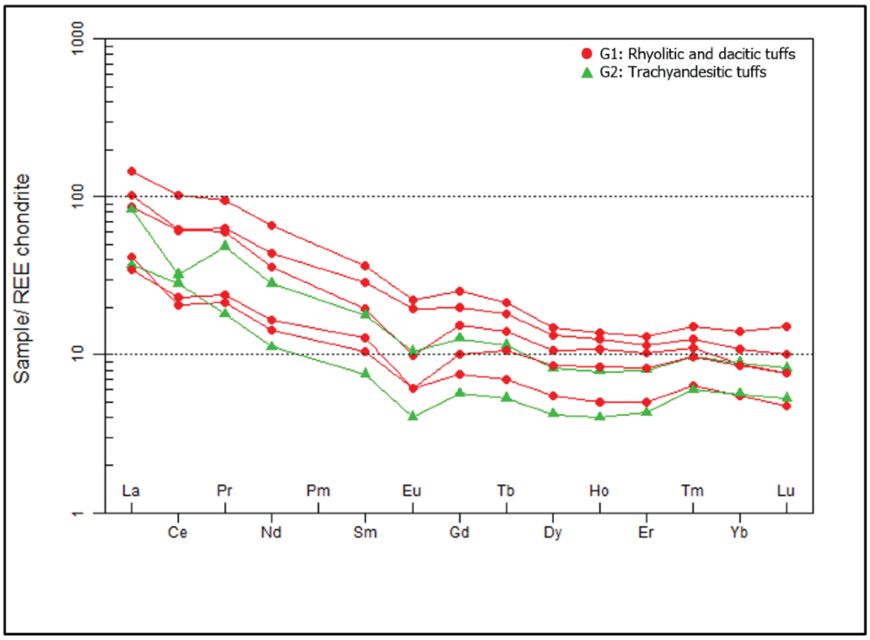

Fig. 6: Chondrite-normalized REE diagram for meta-tuffs (Nakamura, 1974; Janoušek, 2006).

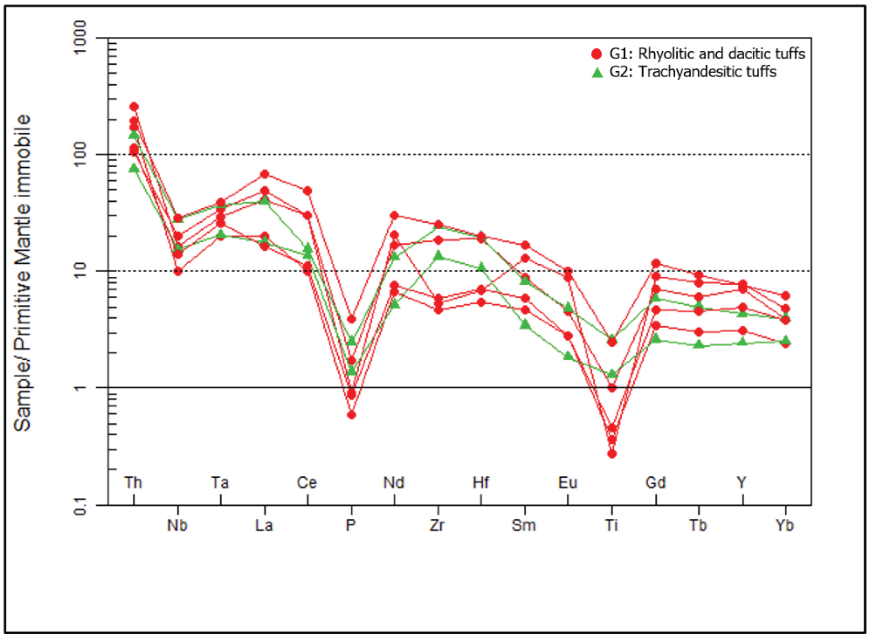

Fig. 7: Primitive mantle-normalized spider diagrams for meta-tuffs (Sun and McDonough, 1989; Janoušek, 2006).

