Geology and Petrochemistry of Basaltic Rocks at Khao Kradong, Burirum, NE Thailand: Implications for Rock Wool Potentials and Tectonic Setting

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Khao Kradong, part of the national park in Burirum, NE Thailand, is a small volcanic cone located within Cenozoic basaltic terrain that covers an area of about 30 km^2. Its main lava flow direction is NE. Both pahoehoe and aa are characteristic lava flows found in the area. The body of Khao Kradong itself consists almost entirely of aggregates of scorias and basaltic bombs with distinctly apparent flow units. The reliable age by whole-rock Ar/Ar dating method is 1 Ma. The field criteria of flows are pahoehoe flow and vesicular texture.

In each flow unit, the surface is reddish brown, vesicular and highly weathered. But beyond the surface, it is grayish to chocolate black, dense and massive aphyric basalt. Remote-sensing information reveals at least six main flow layers. Detailed petrographic study of the basalt from major layer numbers 4 and 5 in an ascending order indicate that the two flow layers have similar mineralogy and texture with olivine microphenocrysts dominant. The groundmass comprises Ca-plagioclase, clinopyroxene, ilmenite, magnetite, apatite and glassy materials. The other textures are vesicular, intersertal, trachytic, glomeroporphyritic and ophitic. However, the contrast between flow layer numbers 4 and 5 is the anorthite content in the plagioclase. The anorthite content of flow layer number 4 varies from 52 to 66 but the anorthite content of flow layer number 5 has a slightly wider range of 40 to 69.

Geochemical results suggest that Khao Kradong basalt is middle to subalkaline basalt. Both petrography and geochemistry indicate that the rocks are transitional from hawaiite to alkali olivine basalt. In terms of tectonic setting, Khao Kradong volcano is regarded as representative of Cenozoic basalts of continental-rift origin. Several lines of evidence, especially the basic chemical properties, indicate that Khao Kradong basalt has good potential for rock wool material. The presense of fayalite (Fe-olivine) as a major phenocrystic constituent can serve as a guide line for rock-wool basalt exploration in the regional reconnaissance survey.

Key words: Petrochemistry, Khao Kradong, Burirum, rock wool and tectonic.

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ธรณีวิทยาและศิลาเคมีของหินบะซอลต์ที่เขากระโดง บุรีรัมย์ ภาคตะวันออกเฉียงเหนือของประเทศไทยที่ส่งผลถึงศักยภาพ ร๊อควูลและสภาพการแปรสัณฐาน

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วารสารวิจัยวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย **29(2)**

เขากระโดงซึ่งเป็นอุทยานแห่งชาติในจังหวัดบุรีรัมย์ภาคตะวันออกเฉียงเหนือของประเทศไทยเป็นเขาหินบะซอลต์ขนาดเล็กรูปกรวย ปกคลุมพื้นที่ประมาณ 30 ตร.กม. โดยมีธารหินละลายทะลักไหลไปทางทิศตะวันออกเฉียงเหนือ ซึ่งมีธารละลายชนิดที่สำคัญ ได้แก่ ธารละลายไหลพาโฮโฮและเอเอ ตัวเขากระโดงประกอบด้วยหินสกอเรียและบอมบ์บะซอลต์ผสมคลุกเคล้ากันในแต่ละชั้นหินละลาย จากการหาอายุหินทั้งก้อนด้วยวิธีอาร์กอน-อาร์กอน พบว่าอายุที่พอเชื่อถือได้คือประมาณ 1 ล้านปี จากเกณฑ์ที่ใช้พิจารณาการไหลในสนามได้จากการไหลแบบพาโฮโฮและลักษณะความเป็นเนื้อพรุนในหิน

ในแต่ละชั้นไหลมักแสดงผิวหินสีน้ำตาลแดงมีรูพรุนและมีการผุพังมาก แต่เมื่อลึกลงไปจากผิวหินเนื้อหินบะซอลต์มีสีดำปนเทาถึงชอกโกแลตเนื้อแน่นและมีผลึกที่มองไม่เห็น จากข้อมูลโทรสัมผัสแสดงว่ามีชั้นธารละลายไหลทั้งขนาด 6 ชั้น การศึกษาศิลาวรรณาของหินบะซอลต์จากชั้นหินบะซอลต์ 4 และ 5 จากล่างขึ้นบนชี้ให้เห็นว่าหินบะซอลต์หลายๆ ชั้นมีวิทยาแร่และหินคล้ายคลึงกัน โดยมีโอลิวีนเป็นแร่ดอกผลึกเล็กและเนื้อพื้นประกอบด้วย แร่แพลจิโอเคลสมีแคลเซียม ไคลโนไพ-รอคซีน อีลมีไนต์ แมกนีไทต์ อาพาไทต์และสารเนื้อแก้ว เนื้อหินอื่น ได้แก่ เนื้อรูพรุน เนื้ออินเทอร์เซอร์ทัล เนื้อธารไหล เนื้อผลึกดอกรวมและเนื้อโอฟิติก อย่างไรก็ตามระหว่างชั้นบะซอลต์ชั้น 4 และ 5 แสดงลักษณะที่ต่างกัน คือ ปริมาณอะนอไทต์ในแร่แพลจิโอเคลส โดยที่ปริมาณอะนอไทต์ของชั้นหินละลาย 4 มีค่าระหว่าง 52 ถึง 66 ส่วนในชั้นที่ 5 ปริมาณอะนอไทต์เปลี่ยนแปลงเล็กน้อย คือ ช่วงจาก 40 ถึง 69

ผลการศึกษาธรณีเคมีแสดงว่าหินบะซอลต์เขากระโดงเป็นหินบะซอลต์ชนิดอัลคาไลต่ำจนถึงปานกลาง ทั้งผลทางศิลาวรรณาและทางธรณีเคมีชี้ให้เห็นว่าหินอยู่ระหว่างหินบะซอลต์ชนิดฮาวายไอต์ถึงโลวีนแอลคาไลต์ ในแง่ของสภาพการแปรสัณฐานภูเขาไฟเขากระโดงบ่งบอกถึงหินบะซอลต์มหายุคซีโนโซอิคซึ่งกำเนิดโดยการแตกแยกในทวีป หลักฐานหลายอย่างแสดงให้เห็นว่าหินบะซอลต์จากเขานี้มีศักยภาพดีพอในการทำวัสดุร๊อควูล โดยเฉพาะจากสมบัติความเป็นเบสทางเคมีของหิน นอกจากนั้นการปรากฏของแร่ไฟยาไลต์หรือแร่โอลิวีนชนิดเหล็กซึ่งเป็นส่วนสำคัญของผลึกดอกส่วนใหญ่ยังสามารถใช้เป็นเครื่องชี้ทางสำหรับการเสาะหาหินบะซอลต์เพื่อทำร๊อควูลในการสำรวจขั้นพื้นฐานบริเวณกว้างได้

คำสำคัญ ปิโตรเคมี เขากระโดง บุรีรัมย์ ร๊อควูล การแปรสัณฐาน

INTRODUCTION

Khao Kradong national park (about 40 km^2) is located about 7 km south of central Burirum in the southern part of Thailand, or about 300 km NE of Bangkok (Figure 1). The study area, (also the sight-seeing place), consists of two small hills (Khao Kradong and Khao Yai, totaling about 2 km^2 in size) is surrounded by nearly flat terrain used for paddy fields. Khao Kradong (also called "Khao Kradong Basalt", by Jungyusuk and Sirinawin;[1] Jungyusuk and Khositanont;[2] Plathong[3]) is a small volcanic cone with a half moon shape. Its diameter is about 100 m and vocalnic flows extensively cover an area of about 70 km^2. There is also a stream nearby terrain which flows northward but shifs its direction when passing this volcanic terrene.

The area was previously mapped by Hinthong *et al.*[4] Barr and Mcdonald[5] made a preliminary study on the petrochemistry of Khao Kradong rocks and classed them as hawaiite, with K/Ar whole-rock age of 0.93 $\pm$ 0.30 Ma. Jungyusuk and Sirinawin[6,7] made a more detialed study on the geology and petrogenesis of Khao Kradong rocks. Jungyusuk and Khositanont[2] performed geochemical and petropragphic studies of Khao Kradong rocks and classified them as hawaiite. Subsequently, Plathong[3] made a very detailed systematic study of the petrochemistry of the Khao Kradong area: He noted an error in the basalt age obtained by K/Ar dating method which made the evolution of the Kradong basalts more difficult to interprete.

The aim of this paper is twofold: first, to describe the Khao Kradong basalt in terms of petrography and geochemistry, and second, using geologic, petrochemical, and radiometric results to discuss, rock wool potential and exploration strategy.

REGIONAL GEOLOGY

The southern region of northeast Thailand (Figure 1) in which the study area is located, is mostly a flat terrain with small hills at the edge of the basin. The majority of rocks of these hills are basalts which are sparsely scattered along the southern margin of the Khorat Plateau near the border between Thailand and Combodia, extending from Nakhon Ratchasima to Burirum, Sisaket and Ubon Ratchathani.

Basalt hills (*e.g.* Khao Kradong in Burirum and Khao Phanom Sawai in Surin) formed when basalts flowed out from volcanic vents, developed higher relief and were preserved as volcanic cones. Some areas of the basalts are covered by Quaternary sediments. Rock formations which underlie basalts are assigned to the Late Mesozoic Maha Sarakham Formation.

