Geol. Soc. Malaysia, Bulletin, 10, Dec. 1978; pp. 25–52.

Geochemistry and Petrogenesis of Late Cenozoic Alkaline Basalts of Thailand

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Abstract: Late Cenozoic basalts of Thailand occur as scattered small plugs, vents, and flows, forming part of a large alkaline basalt province extending through Thailand, Cambodia, Laos, and Vietnam. Several basalt occurrences in this region are important sources of gem-quality corundum and zircon. Basalts in Thailand are classified petrochemically into two main groups: basanitoid basalts (including nephelinite, basanite, nepheline hawaiite, and nepheline mugearite) and hawaiitic basalts (including alkali olivine basalt, hawaiite, and mugearite). Minor tholeiitic basalts also occur. Basanitoid magmas may have formed by partial melting in the mantle at high pressures of 20–30 kb, followed by rapid ascent to the surface. Megacrysts (including corundum and zircon) occur only in the basanitoid basalts and are interpreted to be high-pressure cognate megacrysts. Hawaiitic magmas may also have originated by relatively small amounts of partial melting but apparently at somewhat lower pressures, followed by slower ascent allowing low-pressure differentiation to occur. Tholeiitic magmas probably represented larger amounts of partial melting. The Cenozoic alkaline igneous activity in Southeast Asia may have been related to crustal tension resulting from extensional opening of the China Basin in Late Mesozoic–Cenozoic time.

INTRODUCTION

Geological maps of Southeast Asia show many occurrences of basalt which are generally considered to be Late Cenozoic in age (Fig. 1). Basalts of Cambodia, Laos, and Vietnam have been described by Lacroix (1933) and by Carbonnel (1973) who show them to be alkaline. No equivalent description of occurrences in Thailand is available in the literature but an unpublished preliminary study (Vichit, 1975) indicates that Thai basalts are also alkaline.

At several localities in Southeast Asia these basalts are the sources of gem-quality corundum and zircon, which are usually found in placer deposits adjacent to dissected basalt outcrops. Zircons are most abundant at Bokéo and Xuan Loc in Cambodia and Vietnam respectively, whereas sapphires and rubies are abundant at Pailin in Cambodia and at Chantaburi in Thailand (Carbonnel *et al*, 1972). Gems are also found at several other localities but in lesser amounts. However the majority of basalt occurrences are not known to be gem-bearing. Lacroix (1933) suggested that zircons in alkaline basalts in Indochina represent xenocrysts acquired by the basalt magma as it passed through metamorphic rocks of the deep crust. More recent workers (Lacombe, 1967; Carbonnel and Robin, 1972; Carbonnel *et al*, 1972) suggest that both zircon and corundum crystallized as megacrysts from the alkalic magma. Carbonnel and Robin