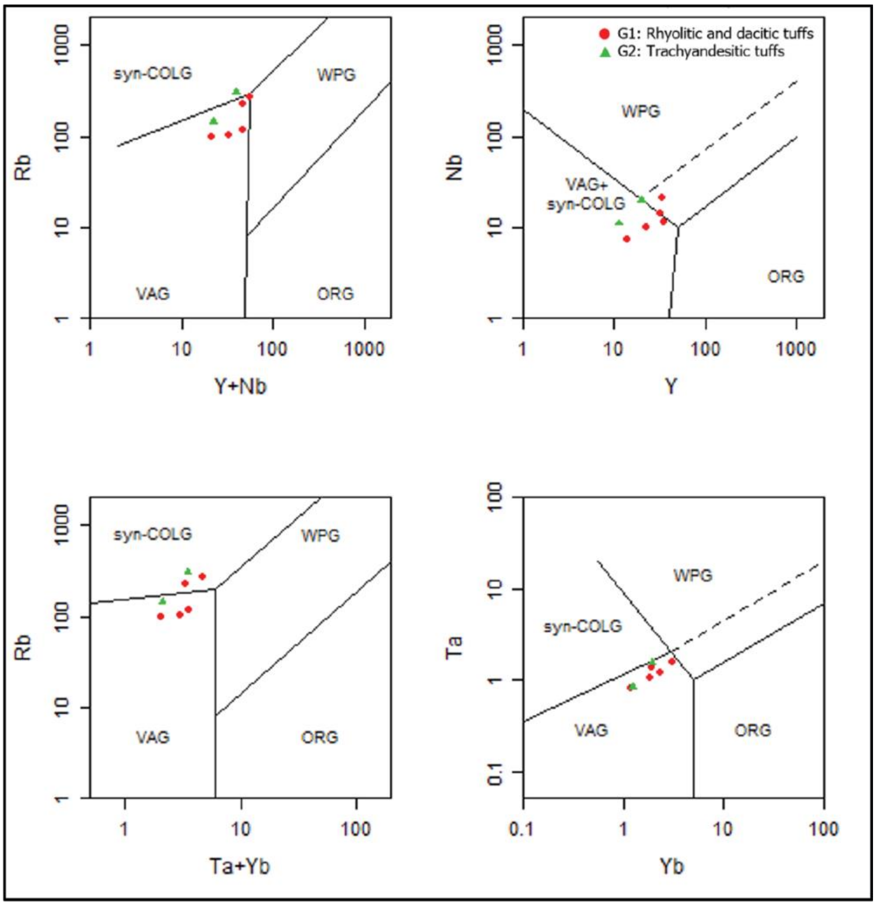

Fig. 8: The Rb-Y-Nb and Rb-Yb-Ta tectonic discrimination diagrams for granites (Pearce et al., 1984; Janoušek, 2006). VAG=volcanic arc granites, WPG=within-plate granites, syn-COLG=syn-collisional granites, ORG=oceanic-ridge granites.

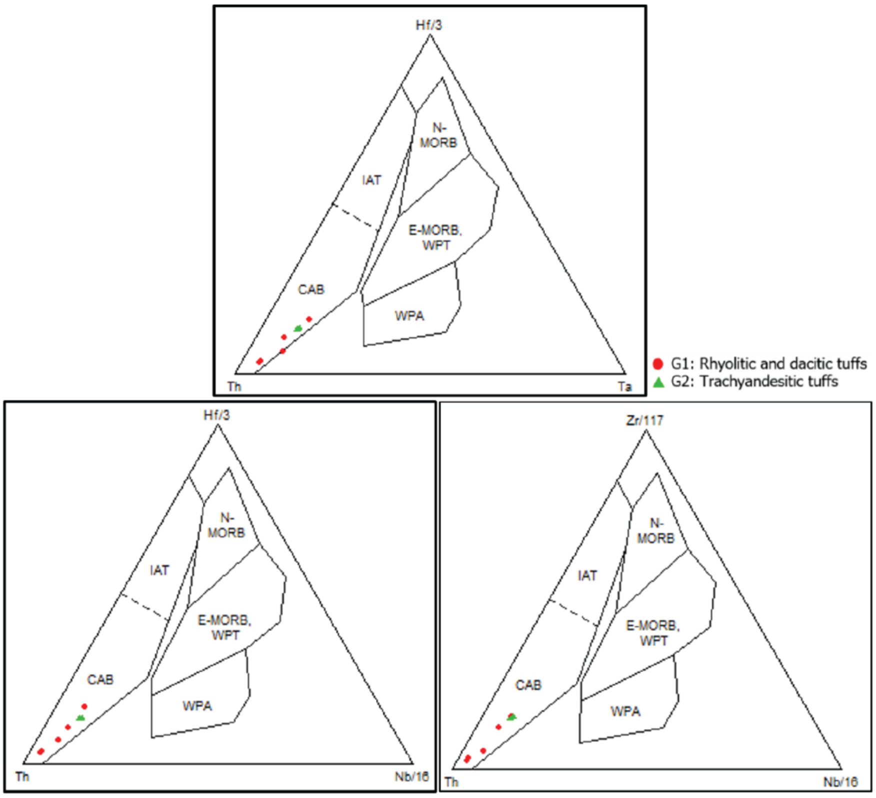

Fig. 9: The Th-Hf-Ta, Th-Zr-Nb, Th-Hf-Nb discrimination diagram for basalts and silicic lavas (Wood, 1980; Janoušek, 2006). WPT=within-plate tholeiites, WPA=within-plate alkaline basalts, CAB=calc-alkaline basalts (Hf/Th < 3), IAT=island-arc tholeiites or primitive arc tholeiites (Hf/Th > 3).