The Maha Sarakham Formation appears to rest unconformably over the underlying Khorat strata.[8] This rock unit consists of the lower, the middle and the upper rock salts, with 2 units of claystones intercalated. The age of this formation is inferrred as the uppermost Cretaceous.[8]

Some areas are covered by Quaternary sediments. The mafic rocks (mostly basalts) are observed in the east and west of the region.[9] Geoscientists who studied basalts in Khorat considered that they mostly erupted in the Cenozoicera.[5,9]
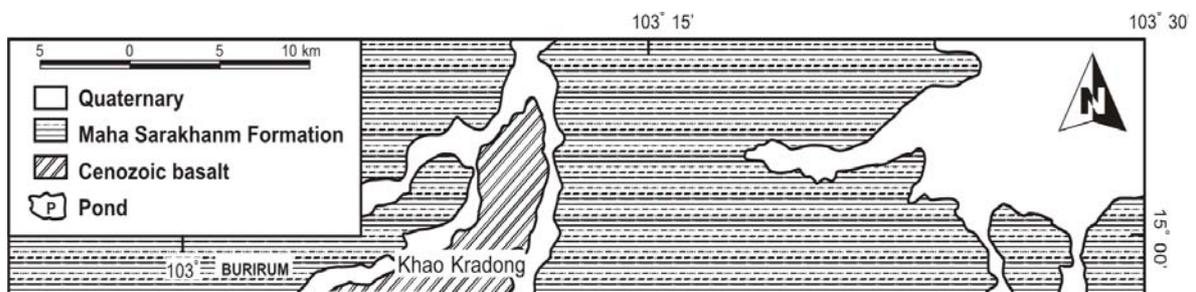
Figure 1. Regional geologic map showing location of the study area.

Geology and Geochronology

Apart from Khao Kradong volcanic cone, another volcanic cone (Khao Yai) is also present in this basaltic Terrane; both cones are about 1 km² in size and located in the Khao Kradong national park. A lake nearby the summit of Khao Kradong is inferred to be crater lake with a diameter of about 100 m and is possibly open to the southern flank.[3]

Results from landsat imagery together with interpretation of aerial photographs and topographic maps reveal that several flow layers are recognizable with six main volcanic layers (or flow numbers, see Figure 2) with the main flow direction to the northeast. Khao Kradong volcanic cone is constructed with vesicular basalt, scoriaceous basalt and basaltic bombs (Figure 3a). The scoriaceous basalt is reddish brown and includes abundant well-rounded sphericales, giving rise to light weight. This basalt was found lying over brown to brownish black vesicular basalt. The basaltic bombs vary considerably in size from 5 cm up to 50 cm with most of 10 cm in diameter. Their shape is usually bipolar, cuneiform and fusiform. Additionally, cylindrical, ribbon, and almond shaped bombs are also encountered, particularly along hill slopes. Vesicles (up to 4 cm) are found also in basaltic bombs. The appearance of volcanic bombs indicates proximity to a volcanic vent. Some basaltic bombs were concealed by scoriaceous basalts. When weathered, the scoriaceous rocks were wiped away and the basaltic bombs have been exposed.

Most of the samples collected for petrographic and chemical studies were sampled from six quarries, namely Silachai II, Silaphet, Nisitsawat, Hinlad, Pumesibrin and Hinburirum quarries. The studied samples were collected along vertical sections of the quarry front from bottom to top. The sampling intervals vary from place to place, but were mostly within the range of 1-3 m based upon the flow thickness and change in lithology. The criteria to defining the top surface of a

flow layer include pahoehoe flow (Figure 3b) and vesicular texture at the surface of the lower layer.

Thickness of flow layers varies from 1.5 to 4 m. In Pumesibrin and Silachai quarries, two flow layers are easily recognized with vesicular and brecciation textures in the lower flow. The other quarries have only one flow layer. In each flow layer, the top surface is indicated by vesicular and highly-weathered features.

In terms of physical appearance, lava flows of Khao Kradong can be classified into 2 types; aa (indicative of high viscosity) near the volcanic vent and pahoehoe (lower viscosity) located distal to the vent source, particularly at Silachai II quarry (Figure 3b).

But beyond the surficial weathered zone, the rock appears as massive, greyish-black, dense basalts. At some quarries, spheroidal weathering and xenoliths, particularly sandstone xenoliths (Figure 3c) are found on the surface. At Silachai II quarry, massive basaltic autoliths in the flow are also observed (Figure 3d). At Hinburirum quarry, vesicular basaltic autoliths were recognized in the flows. These field observations strongly indicate that there is more than one flow layers. Columnar jointing indicating the upper part of a flow layer, developed at most quarry fronts 0oobut was difficult to observe. At Hinburirum quarry, the columnar jointing is clearly visable.

Calcite (Figure 3e), always occurring as a secondary mineral and deposited in vugs of basalts, was found in most quarries. The grain sizes vary considerably from 1 to 15 cm. Microscopic and XRD results confirm the secondary minerals to include calcite, aragonite and zeolite.

According to the regional geologic map, Khao Kradong basalt extruded onto rocks of the Khorat Group (Figure 1). At Hinburirum quarry, a sandstone xenolith was observed in basalts (Figure 3c). Based upon this field evidence the age of the Khao Kradong basalt is younger than Mesozoic. In addition, at the Silaphet quarry, dark soil (paleosol) was observed to overlie the basalt layer (Figure 3f). So, the age of basalt must be obviously young. The presence of volcanic bombs and the preservation of a volcanic crater seem to support the very young age of the Khao Kradong basalt. Moreover, the ages obtained from isotopic dating data are also in a good agreement with the field evidence mentioned above. K/Ar age of whole-rock basalt is 0.92 ± 0.3 Ma[10] whereas the age of the basalt using Ar/Ar dating is *ca*. 1.11 ± 0.26 Ma.[11] According to Sutthirat *et al*.,[12] these age records classify the Khao Kradong basalt as the youngest episode of basaltic eruption in Thailand.