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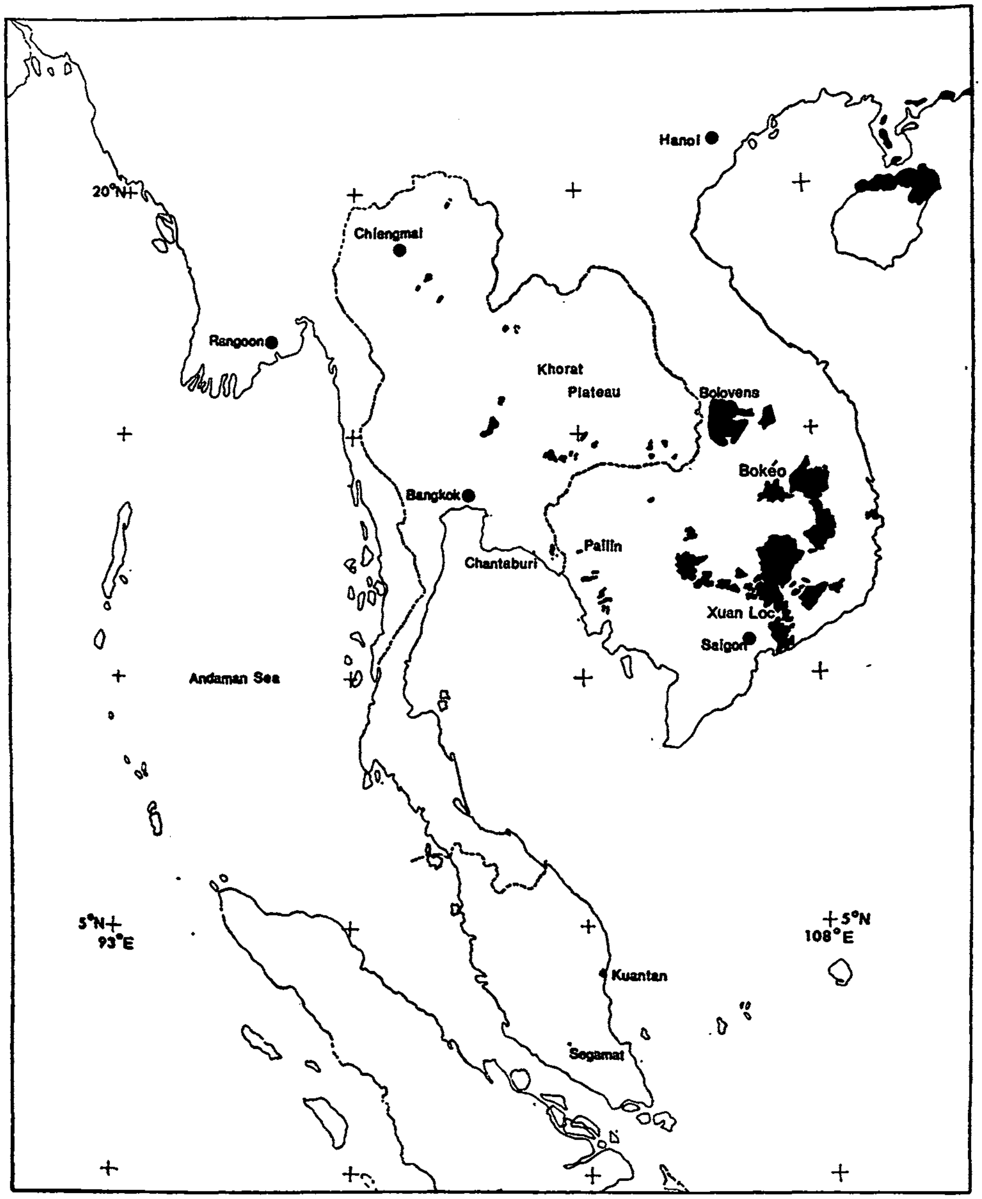

Fig. 1. Distribution of Late Cenozoic Basalts in Southeast Asia. After Geological Map of Asia and the Far East, ECAFE, 1971.

(1972) show that gem-quality zircons from Indochina, Madagascar, Sahara, Senegal, and France occur in alkaline basalts with relatively low Al_2O_3 and high MgO, and that zircons are generally associated with olivine nodules and spinel. Vichit (1975) in his preliminary study of Thai basalts suggests similar relationships.

Basalt samples from Thai occurrences (gem-bearing and non-gem-bearing) were collected by the authors on field trips during 1974-76. In this paper, the petrography and chemistry of the sampled occurrences are compared, and petrochemical differences between gem-bearing and non-gem-bearing basalts of Thailand are defined. Speculations are offered concerning the origin of the basalts and the tectonic environment in which they formed.

DESCRIPTION OF BASALT OCCURRENCES

Basalts in Thailand occur as scattered small bodies forming a zone trending northwest-southeast and becoming progressively more voluminous southeastwards into Cambodia, Laos, and Vietnam (Figs. 1 and 2). Each occurrence in Thailand has been named using the initials of a nearby town or village, as shown in figure 2.

The basalts generally occur as flows covering areas of 10 km^2 up to several 100 km^2, but smaller subvolcanic bodies are also found at several localities. Flows are generally thin (1—5 m in thickness) and few in number (less than 10?) and their local distribution is commonly controlled by topographic and structural grain in the area. Most flows occur in areas of low relief and/or in valley floors, and are therefore relatively undissected. However, a few such as SP, BCK, and DC are located in hilly terrain and are consequently more dissected. The forms of the occurrences also vary considerably. Some are simple sheet-like flows, covered with thick red soil and poorly exposed (NR and K). Most have more relief, are less soil-covered, and are clearly derived from central vents constructed of scoriaceous and brecciated basalts and minor tuffs (PS, BR, S, SP, LMP, and TM). Subvolcanic occurrences have the form of plug-like bodies (BP, KH, and BHS) and dyke-like bodies (in the Mekong River near BHS).