in the source (Weill and Drake, 1973; Drake and Weill, 1975). The negative Ce anomalies possibly indicate a subducted slab of sediment migrated into the mantle wedge source region of the arc because Ce^{3+} is generally fractionated from other REEs to Ce^{4+} under oxidizing conditions in near-surface environments (Class and Roex, 2008).

In the Sibumasu Terrane, Thailand, Cambrian-Ordovician magmatism is rarely found. The zircon U-Pb dating of Kao Tao gneiss in Hua Hin area (Lin *et al*., 2013) and Khao Dat Fa granite in Khanom area (Kawakami *et al*., 2014) yields ages of 501± 7 Ma and 477±7 Ma, respectively. According to our U-Pb zircon dating, the meta-tuffs are 498.4+2.40/-3.0 Ma and 482.7+3.6/-1.0 Ma. These meta-tuffs (ca. 498-482 Ma) support the Cambrian Kao Tao gneiss and Ordovician Khao Dat Fa granite, which related to the closure of a Proto-Tethys (Lin *et al*., 2013). These meta-tuffs mark the most significant magmatic event in that period and represented the Sibumasu basement.

Therefore, the synthesis of all data suggests that group 1 and 2 rocks were emplaced in a volcanic arc environment possibly related to the closure of a Proto-Tethys ocean along the margin of Gondwana in the late Cambrian to early Ordovician (Fig. 10), extending from Turkey, Iran, Tibetan Plateau, Tengchong, Baoshan, Western Thailand (Ustaomer et al., 2009; Ramezani & Tucker, 2003; Cawood et al., 2007; Zhao et al., 2017; Zhang *et al*., 2019; Wang et al., 2012; Wang *et al*., 2013; Lin et al., 2013; Kawakami et al., 2014; Zhu et al., 2012; Hu et al., 2013; Ding et al., 2015).

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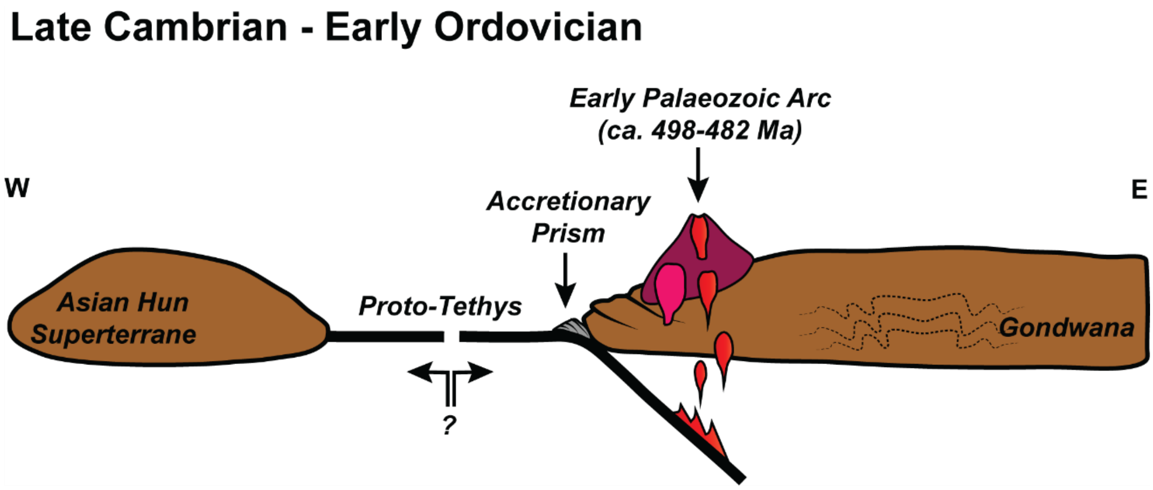

Fig. 10: Cartoon showing the tectonic evolution of western margin of Gondwana from the late Cambrian-early Ordovician.

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References

Barr, S. M., & Macdonald, A. S. (1991). Toward a late Palaeozoic-early Mesozoic tectonic model for Thailand. *Journal Thai Geoscience*, 1, 11 – 22.