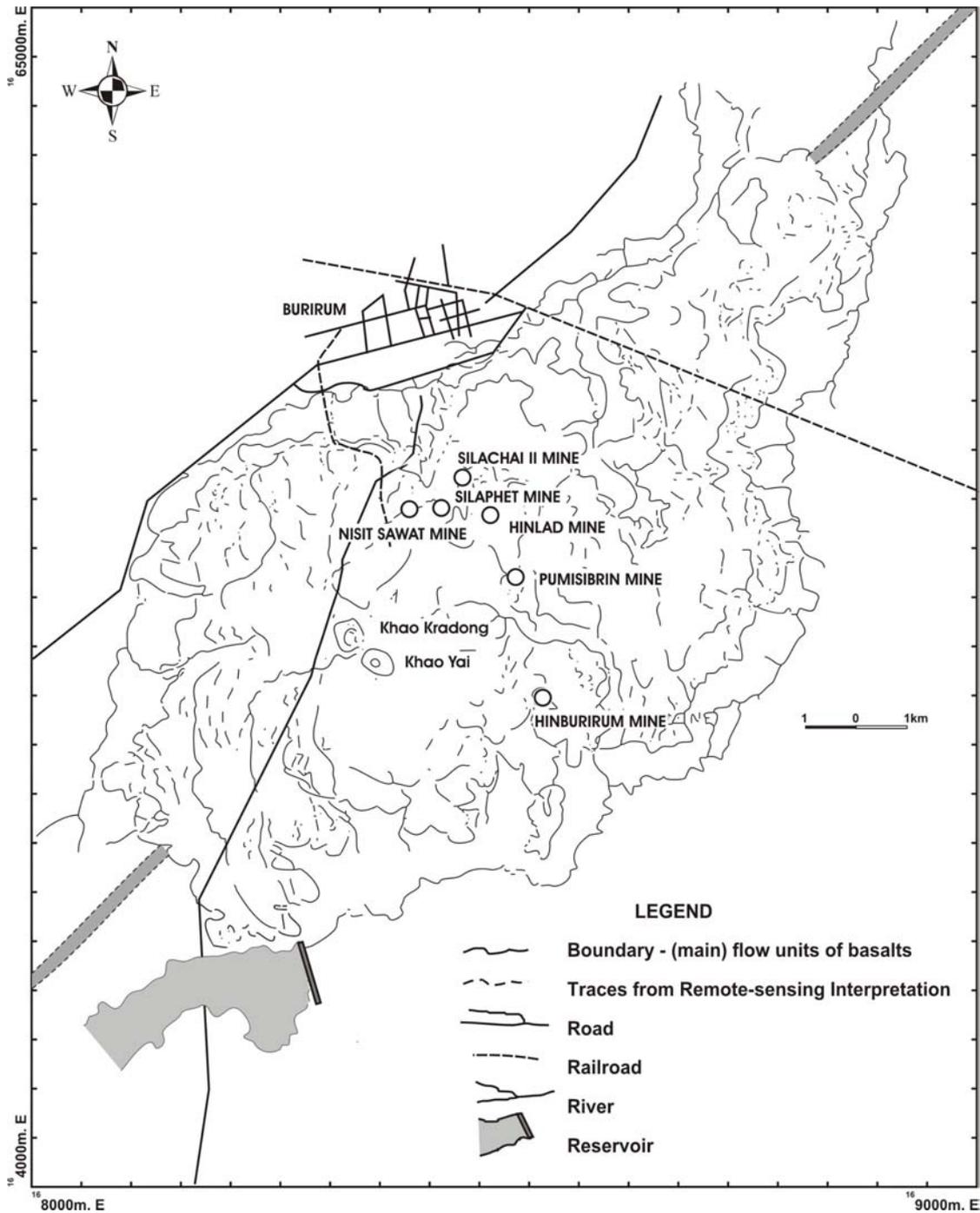**Figure 2. Flow layers of Khao Kradong area in the vicinity of Burirum district, interpreted from landsat imagery and aerial photographs.**
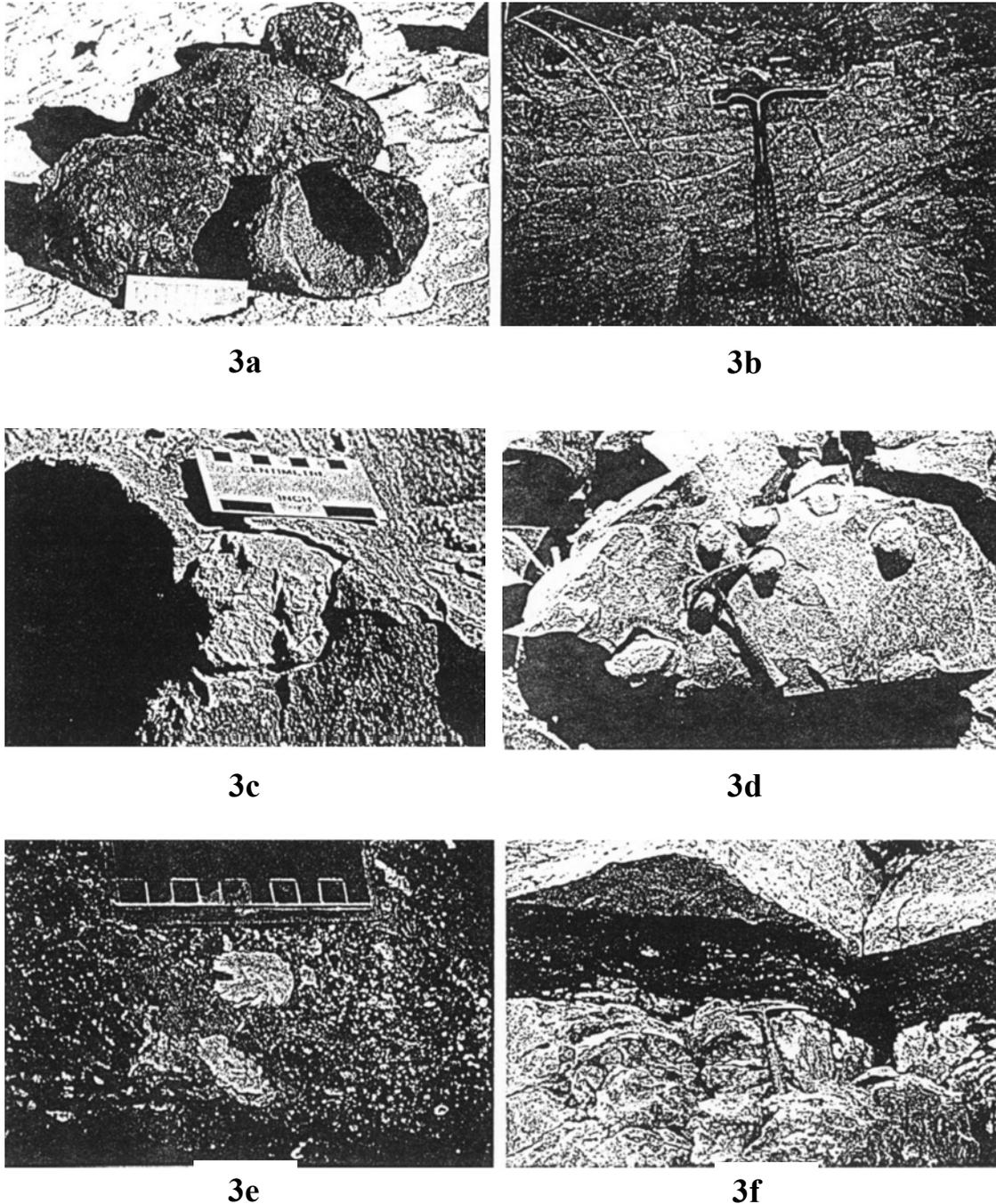
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3a

3b

3c

3d

3e

3f

Figure 3. **a) Khao Kradong volcanic bombs showing traces of flow on weathered surface and vesicular texture inside.**
b) Pahoehoe flow (or ropy basalt) at the northern side of the Silachai quarry. Note, vesicular texture at the hammer head.
c) Sandstone xenolith in basalt, Hinburirum quarry.
d) Vesicular basalt autolith, indicating preceeding eruption, at the Hinburirum quarry.
e) Secondary minerals such as carbonate minerals showing radiating calcite with the size of 15 cm.
f) Contact between basalt (upper part) and dark paleosol (lower part), indicative of young age of basalt.

4a   **4b**

4c   **4d**

4e   **4f**

Figure 4. Photomicrographs of Khao Kradong basalt, Burirum. Under crossed nicols; unless specified, long axis of photo is about 2 mm.

    a) Intersertal texture with glass surrounded by subhedral plagioclase in association with olivine.

    b) Trachytic (or flow) texture as characterized by orientation of plagioclase laths in groundmass.

    c) Subhedral microphenocrystic olivine with fibrous chlorite filled in fractures and rims, set in groundmass rich in microlite.

    d) Intergranular texture with opaque mineral surrounded by long plagioclase laths.

    e) Tiny acicular apatite, subhedral opaques (possibly magnetite) and plagioclase lath set in groundmass (long axis of photo = 1 mm).

    f) Basalt autolith showing microporphyritic texture with abundant lassy materials (dark grey to black).

PETROGRAPHY

Since flow layer numbers 1, 2 and 3 are poorly exposed and flow layer number 6 is located in the Khao Kradong national park, the samples available for petrographic investigation are limited to those of flow numbers 4 and 5. Petrographically, flow layers 4 and 5 have similar textures and mineral constituents. The only contrast (*i.e.* anorthite contents) between the flow layer numbers 4 and 5 is observed through microscopic study.

Microscopically, major textures are aphanitic, equigranular and vesicular. The last feature indicates volcanic character. Average grain size is less than 1 mm. These features indicate the volcanic character and the dark-colored tonation supports mafic affinity.

In individual flow layers, the rocks are dominated by grayish-black, rather massive, aphanitic basalts in the lower part and strongly weathered, more vesicular, reddish basalts in the upper.

Microscopically, a rock exhibits rather uniform basaltic texture, typically fine-grained, hypidiomorphic, equigranular grading into allotriomorphic. Micro-porphyry is always the essential texture with abundant olivine and rare plagioclase (a n d e s i n e   t o   l a b r a d o r i t e) microphenocrysts. Mineral compositions of groundmass are plagioclase, clino-pyroxene, ilmenite, magnetite, apatite and glassy materials. Other textures include glassy, vesicular, intergranular, intersertal, trachytic, glomeroporphyritic and subophitic. The intersertal texture (Figure 4a) is characterized by glassy materials surrounded by plagioclase. The basalt vesicules are commonly filled by secondary minerals including calcite, aragonite and zeolite. The plagioclase laths are aligned in a preferred orientation, the so-called trachytic (Figure 4b) texture (or flow texture). Glomeroporphyritic texture (clinopyroxene) is strongly developed in most sections. Ophitic texture is sparsely distributed in basalts of both flow layers.

Olivine (a.v. 0.8 mm, 15% mode) shows euhedral and microphenocryst grains with high relief and many fractures and cracks (Figure 4c). Optically olivine composition is between frostbite and fayalite, the latter being much more common. Alteration products (mostly chlorite and iddingsite) invariably occur along rims and cracks of olivine grains.

Plagioclase (0.1 x 0.4 mm, up to 35%) are frequently subhedral to euhedral laths with simple twinning and oscillatory zoning. Plagioclase (Figure 4d). ranges in composition from An_{52} to An_{66} (within labradolite range) in basalts of flow layer number 4 and from An_{40} to An_{69} (andesine to labradolite) for those of the layer number 5.

Clinopyroxene (0.2 mm, 14-18%) is present in both flow layers and frequently appears as subhedral short prismatic forms. The clinopyroxene (mostly, augite) is typical colorless to pale yellow, in thin sections and always shows one perfect closely-spaced clevage. Sometimes, it occurs as granular crystalline aggregate among plagioclase laths in groundmass.

Opaque minerals (0.1-0.3 mm, 15-20%) always occur as subhedral to euhedral crystals (Figures 4d and 4e). Skeleton texture, a diagnostic feature of ilmenite and square-shaped habits for magnetite, are quite common in the flow number 5 basalt.

Glassy material (15-20%), a typical characteristic of volcanic rocks, is also found in most sections. It occurs as essential groundmass (Figure 4f). Some are devitrified and altered to chlorite.

Important accessories and secondary minerals (Figure 4b) include apatite, chlorite, iddingsite, zeolite and calcite. Apatite (0.3 mm, 10%) occurs as minute, euhedral, long prismatic crystals (Figure 4e) in close association with plagioclase and clinopyroxene or occasionally present as tiny inclusions in plagioclase. Chlorite (0.3 mm, up to 10%) usually occurs along olivine cracks and is likely altered from

olivine. It is always present as anhedral crystals and shows yellowish green to green pleochroism. Fe-rich iddingsite (0.2 mm av. 7%), like chlorite, is altered from olivine and found in cracks or around olivine grains. In thin sections and without nicols, it shows the typical feature of a deep orange color. Both calcite and zeolite are major secondary minerals and mostly found in vesicles of basalt forming well-defined amygaloidal texture. Zeolite is also formed as radiated crystals in which irregular branching fibre minerals have crudely spherical in shape.