To what extent these variations in form reflect different modes of eruption and/or different ages of eruption (and hence degrees of erosion) is not clear. For example, basalts on the Khorat Plateau (Fig. 2) show a variety of forms but, as will be described, are petrochemically very similar. Until more detailed age data are obtained from the basalts, the observed variations in form cannot be adequately interpreted.

AGE OF THE BASALTS

Very little direct dating of Thai basalt occurrences has been attempted. One age of 2.57 ±0.20 Ma was obtained by the fission-track method for a zircon from basalt east of Chantaburi (Carbonnel *et al*, 1972). However, ages of 29.0 ± 1.70 Ma and 23.6 ± 1.20 Ma were obtained by the same authors for zircons thought to be from Kra (TM?), west of Chantaburi. As noted by Carbonnel *et al* (1972), the general appearance of this basalt as well as the young ages obtained for zircons from other basalts in Southeast Asia suggest that these latter ages are in error, although the source of the error is not known.

Attempts to date the Lampang Basalt (LMP) in northern Thailand (Fig. 2) have produced limited results (Barr *et al*, in press). Fission-track dating of basaltic glass indicated an age less than about 1.7 Ma. Potassium-argon dating of 3 samples gave er-

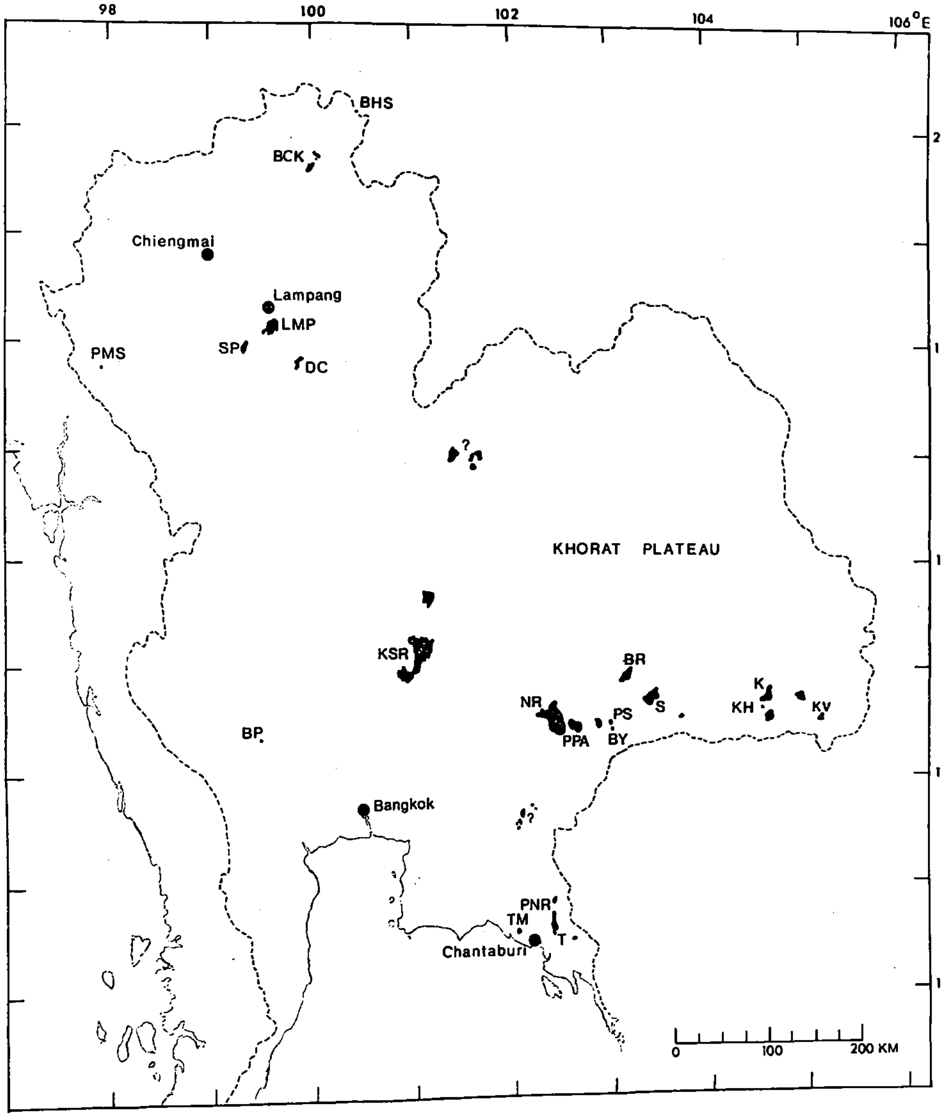

Fig. 2. Distribution of Late Cenozoic Basalts in Thailand. Each occurrence is designated by initials derived from names of adjacent villages or towns. Map is based on Geological Map of Thailand, Dept. of Mineral Resources, Bangkok, 1969.