Barr, S. M., & Charusiri, P., (2011). Volcanic rocks. In: Ridd, M. F., Barber, A. J., & Crow, M. J. (Eds.), *The Geology of Thailand* (pp. 415-439). Geological Society of London.

Bunopas, S., (1976). Geologic map of Changwat Suphanburi, Sheet ND 47-7. Geologic map of Thailand, Series 1:250,000. Department of Mineral Resources, Bangkok.

Bunopas, S., (1980). *Geological Survey Report No 2, Sheet Suphan Buri (ND 47-7), Scale 1:250,000.* Department of Mineral Resources, Thailand.

Bunopas, S. (1981). *Paleographic history of western Thailand and adjacent parts of Southeast Asia: A plate tectonics interpretation* (Doctoral dissertation). Victoria University of Wellington, New Zealand.

Bunopas, S., & Bunjitradulya, S. (1975). Geology of Amphoe Bo Phloi north Kanchanaburi with special notes on the Kanchanaburi Series. *Journal of Geological Society of Thailand*, 1, 51-67.

Bunopas, S., & Vella, P. (1978). Late Palaeozoic and Mesozoic structural evolution of northern Thailand, a plate tectonic model. In *Regional conference on geology and mineral resources of Southeast Asia 3*(pp. 133-140).

Cawood, P. A., Johnson, M. R., & Nemchin, A. A. (2007). Early Palaeozoic orogenesis along the Indian margin of Gondwana: Tectonic response to Gondwana assembly. *Earth and Planetary Science Letters*, *255*(1-2), 70-84.

Class, C., & le Roex, A. P. (2008). Ce anomalies in Gough Island lavas—trace element characteristics of a recycled sediment component. *Earth and Planetary Science Letters*, *265*(3-4), 475-486.

Ding, H., Zhang, Z., Dong, X., Yan, R., Lin, Y., & Jiang, H. (2015). Cambrian ultrapotassic rhyolites from the Lhasa terrane, south Tibet: evidence for Andean-type magmatism along the northern active margin of Gondwana. *Gondwana Research*, *27(4)*, 1616-1629.

Drake, M. J., & Weill, D. F. (1975). Partition of Sr, Ba, Ca, Y, Eu^{2+}, Eu^{3+}, and other REE between plagioclase feldspar and magmatic liquid: an experimental study. *Geochimica et Cosmochimica Acta*, *39*(5), 689-712.

Fisher, R.V., & Schmincke, H.U. (1984) *Pyroclastic Rocks.* Springer Berlin Heidelberg, New York.

Hu, P., Li, C., Wang, M., Xie, C., & Wu, Y. (2013). Cambrian volcanism in the Lhasa terrane, southern Tibet: record of an early Paleozoic Andean-type magmatic arc along the Gondwana proto-Tethyan margin. *Journal of Asian Earth Sciences, 77*, 91-107.

Janoušek, V., Farrow, C. M., & Erban, V. (2006). Interpretation of whole-rock geochemical data in igneous geochemistry: introducing Geochemical Data Toolkit (GCDkit). *Journal of Petrology*, *47*(6), 1255-1259.

Jatupohnkhongchai, S. (2018). *The discovery of ignimbrite and associates in Western Shan-Thai, Kanchanaburi* (Unpublished undergraduate thesis). Mahidol University, Kanchanaburi campus, Thailand [In Thai].

Jatupohnkhongchai, S., Salyapongse, S., Phajuy, B., Gallhofer, D., & Hauzenberger, C. (2020). Pyroclastic rocks from Kanchanaburi and Uthai Thani

Province, Inthanon Zone, Western Thailand. In *EGU General Assembly Conference Abstracts* (p. 19604).

Kawakami, T., Nakano, N., Higashino, F., Hokada, T., Osanai, Y., Yuhara, M., Charusiri, P., Kamikubo, H., Yonemura, K., & Hirata, T. (2014). U-Pb zircon and CHIME monazite dating of granitoids and high-grade metamorphic rocks from the Eastern and Peninsular Thailand—A new report of Early Paleozoic granite. *Lithos*, *200*, 64-79.

Lin, Y. L., Yeh, M. W., Lee, T. Y., Chung, S. L., Iizuka, Y., & Charusiri, P. (2013). First evidence of the Cambrian basement in Upper Peninsula of Thailand and its implication for crustal and tectonic evolution of the Sibumasu terrane. *Gondwana Research*, *24*(3-4), 1031-1037.

Ludwig, K. R. (2008). *Manual for isoplot 3.7.* Berkeley Geochronology Center Special Publication.