Table 1A. Ranges and averages of major oxides (wt%) for basalts of flow layer number 4, Khao Kradong basalts.

Quarry	Total		Silachai II		Silaphet		Nisitsawat	
Major Oxides	Range	Av.	Range	Av.	Range	Av.	Range	Av.
SiO_2	47.57-49.46	48.35	47.89-49.46	48.84	47.57-48.50	48.14	48.12-49.05	48.66
TiO_2	2.74-3.09	2.87	2.82-2.89	2.85	2.78-3.09	2.89	2.74-3.02	2.86
Al_2O_3	14.02-14.59	14.37	14.26-14.45	14.33	14.02-14.59	14.31	14.43-14.57	14.50
Fe_2O_3	3.83-7.27	4.85	4.52-5.01	4.7	3.83-7.27	5.31	+4.13-5.22	4.53
FeO	3.32-7.14	5.97	5.64-6.35	5.98	3.32-7.14	5.59	5.63-6.84	6.34
MnO	0.12-0.15	0.14	0.14-0.14	0.14	0.12-0.15	0.14	0.14-0.15	0.143
MgO	6.01-7.29	6.96	7.09-7.29	7.19	6.01-7.18	6.78	6.63-7.19	6.92
CaO	7.23-8.12	7.80	7.23-8.04	7.63	7.79-7.96	7.89	7.60-8.12	7.87
Na_2O	2.34-2.83	2.61	2.34-2.56	2.45	2.49-2.83	2.67	2.52-2.83	2.70
K_2O	1.78-1.98	1.86	1.80-1.98	1.86	1.81-1.97	1.87	1.78-1.93	1.85
P_2O_5	0.74-0.80	0.77	0.75-0.79	0.77	0.74-0.80	0.76	0.74-0.80	0.76
H_2O	1.10-1.87	1.49	1.35-1.87	1.57	1.10-1.72	1.64	1.17-1.34	1.25
No. of samples	9		3		3		3	

Table 1B. Ranges and averages of major oxides (wt%) for basalts of flow layer number 5, Khao Kradong basalts.

Quarry Hinburirum	Total		Hinlad		Pumesibrin		Nisitsawat	
Major Oxides	Range	Av.	Range	Av.	Range	Av.	Range	Av.
SiO_2	47.00-49.75	48.91	47.80-49.75	49.00	49.75-49.75	49.75	47.00-47.80	48.43
TiO_2	2.03-2.55	2.18	2.03-2.06	2.04	2.12-2.25	2.185	2.09-2.55	2.29
Al_2O_3	14.85-16.50	15.88	15.60-16.50	15.09	15.90-16.50	16.20	14.85-16.50	15.71
Fe_2O_3	9.73-10.56	10.06	9.73-9.88	9.78	9.73-9.73	9.73	10.28-10.56	10.43
MnO	-		-		-		-	
MgO	5.24-6.00	5.53	5.24-5.42	5.35	5.48-5.48	5.48	5.50-6.00	5.68
CaO	5.40-6.30	5.76	5.50-5.80	5.60	5.40-5.50	5.45	5.82-6.30	6.04
Na_2O	2.70-3.80	3.33	3.24-3.40	3.31	3.70-3.80	3.75	2.70-3.70	3.13
K_2O	1.45-2.18	1.87	1.85-2.18	2.03	1.80-1.95	1.875	1.45-2.10	1.75
P_2O_5	1.59-3.37	2.70	2.22-3.37	2.90	2.00-2.98	2.49	1.59-3.11	2.65
H_2O	-		-		-		-	

*Total Fe+3 + Fe+2

Note : "-" Symbol means "not determined"

No. of samples	19		6		6		7	

Table 2. Ranges and averages of trace elements (in ppm) for Khao Kradong rocks.

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Quarry	Silachai II		Silaphet		Nisitsawat		Total	
Trace Ele.	Range	Av.	Range	Av.	Range	Av.	Range	Av.
Cr	125-155	143.67	127-145	136.67	112-169	139.67	112-169	140
Ni	58-175	106.67	75-100	86.67	39-114	80	39-175	91.11
V	331-341	336.33	323-345	332	321-357	333.67	321-357	334
Cu	36-63	52.67	49-54	51.67	13-68	41.33	13-68	48.56
Pb	<5	<5	<5	<5	<5	<5	<5	<5
Zn	126-129	128	122-138	128	141-145	143	122-145	133
Rb	45-49	47	23-42	35	18-27	23.67	18-49	35.22
Ba	608-667	641	617-846	704.67	621-673	641.67	608-846	662.44
Sr	928-1029	972.67	890-1301	1071	963-1057	1003.33	890-1301	1051.67
Nb	56-63	59	47-59	52.67	<10-46	32.67	<10-63	48.11
Zr	187-194	191	185-204	192	199-216	205.33	185-216	196.11
Y	71-82	75.67	41-78	63.67	39-44	42.33	39-82	60.56
Ce	25-46	34	22.53	33	39-51	44	22-53	37
No. of samples	7		6		4		17	

Table 3. CIPW molecular norms of basalts of flow layer number 4, Khao Kradong basalts.

	Silachai II			Sillapher			Nisitsawat		
Sample	BR-1-2	BR-1-5	BR-1-8	BR-2-1	BR-2-5	BR-2-8	BR-3-1	BR-3-4	BR-3-6
Q	1.41	3.82	5.19	1.49	-	4.8	1.14	0.53	3.59
Z	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Or	11.72	10.66	10.66	11.66	10.89	10.71	10.94	10.53	11.42
Ab	20.64	21.66	19.80	21.07	23.94	22.63	23.94	23.35	21.32
An	22.24	22.67	23.15	21.33	21.72	21.75	21.64	21.78	22.61
Di	10.34	8.39	5.56	10.79	10.63	9.73	10.45	11.34	8.19
Hy	16.49	16.38	16.91	15.51	16.63	10.47	16.42	17.40	14.00
Mt	6.55	6.71	7.26	7.00	5.55	2.98	6.13	5.99	7.57
Cm	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.02
Il	5.49	5.37	5.36	5.87	5.28	5.32	5.37	5.20	5.74
Ap	1.88	1.84	1.79	1.91	1.76	1.79	1.79	1.76	1.91
Ol	-	-	-	-	1.31	.	-	-	-
Hm	-	-	-	-	-	5.22	-	-	-
100*An/Ab+An	51.86	51.139	53.899	50.306	47.56	48.95	47.476	48.26	51.468

GEOCHEMISTRY

Secondary minerals, such as calcite and zeolite, have been removed from specimens prior to chemical analyses. Twenty eight fresh rock samples from six quarries were chemically analysed for major oxides (Tables 1A and B) and seventeen samples for trace elements (Table 2). X-ray fluorescence spectrometry (XRF) was applied for non-alkali oxide and trace-element analyses and atomic absorption spectrometry (AAS) for alkali and alkali-earth oxides.

The chemical data from XRF analysis were subsequently treated and processed by NewPet software (obtained from the Geological Survey of Canada) for calculating CIPW norms and ploting various diagrams.

Data from field investigation and petrographic studies indicate that all groups of Khao Kradong rocks are of the same type. The result from chemical analyses also strongly indicates that flow layer numbers 4 and 5 show little variation from each other.

Geochemical Classification of Basalts

The normative minerals from CIPW norms calculation were reported only for flow layer number 4 (Table 3) and included quartz, zircon, orthoclase, albite, anorthite, diopside, hypersthene, magnetite, chromite, ilmenite, apatite, olivine and hematite. In this study, the norms of hypersthene, albite and anorthite normatives[13] are used for classification of basalt (Figure 5).

Chemical analyses and normative percentages of Khao Kradong rocks are used to classify the types of mafic rocks[14] and those are shown in Figures 5-12. Total alkali *versus* SiO_2 plots[15] indicate that the rocks are located both in alkaline and sub-alkaline basalt fields (Figure 6). Weight %SiO_2 *versus* log (Zr/TiO_2) and Zr/TiO_2 against Nb/Y plots[16] are quite interesting, they reveal that the rocks are also plotted in subalkaline and alkaline basalt fields, respectively (Figures 7a and b). The AFM variation triangular diagram[15] clearly indicates that Khao Kradong rocks are calc-alkaline basaltic rocks (Figure 8). The 2Nb-Zr/4-Y tectonomagmatic discrimination diagram[17] reveals that most samples are plotted in the within-plate basalt fields (Figure 9). In Figure 5 all rocks of Khao Kradong are ploted in the transitional zone of hawaiite to alkali olivine basalt fields. K_2O versus Na_2O plots[13] indicate that Khao Kradong basaltic rocks are in K subseries' subdivision (Figure 10). In addition, some correlations were also made for recognition of fractionation trend in terms of SiO_2 contents. Figures 11a and b show the negative correlation between K_2O and SiO_2; *i.e.*, the value of SiO_2 increases while the value of K_2O decreases. Ti/100-Zr-Y*3 triangular diagram[17,18] in Figure 12 indicates that most Khao Kradong rocks are located in the within-plate basalt series.