ratic ages of 0.16 ± 0.023 Ma, 0.038 ± 0.019 Ma, and 0.204 ± 0.030 Ma. This spread of ages was interpreted to indicate loss of argon, and none of the ages was considered reliable. However, palaeomagnetic studies suggested that a magnetic reversal is recorded near the base of the Lampang Basalt sequence. Given the upper limit of 1.7 Ma provided by fission-track age, the age of the Lampang Basalt may be either about

0.69 Ma (corresponding to the end of the Matuyama Epoch) or about 0.95 Ma (corresponding to the beginning of the Jaramillo Event).

More data are available from Indochina (Carbonnel *et al*, 1972) where 15 ages obtained for zircons by the fission-track method indicate three episodes of zircon-bearing basalt eruptions:

(a) 2.46 ± 0.19 Ma (Pailin area)
(b) 1.29 ± 0.23 Ma (Bokéo area)
(c) 0.64 ± 0.11 Ma (Bolovens and Xuan Loc areas)

However, more recent K-Ar dating of basalts from Vietnam indicates that basalts from older plateaux lacking primary volcanic landforms give Miocene ages whereas samples from younger plateaux showing primary volcanic landforms give Upper Pliocene dates (J. P. Berrangé, written comm., 1976).

In addition, nepheline basalt from an isolated occurrence at Kuantan on the east side of the Malay Peninsula (Fig. 1) has given an age of 1.6 Ma by the K-Ar method (Bignell, 1972).

Thus, from limited age data and by camparison with other basalt occurrences in the region, it seems likely that Thai basalts (which generally show volcanic landforms) are younger than 3.0 Ma, but the geographical and chronological distribution of igneous activity within this time period is not known. Dating by the fission-track method of zircons from several localities of Thailand is now in progress.

PETROGRAPHY OF THE BASALTS

Apart from the usual textural variants produced by differing eruptive and cooling conditions in the subaerial environment, two main types of basalts are distinguished petrographically: olivine basalts and basanitoid basalts.

The olivine basalts are typically grey in colour, fine- to medium-grained, and porphyritic, containing phenocrysts and microphenocrysts of olivine, clinopyroxene, and plagioclase. Groundmass is either a holocrystalline assemblage of plagioclase, clinopyroxene, and magnetite, or, less commonly, devitrified brown glass. Alteration has affected these rocks to a variable extent, most obviously in progressive alteration of olivine to iddingsite.

The basanitoid rocks may be distinguished in part by their dark colour, dense aphanitic appearance, and the frequent occurrence, particularly near vents, of megacrysts, ultramafic nodules, and inclusions. In thin section, phenocrysts of olivine and clinopyroxene occur in a groundmass of clinopyroxene microlites, plagioclase, nepheline, alkali feldspar, opaque minerals, and analcime. The mineralogy is complicated by the presence of megacrysts which may include quartz, nepheline, sanidine, anorthoclase, oligoclase, clinopyroxene, orthopyroxene, spinel, and magnetite. Although corundum, zircon, garnet, and rutile were not actually observed by the authors as megacrysts in basalt, they were identified in mineral separates obtained from miners who had concentrated them from weathering products of the basalt. Gems have been found within basanitoid basalts at Pailin in Cambodia and at Xuan Loc in Vietnam (Carbonnel and Robin, 1972; Carbonnel *et al.*, 1972) and there is no doubt that they do originate as megacryst minerals in the basanitoid basalts in Thailand. The megacrysts may be very large (for example, black clinopyroxene crystals up to 5 cm in length), and generally show vitreous lustre and conchoidal fracture. They apparently resemble megacrysts from Cenozoic alkaline volcanic rocks in New South Wales described by Binns *et al.* (1970). More detailed studies of the geochemistry of the megacrysts are now in progress.