Metcalfe, I. (1984). Stratigraphy, paleontology and paleogeography of the Carboniferous of Southeast Asia. *Mémoires de la Société géologique de France (1924)*, (147), 107-118.

Metcalfe, I. (2013). Gondwana dispersion and Asian accretion: Tectonic and palaeogeographic evolution of eastern Tethys. *Journal of Asian Earth Sciences*, *66*, 1-33.

Nanorn, S. (2016). *Increasing grades of metamorphism due to the intrusion of S-type granite pluton in Khao Tham (Khun Krai) and adjacent areas, Maung district, Kanchanaburi province* (Unpublished undergraduate thesis). Mahidol University, Kanchanaburi campus, Thailand.

Panjamart, H. (2016). *A Study on Structural Geology in Khao Noen Prang, Khao Hua Lan, KhaoPhu Rang and Khao Phra Tumbon Kaeng Sian, Amphoe Muang, Changwat Kanchanburi* (Unpublished undergraduate thesis). Mahidol University, Kanchanaburi campus, Thailand.

Pearce, J. A. (1996). A user's guide to basalt discrimination diagrams. *Trace element geochemistry of volcanic rocks: applications for massive sulphide exploration. Geological Association of Canada, Short Course Notes*, *12*(79), 113.

Pearce, J. A., Harris, N. B., & Tindle, A. G. (1984). Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of petrology*, *25*(4), 956-983.

Ramezani, J., & Tucker, R. D. (2003). The Saghand region, central Iran: U-Pb geochronology, petrogenesis and implications for Gondwana tectonics. *American journal of science*, *303(7)*, 622-665.

Sone, M., & Metcalfe, I. (2008). Parallel Tethyan sutures in mainland Southeast Asia: new insights for Palaeo-Tethys closure and implications for the Indosinian orogeny. *Comptes Rendus Geoscience*, *340*(2-3), 166-179.

Ueno, K. (1999). Closure of the Paleo-Tethys caused by the collision of Indochina and Sibumasu. *Chikyu Monthly*, *21*, 832-839 [in Japanese].

Ustaömer, P. A., Ustaömer, T., Collins, A. S., & Robertson, A. H. (2009). Cadomian (Ediacaran–Cambrian) arc magmatism in the Bitlis Massif, SE Turkey: magmatism along the developing northern margin of Gondwana. *Tectonophysics*, *473*(1-2), 99-112.

Wang, X., Zhang, J., Santosh, M., Liu, J., Yan, S., & Guo, L. (2012). Andean-type orogeny in the Himalayas of south Tibet: Implications for early Paleozoic tectonics along the Indian margin of Gondwana. *Lithos*, *154*, 248-262.

Wang, Y., Xing, X., Cawood, P. A., Lai, S., Xia, X., Fan, W., Liu, H., & Zhang, F. (2013). Petrogenesis of early Paleozoic peraluminous granite in the Sibumasu Block of SW Yunnan and diachronous accretionary orogenesis along the northern margin of Gondwana. *Lithos*, *182*, 67-85.

Weill, D. F., & Drake, M. J. (1973). Europium anomaly in plagioclase feldspar: experimental results and semiquantitative model. *Science*, *180*(4090), 1059-1060.

Wood, D. A. (1980). The application of a ThHfTa diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary Volcanic Province. *Earth and planetary science letters*, *50*(1), 11-30.

Zhang, L. K., Li, G. M., Santosh, M., Cao, H. W., Dong, S. L., Zhang, Z., Fu, J. G., Xia, X. B., Huang, Y., Liang, W., & Zhang, S. T. (2019). Cambrian magmatism in the Tethys Himalaya and implications for the evolution of the Proto-Tethys along the northern Gondwana margin: A case study and overview. *Geological Journal*, *54*(4), 2545-2565.

Zhao, T., Feng, Q., Metcalfe, I., Milan, L. A., Liu, G., & Zhang, Z. (2017). Detrital zircon U-Pb-Hf isotopes and provenance of Late Neoproterozoic and Early Paleozoic sediments of the Simao and Baoshan blocks, SW China: Implications for Proto-Tethys and Paleo-Tethys evolution and Gondwana reconstruction. *Gondwana Research*, *51*, 193-208.

Zhu, D. C., Zhao, Z. D., Niu, Y., Dilek, Y., Wang, Q., Ji, W. H., Dong, G. C., Sui, Q. L., Liu, Y. S., Yuan, H. L., & Mo, X. X. (2012). Cambrian bimodal volcanism in the Lhasa Terrane, southern Tibet: record of an early Paleozoic Andean-type magmatic arc in the Australian proto-Tethyan margin. *Chemical Geology*, *328*, 290-30.