DISCUSSIONS
Geochemical Aspect

As shown in Figures 6, 7 and 11, Khao Kradong basalts are of alkaline to near subalkaline type. Middlemost[11] had divided the alkaline magma into 3 types: high K-series, K-series and Na-series based on the relationship between K_2O and Na_2O values (Figure 10). After plotting Khao Kradong data of Na_2O and K_2O, the Khao Kradong basalts are regarded as beloning to the K-series alkali magma (Figure 10).

When the geochemical data of Khao Kradong basalt (only flow layer number 4) were plotted in the Ne/Hy norms and % (An/Ab+An) diagram (Figure 5), it was concluded that Khao Kradong basalt was transitional from hawaiite to alkali olivine basalt type. Our result is, therefore, dissimilar to those reported earlier by Barr and Macdonald[2] and Jungyusuk and Sirinawin,[6] who both advocate Khao Kradong basalt as being of the hawaiite type.
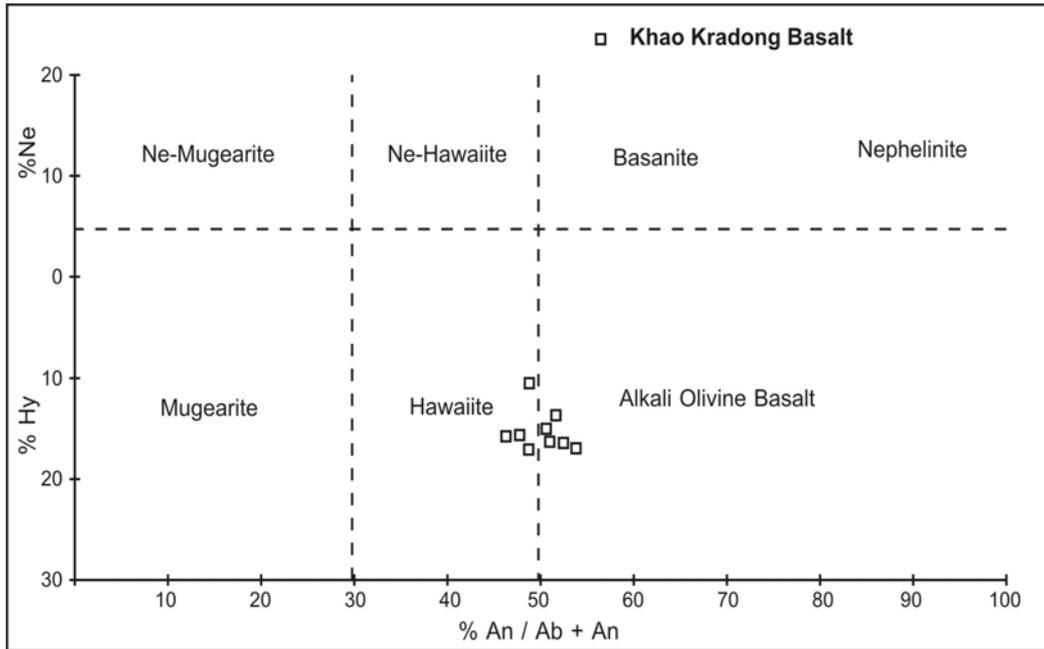
Figure 5. Plots of normative hypersthene or nepheline against normative plagioclase composition of Khao Kradong basalt. Fields boundary modified after Coombs and Wilkinson.[24]
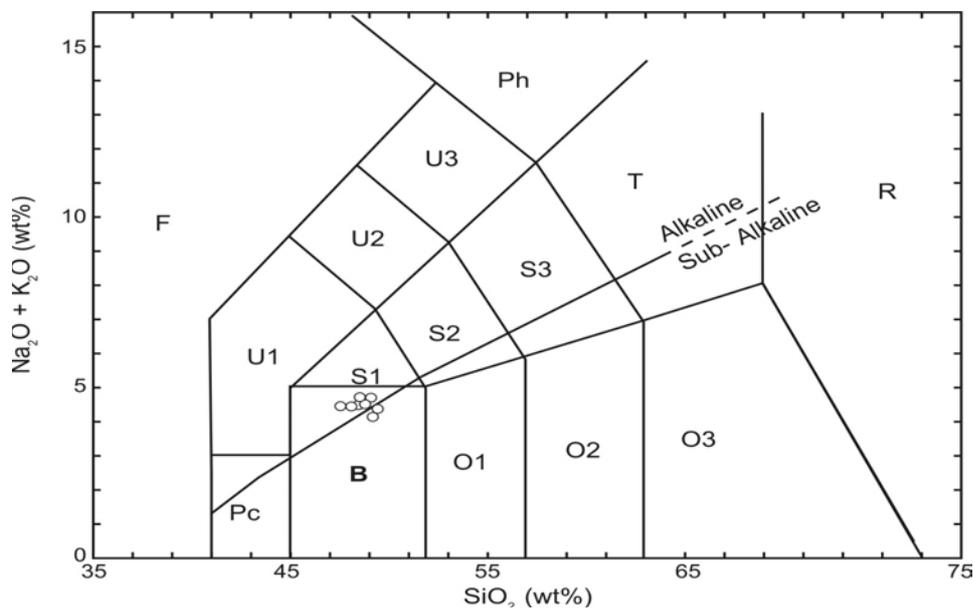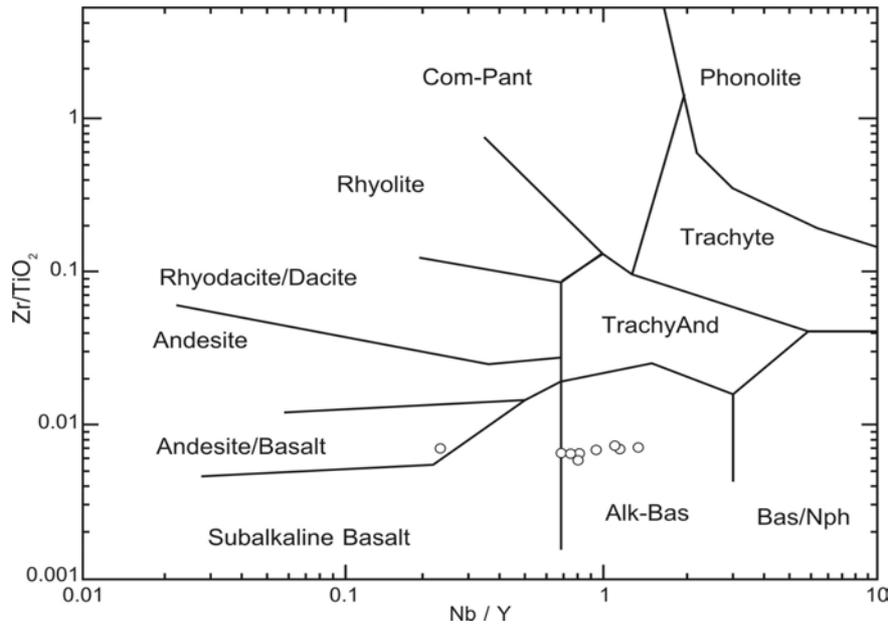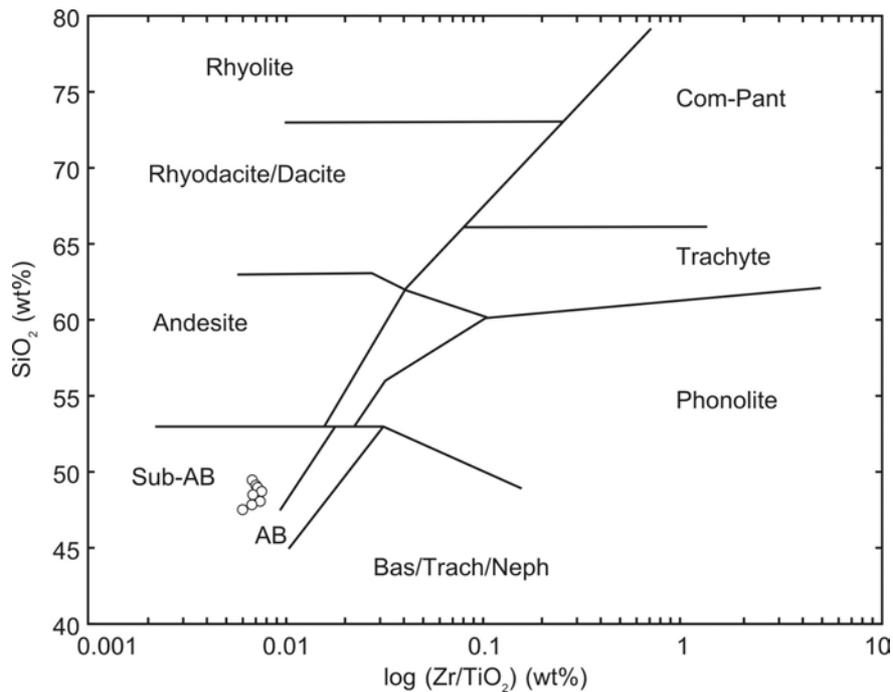

Figure 6. Classification of alkalic and subalkalic basalts in terms of wt% Na_2O+K_2O *versus* % SiO_2, alkaline-subalkaline after Irvine and Baragar, 1971) and fields after Le Maitre, 1989), for basalts of Khao Kradong. Note B = basalt.