Ultramafic nodules are generally spinel lherzolite, although pyroxenite nodules also occur. Some nodules appear to have partially disintegrated to produce glomeroporphyritic clusters of olivine or pyroxene grains. However, most megacrysts are too big or of unsuitable composition to have originated as components of nodules.

Observed inclusions are gabbroic xenoliths, "granitic"-gneiss xenoliths, quartz aggregates, and various crystal pseudomorphs as yet unidentified.

In general, basanitoid rocks appear less altered than the olivine basalts.

Because of the generally fine-grained to glassy textures of the basalts, detailed classification is based on petrochemistry rather than petrography. More detailed petrographic descriptions are included in the petrochemical classification.

PETROCHEMISTRY OF THE BASALTS

Analytical Methods

Rock samples were prepared for analysis by breaking down large samples with a steel hammer and then further disintegrating these fragments in a jaw crusher to about 0.5 cm^2 in size. These fragments were blown clean with compressed air and then sorted, taking care to avoid xenoliths, megacrysts, amygdales, and obviously weathered material. About 50–100 g of this selected sample material was then powdered to –100 mesh using a ceramic mortar and pestle.

Chemical analyses were done by "rapid" methods based on those employed by the Institute of Geological Sciences, London. Silicon, aluminium, total iron, manganese, titanium, and phosphorous were determined absorptiometrically using a Pye-Unicam SP-500 Spectrophotometer. Ferrous iron was determined by titration to a visual end point against potassium dichromate using barium diphenylamine sulphonate as indicator, and ferric iron was found by subtraction.

Calcium and magnesium were determined by atomic absorption spectrophotometry using a Pye-Unicam SP-90A Spectrophotometer, and sodium and potassium were found by flame emission spectrophotometry on a Pye-Unicam SP-90A Spectrophotometer.

Moisture (H_20^-) was determined as the percentage loss on drying to constant weight at 100°C. Total water was determined using a variant of the Penfield method described by Maxwell (1968). Combined water (H_2O+) was then found by subtraction. CO_2 was determined by a simple gas volumetric method.

All samples were analyzed in duplicate. Standard basalts W-1 and BR-1 (CO_2 only) were also analyzed and results show good agreement with accepted values (in brackets): SiO_2, 52.6 (52.64); TiO_2, 1.1 (1.07); Al_2O_3, 15.3 (15.00); Fe_2O_3, 1.7 (1.40); FeO, 8.7 (8.72); MnO, 0.18 (0.17); MgO, 6.7 (6.62); CaO, 11.0 (10.96); Na_2O, 2.1 (2.15); K_2O, 0.6 (0.64); P_2O_5, 0.13 (0.14); CO_2, 0.8 (0.86). Accepted values are from Flanagan (1973).

Treatment of Analytical Data

In Table 1, 30 new chemical analyses of Thai basalts are presented, together with 4 analyses of Thai basalts from other sources (Lacroix, 1933; Carbonnel, 1973; Vichit, 1975). Sample localities are indicated on figure 2. Specimen CAM 526 is from the Khorat Plateau but the exact location is not specified (Carbonnel, 1973).

The two analyses from Vichit (1975) are incomplete. However, they represent occurrences on the Khorat Plateau which could not be sampled by the present authors and hence their inclusion seems warranted. Other analyses of Thai basalts reported by Vichit (1975) were not extensively used by the authors because many are incomplete, totals are erratic, and details of sample locality, petrography, and freshness are not available. However, in general the analyses show trends similar to analyses reported in table 1.

To reduce the varying effects of alteration and oxidation on the chemistry of the basalts since eruption, and thus make comparison between samples more meaningful, the primary analytical data were modified in the following ways:

(a) Ferric to ferrous iron oxide ratios were adjusted on the basis of minimum observed natural values in the freshest samples, as proposed by Irving and. Green (1976). The ratios used are as follows: basanitoid basalts, 0.20; alkali olivine basalts, 0.25; hawaiites and mugearites, 0.40; tholeiitic basalts, 0.25. In general, these ratios are lower than those obtained by the method of Irvine and Baragar (1971).

(b) Oxides (weight percent) were recalculated to total 100% free of water and CO_2, using the selected "original" ratios of Fe_2O_3 to FeO before the data were plotted on figures 3 to 5.

CIPW Norms were calculated using these recalculated analyses (Table 1). Four samples (LMP-1, LMP-3, LMP-4 and PNR-1) contain relatively large amounts of CO_2. For comparison, these analyses were also recalculated to 100% free of water and $CaCO_3$, assuming that CO_2 may have been added to the rocks as $CaCO_3$. Normative data for both types of recalculation are shown for these four samples on figure 7. The degree of undersaturation is little affected by the recalculation free of $CaCO_3$, and the basalts remain basanitoid.

PETROCHEMICAL CLASSIFICATION OF THE BASALTS

An alkalies-silica diagram (Fig. 3) shows that most Thai basalts are alkaline, and some are strongly alkaline. Ratios of K_2O to Na_2O range from 0.15 to 1.0, with strongly alkaline basalts in general possessing higher ratios (Fig. 4). Plots of individual oxides against silica (Fig. 5) illustrate:

(a) a wide range of silica values,
(b) negative correlation between silica and MgO, CaO, P_2O_5, and TiO_2,
(c) positive correlation between silica and Al_2O_3,
(d) no correlation between silica and Na_2O and K_2O.

However, the AFM plot (Fig. 6) suggests that the basalts are not simply related by differentiation from a single parent magma, as will be discussed later.

TABLE 1

Chemical analyses and CIPW normative mineralogies of Thai basalts. Analyses KV–11 and KV–12 from Vichit (1975); BHS–132 from Lacroix (1933); CAM 526 from Carbonnel (1973). Rock types are named according to Figure 7. Analyses were recalculated to total 100% free of volatiles and using selected "original"ferric to ferrous iron ratios as described in the text prior to norm calculation. Mg-values (100 Mg/Mg + Fe^{2}–) were calculated using these selected "original" iron ratios.

ROCK TYPE	NEPHELINITE		BASANITE						NEPHELINE HAWAIITE			NEPHELINE MUGEARITE	
	TM–1	TM–2	PNR–1	DC–10	LMP–1	LMP–2	LMP–3	LMP–4	BP–2	BP–3	KV–11	KH–5	KH–9
SiO_2	40.6	40.2	42.6	45.9	47.2	48.0	46.3	44.4	45.4	45.9	49.52	50.4	50.1
TiO_2	3.3	3.1	2.8	2.1	2.3	2.3	2.3	2.1	2.0	1.9	1.82	2.3	2.2
Al_2O_3	10.8	11.6	12.2	15.7	15.9	15.4	16.0	13.7	13.2	13.3	17.65	15.3	15.1
Fe_2O_3	5.2	4.1	2.7	2.0	1.8	2.2	2.1	2.4	3.4	2.8	7.90*	2.7	2.3
FeO	8.5	9.6	8.2	7.5	5.9	6.1	5.5	4.9	6.3	6.6	—	6.9	6.9
MnO	0.20	0.16	0.19	0.14	0.15	0.15	0.17	0.19	0.18	0.19	0.22	0.13	0.13
MgO	10.4	9.6	8.2	8.4	6.6	8.2	6.0	7.3	9.0	9.2	4.54	5.0	5.7
CaO	10.1	10.1	12.3	8.2	9.3	8.1	9.6	11.7	9.3	8.8	7.66	7.7	7.6
Na_2O	4.3	4.9	2.7	3.4	4.1	3.3	3.4	4.5	5.2	5.0	4.84	5.1	5.2
K_2O	2.4	2.2	2.3	2.5	3.0	3.1	3.4	1.4	2.5	2.4	3.81	2.5	2.6
P_2O_5	1.1	1.1	0.8	0.55	0.7	0.6	0.7	0.6	0.8	0.8	0.50	0.7	0.7
CO_2	0.2	0.2	2.5	0.2	0.9	0.2	1.2	3.8	0.1	0.1	—	0.2	0.2
H_2O^+	1.8	1.6	2.9	2.1	2.0	2.2	2.4	1.0	2.0	2.4	—	1.5	2.0
H_2O^-	0.7	0.6	0.2	1.0	0.4	0.4	0.7	1.5	0.8	0.3	—	0.4	0.3
TOTAL	99.6	99.1	100.6	99.7	100.3	100.3	99.8	99.5	100.2	99.7	98.46	100.8	101.0
Q	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0
Or	5.2	2.2	14.3	15.4	18.3	18.8	21.1	8.9	15.2	14.7	23.02	15.0	15.6
Ab	0.0	0.0	0.9	15.9	13.5	18.2	10.7	10.2	7.9	12.0	17.98	30.0	27.7
An	3.2	3.3	15.2	21.0	16.6	18.5	19.2	14.0	5.4	7.0	15.50	11.6	10.3
Ne	20.4	23.3	12.6	7.6	12.1	5.7	10.5	16.6	20.2	17.2	12.93	7.5	9.2
Lc	7.5	8.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0
Di	33.6	33.5	35.4	14.2	21.2	15.1	20.9	35.5	29.3	26.2	16.15	18.2	18.8
Ol	17.8	16.7	11.4	18.2	10.2	15.7	9.3	7.2	12.0	13.4	6.61	7.7	8.7
Mt	3.3	3.4	2.7	2.4	1.9	2.0	1.9	1.9	4.1	4.0	3.10	4.0	3.9
Il	6.5	6.1	5.6	4.1	4.5	4.5	4.6	4.3	3.9	3.7	3.53	4.4	4.2
Ap	2.6	2.7	2.0	1.3	1.7	1.4	1.7	1.5	1.9	1.9	1.18	1.7	1.7
TOTAL	100.1	100.1	100.1	100.1	100.0	99.9	99.9	100.1	99.9	100.1	100.00	100.1	100.1
100 An/An+Ab	100	100	95	57	55	50	64	58	41	37	46	28	27
100 Mg/Mg+Fe^{2+}	63	60	62	66	65	68	63	68	70	71	61	57	61