(a)

(b)

Figure 7. Zr/TiO₂ *versus* Nb/Y (a) and weight % SiO₂ *versus* log (Zr/TiO₂), (b), showing classification of Khao Kradong rocks. AB = Alkaline basalt, Alk = Alkaline, And = Andesite, Bas = Basalt, Com = Comendite, Neph = Nephelinite, Nph = Nephelinete, Pant = Pantellerite, Sub = Subalkaline basalt and Trach = Trachyte, field after Winchester and Floyd.[16]

Tectonic Aspect

In the case of tectonic setting, geochemical values in Figures 9 and 12 indicate that Khao Kradong basalts were significantly classified as within-plate basalt type. The within-plate basalt can be divided into 2 types; *i.e.*, intra-oceanic basalts (OIB) and intra-continental basalts (CIB). Khao Kradong basalts are not the intra-oceanic (-oceanic islands basalts) since flows of basalts over paleosols[3] strongly suggest on-land origin and the CIB have differentiated magma from tholeiite to Na-type and K-type of alkali magma, a characteristic of CIB affinity.[14] It is clear that Khao Kradong basalts were of the K-type alkalic magma (see Figures 10 and 11a), so Khao Kradong basalts were inferred geochemically to be intra-continental basalt type. This result is in good agreement with observed field evidence.

CIB can be further subdivided into continental rift zone (CRZ) and continental flood basalts (CFB).[14] The characteristics of CRZ which is based principally on geochemistry include the presence of alkali basalts, an increase of SiO_2 with respect to the decrease of K_2O and the increase of Na_2O. In terms of petrography, CRZ is characterized by the presence of olivine monomineral and a maximum quantity of phenocryst of 15%.[14] On the other hand, the characteristics of CFB, on the basis of petrography and geochemistry, are the widespread occurrence of tholeiite basalt, the increase of SiO_2 with respect to K_2O, up to 25% of the maximum quantity of phenocrysts, more abundance of plagioclase than olivene phenocrysts and clinopyroxene as augite. This assemblage suggests that the magma have been possibly involved in low-pressure crystal fractionation process.[14]

The petrographic investigation reveals that the amount of olivine phenocrysts are 10 to 15%. Geochemical evidence advocates that Khao Kradong basalt is alkali basalt. Figures 11a and b clearly depict that as the SiO_2 content increases, the K_2O content decreases and Na_2O content increases. Taking all these findings into account, it is clear that Khao Kradong is CRZ basalt affinity.

CRZ is also divided into two types: high volcanicity with the characteristic of middle to subalkali basalt; and low volcanicity with characteristic high alkali basalt.[14] These geochemical results together with field investigation strongly support the conclusion that Khao Kradong is the high volcanicity CRZ basalt type.

Geochronological Aspect

The fractures on the continental basalts in SE Asia (Figure 13) are mostly aligned in 3 directions[3] (*i.e.*, NW-SE, NE-SW and N-S) with a minority of the E-W direction and the angles between these fractures are approximately $120°$.

Tectonically, it is believed that hot spots beneath the continents may have caused the typical structures or fractures (the so-called aulacogen, Figure 14). The possible occurrence of hot spots indicates that the vertical stress is prominent and the dilational stress is lateral, causing the rifting structure. In general only one dilational stress axis is a major component. The result is fractures in two directions which continued to develop to become rift fractures, while the other one halts causing a "failed rift" or "dead rift". In the case of Khao Kradong, the trend of basalt is in the NE direction which probably follows one of the major fracture directions.

When considering the relationship between the stream course and the generation of basalts, two hypotheses regarding the development of basalts arise one is based upon geomorphological and one on geochronological parameters. The average age, ~1 Ma, of basalts based upon $^{40}Ar/^{39}Ar$ results[11] and the K-Ar method.[2] However, the average age of several streams is which developed in the south of northeastern Thailand is 0.7 Ma (Narong Thiramongkhon, pers. comm.) based upon the appearance and distribution of tektites in this region. The tektites are believed to have formed coeval with the streams.

The first hypothesis, as believed by several geoscientists[3] and based on geomophological evolution, proposes that the stream developed first along the large NE-trending fracture and then Khao Kradong basalts may have extruded along the weak zone. This possibly caused the change in stream course afterward, since it is unlikely to have had such a stream course.

The second hypothesis, which is by these current authors and based mainly on chronological data, inferres that the generation of basalts predated the stream course. Firstly, the NE fractures (produced by the aulacogen process) had occurred.

After that, Khao Kradong basalts were extruded onto the rocks of the Khorat Group along the weak zone of the continental crust. Subsequently the stream course developed around the boundary of basalts and country rocks which acted as the weak zone.

Plathongs[3] however, cannot specify which hypothesis has the higher possibility since the age of basalts is based solely upon K/Ar dating and can vary from 1.22 Ma to 0.62 Ma due to analytical errors. The age of streams is usually 0.7 Ma. When considering the more reliable Ar/Ar date, it is strongly inferred that the second hypothesis is quite the more likely.
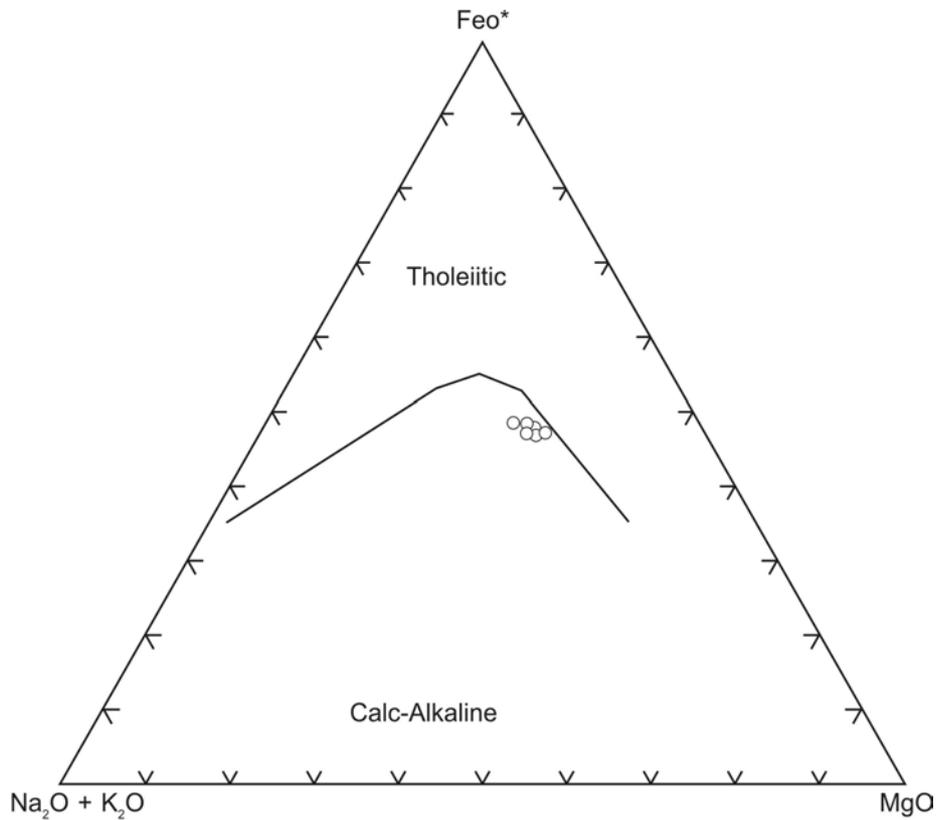
Figure 8. AFM plot of Khao Kradong volcanic rocks (diagram after Irvine and Baragar.[15]

Geology and Petrochemistry of Basaltic Rocks at Khao Kradong, Burirum, NE Thailand: Implications for
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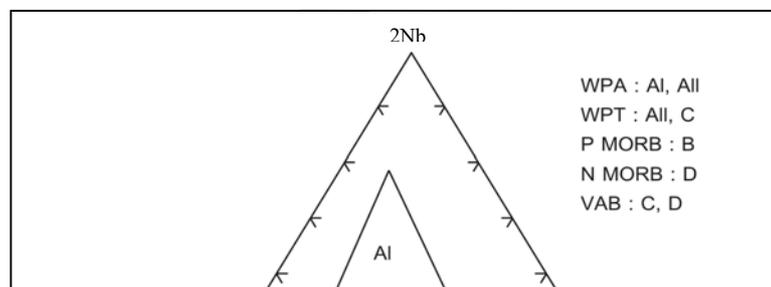*Setting…………………………………………………………………*

Figure 9. 2Nb-Zr/4-Y tectonomagmatic discrimination diagram plotted for Khao Kradong basalt (diagram after Meschede, 1986). AI = Within-plate alkaline basalts, AII = Within-plate tholeiitic basalts, B = Primitive mid-oceanic ridge basalts, C = Within-plate tholeiitic basalts & Volcanic-arc basalts and D = Volcanic-arc basalts, Normal mid- oceanic ridge basalts.
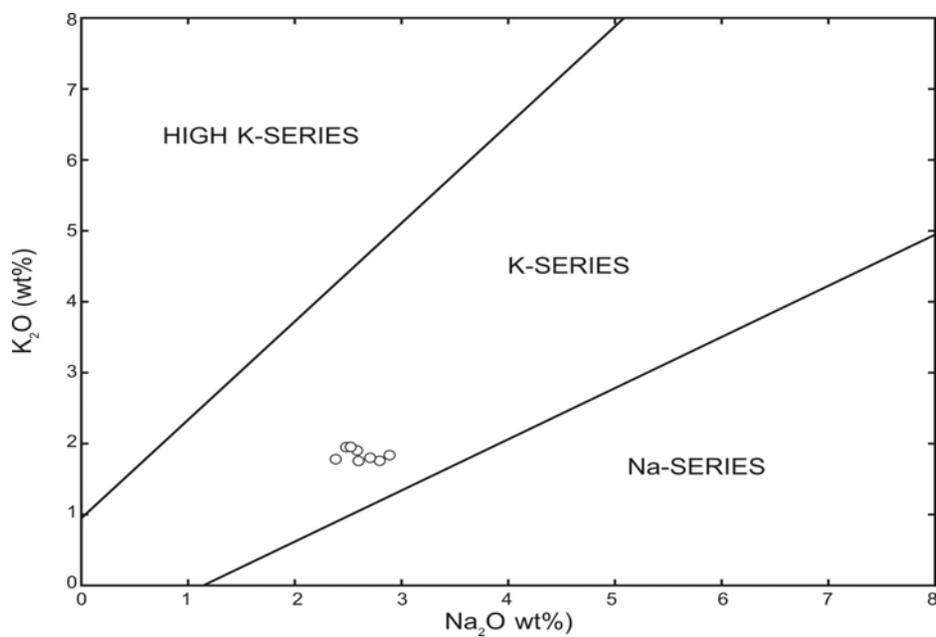
Figure 10. K_2O *versus* Na_2O (wt%) diagram showing the subdivision of alkalic magma series to high K-, K- and Na-subseries.[13]

(a)

(b)
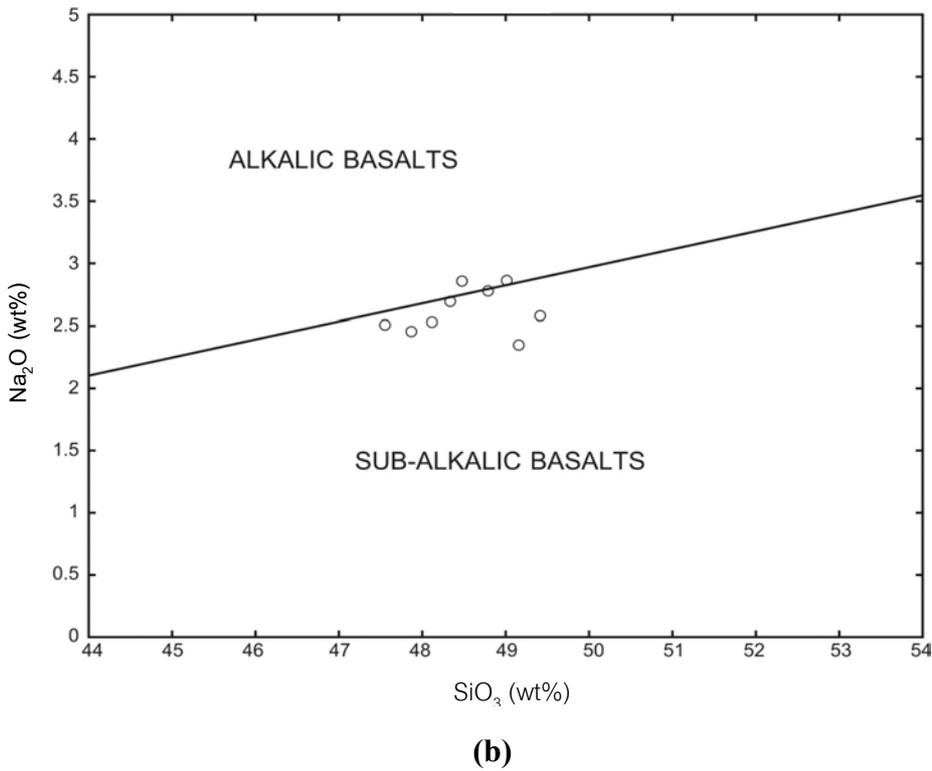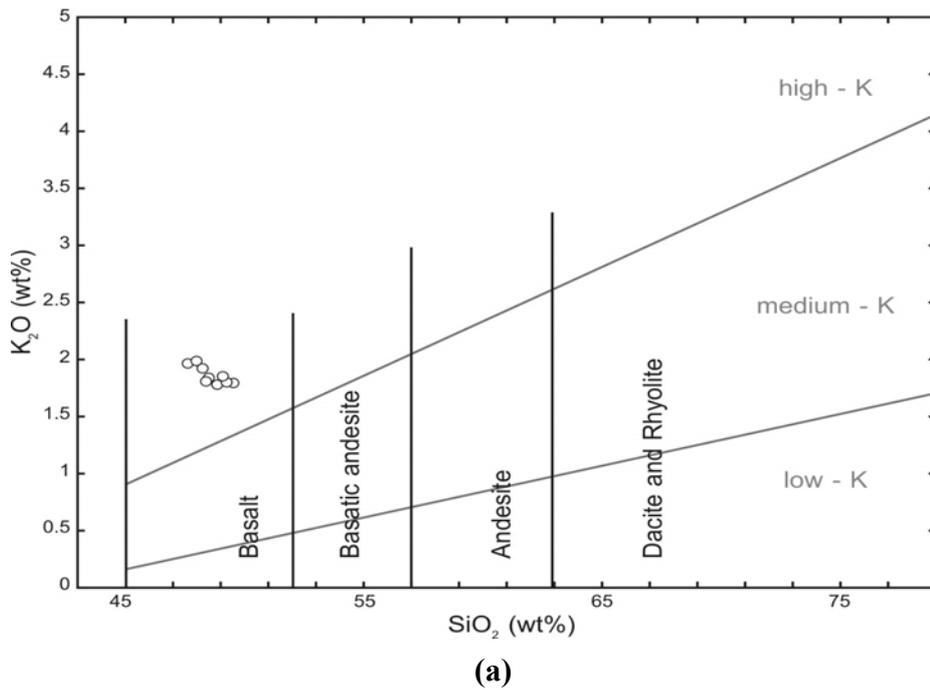
Figure 11. **Plots of wt% K$_2$O (a, fields after Le Maitre)[19] and Na$_2$O (b, fields after Middlemost)[13] *versus* SiO$_2$, showing high K-series (a) and transitional alkalic-subalkalic (b) basalts for Khao Kradong.**

Rock Wool Aspect

The expected properties of rock wool consist of an the average value of SiO_2 that is generally less than 48% and an average of MgO that is less than 8%, in addition, the rock is expected to be a fine-grained material with an absence of large inclusions of chromite, olivine magnetite and quartz.[20] For the lithochemistry of the Khao Kradong basalt, the average value of SiO_2 (48.55%) is a little more than 48% and the average value of MgO (6.96%) does not exceed 8%. So it is suggested that flow layer number 4 has good potential for rock wool. The average value of SiO_2 in flow layer number 5 (48.91%) is a little higher and the average value of MgO is 5.53%, much less than the maximum limit, 8%. For this reason, we believed that a great care has to be taken to choose basalts from flow layer number 5 for rock wool raw material. When all data are taken into account for rock wool potential, it is quite likely that rocks of the Silaphet quarry are the best potential source from among those examined.

Exploration Aspect

The information deduced from the petrography of Khao Kradong basalt is very useful for basic exploration for rock wool. The petrographic investigation is inevitably required for the reconnaissance stage of exploration,[10,12,21-23] since only a small amount of fresh samples which can be obtained at a low cost of exploration are required. Next, another low-cost investigation takes place to determine the optical property of the olivine phenocrysts in order to determine if the olivine is of the fayalite-type (Fe-olivine) or the forsterite-type (Mg-olivine). If the olivine is forsterlite, it is expected that the value of MgO would be more than 8 wt % and thus an unsuitable composition for rockwool processing. The area concerned is subsequently discarded as a target of interest. Vice versa, if the phenocryst is fayalite, a more detailed investigation is planned particularly for lithogeochemical analyses. This method of investigation could be expanded to the exploration of rock-wool potentials in our neighbouring countries of Cambodia, southern Laos and Vietnam.
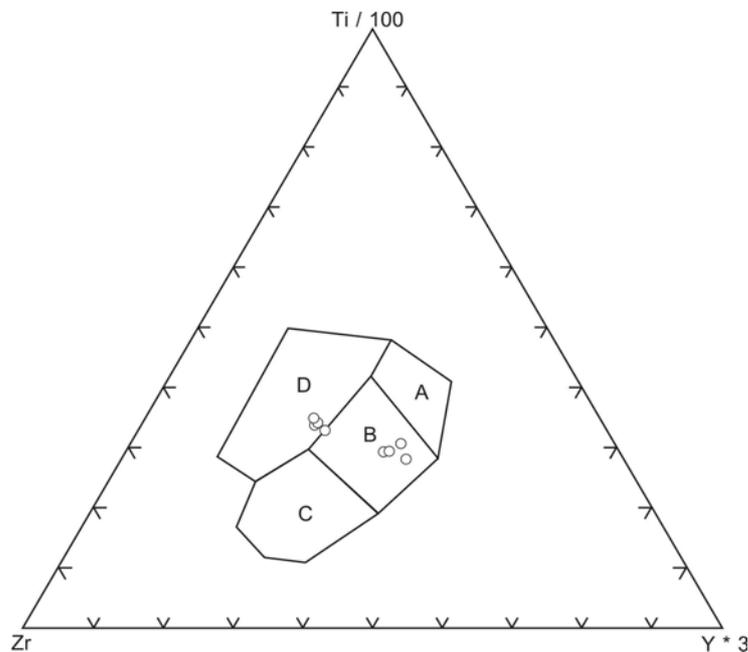

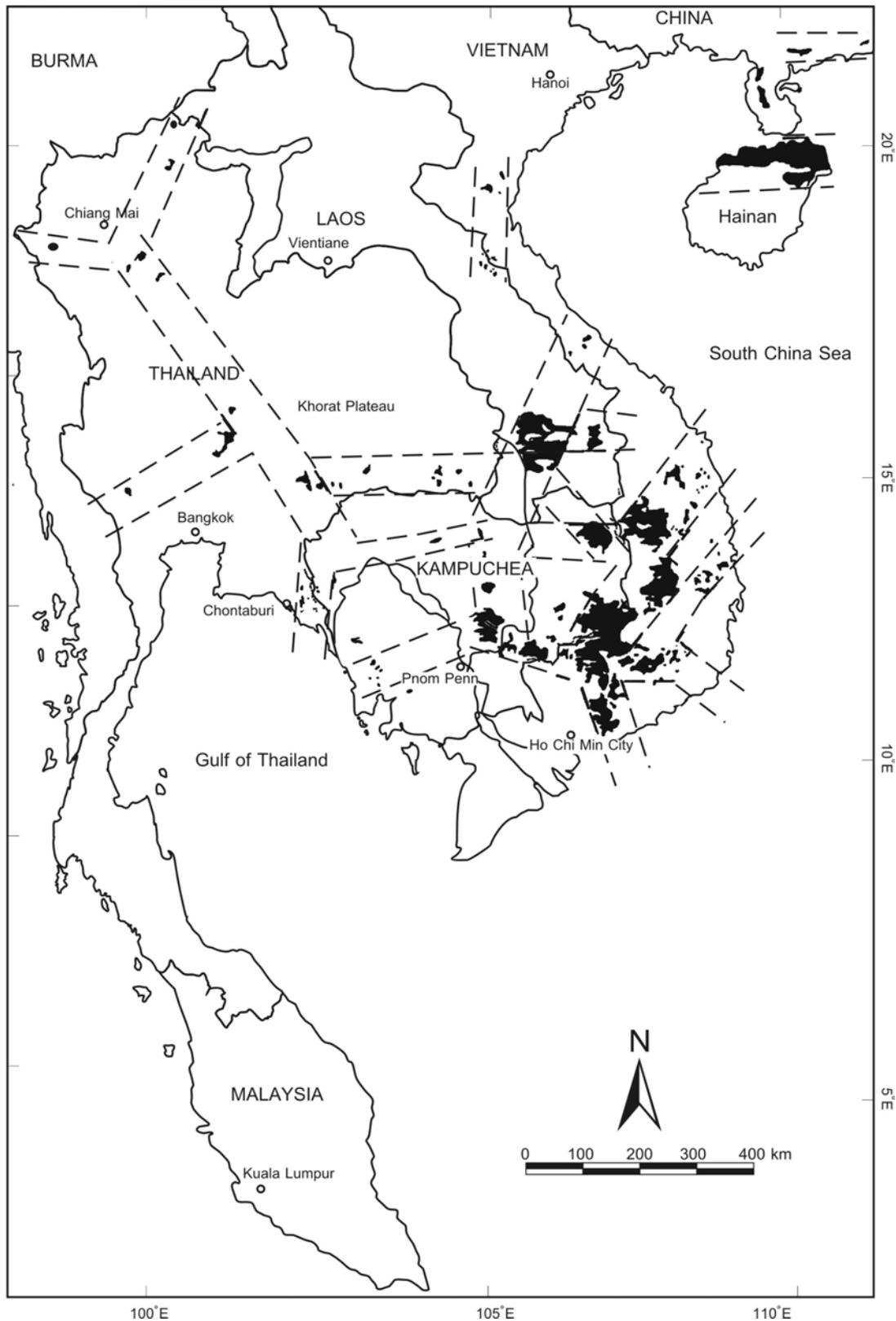**Figure 12. Plot of Ti/100-Y*3-Zr triangular diagram showing fields of Khao Kradong basalt.**

Figure 13. Major lineaments of Late Cenozoic basalt distribution in Thailand and Indochina.

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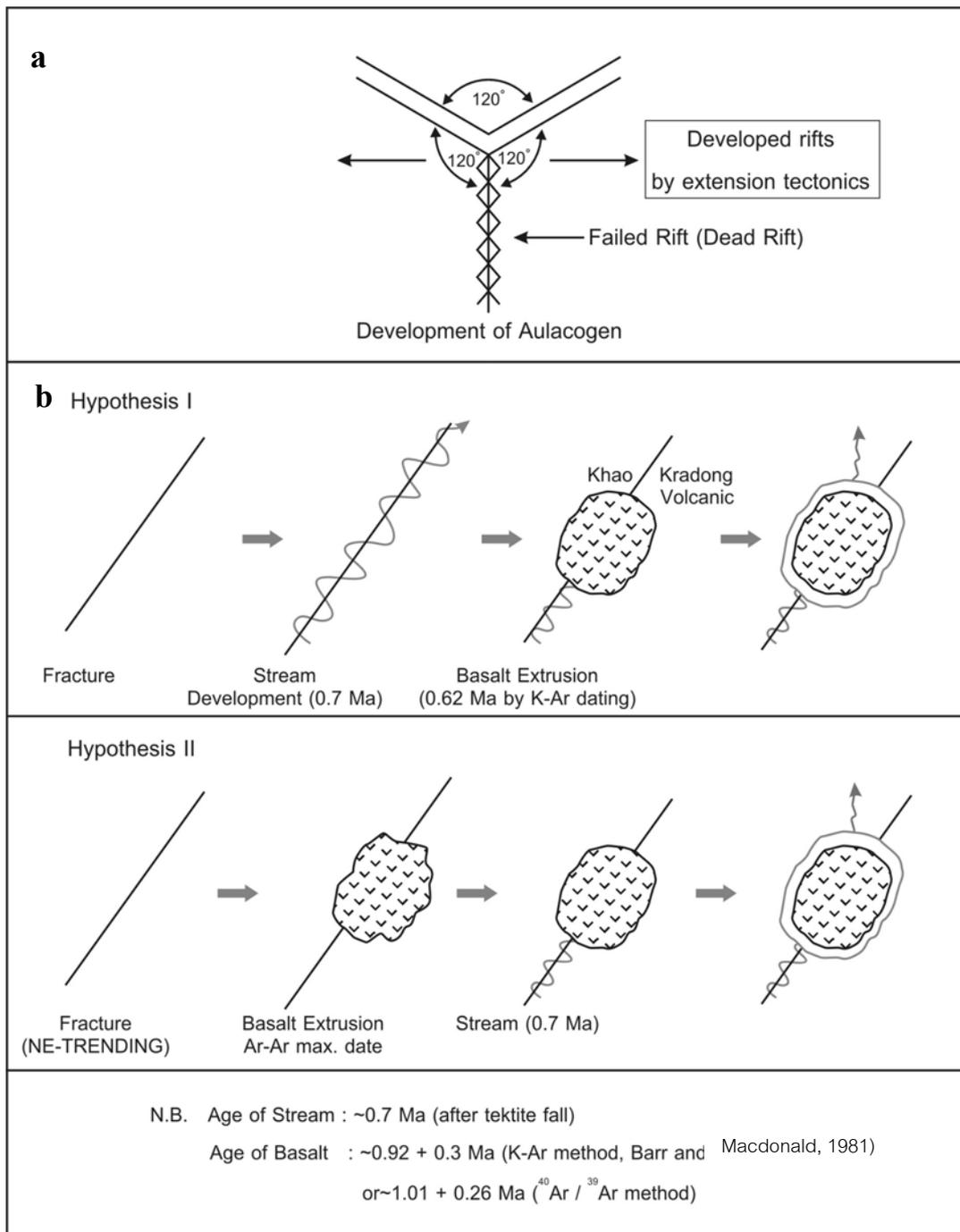*Setting…………………………………………………………………*

Figure 14. a) Development of aulacogen b) Two hypotheses proposed for the relationships between development of Khao Kradong basalt and stream course.

CONCLUSIONS

Judging from all the available information, conclusions can be drawn as below:

1. Basalts and their volcanic equivalents constitute the Khao Kradong cone-shaped volcanoes.
2. Basaltic lava can be divided into 6 major flow layers (units) within the NE-trending main flow direction.
3. Geochronologically, Khao Kradong is considered to be Cenozoic (~1Ma) based upon radiometric $^{40}Ar/^{39}Ar$ dating results together with the geomorphological characteristics.
4. Petrographically, Khao Kradong consists of basaltic rocks with olivine microphenocryst, vesicular basalts, scorias, Aa and pahoehoe in the upper surface layers whereas somewhat massive and columnar-jointed basalts represent the lower and central parts of flow layers.
5. Geochemically, Khao Kradong comprises alkaline basalts and the classification of Khao Kradong is transitional hawaiite to alkali olivine basalt.
6. In term of tectonic settings, Khao Kradong is inferred to be basalt of continental rift origin (high volcanicity type).
7. Basaltic rocks at Khao Kradong have been determined both physically and chemically to possess a good potential for rock wool.
8. In the case of regional exploration for rock-wool raw materials, the olivine phenocryst examined should be fayalite (Fe-rich olivine).

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