*Total iron as Fe_2O_3

TABLE 1. (*Continued*)

ROCK TYPE	ALKALI OLIVINE BASALT			HAWAIITE									
	BHS132	KSR-7	DC-15	DC-3	DC-5	SP-1	KSR-1	KSR-2	KSR-4	NR-3	NR-7	PPA-1	BY-2
SiO_2	45.44	47.1	47.6	50.9	50.9	48.2	48.0	52.7	53.1	48.1	49.1	52.4	52.4
TiO_2	2.22	1.4	1.8	1.7	1.7	2.0	2.1	1.3	1.6	2.2	2.1	2.6	2.8
Al_2O_3	16.14	16.3	15.7	16.3	16.5	17.8	16.3	15.9	16.2	15.2	14.9	14.4	14.4
Fe_2O_3	3.89	2.2	1.7	2.9	3.8	4.9	4.3	5.5	6.4	6.0	7.8	3.5	2.9
FeO	7.22	7.4	8.2	5.3	4.5	3.2	7.9	3.0	1.2	5.2	4.3	5.6	6.4
MnO	0.23	0.16	0.15	0.10	0.12	0.14	0.18	0.14	0.13	0.17	0.15	0.12	0.14
MgO	9.02	7.9	8.35	6.8	6.4	4.7	5.5	6.3	4.0	5.1	5.3	5.1	5.5
CaO	8.98	10.1	8.6	6.9	7.0	7.3	7.2	8.7	7.8	9.1	9.5	6.9	7.2
Na_2O	3.02	3.1	2.3	3.1	3.2	4.4	4.0	3.9	4.5	3.3	4.0	4.2	4.3
K_2O	1.63	0.7	1.9	2.3	2.4	2.0	0.9	1.2	2.3	1.4	1.2	1.5	1.5
P_2O_5	0.32	0.2	0.5	0.5	0.5	0.8	0.3	0.3	0.5	0.4	0.5	0.9	0.7
CO_2	—	0.1	0.2	0.1	n.d.	0.2	0.1	0.1	0.1	0.1	0.1	n.d.	0.1
H_2O+	1.87	3.3	2.5	2.2	1.6	3.1	2.6	0.7	1.3	1.1	0.9	1.3	1.4
H_2O^-	0.72	0.8	0.4	1.4	2.1	1.7	1.4	0.6	2.7	1.7	1.0	1.4	1.8
TOTAL	99.98	100.8	99.9	100.5	100.7	100.4	100.8	100.3	101.8	99.2	100.9	99.9	101.5
Q	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.8
Or	9.84	4.3	11.6	14.1	14.6	12.4	5.5	7.2	14.0	9.3	7.2	9.1	9.0
Ab	16.89	25.5	20.1	27.1	27.9	33.9	35.0	33.5	39.2	29.1	31.9	36.6	37.0
An	26.21	29.5	27.8	24.6	24.3	24.1	24.7	22.7	17.7	23.2	19.5	16.5	15.8
Ne	4.98	0.9	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0	1.4	0.0	0.0
Di	13.87	17.1	10.5	6.0	6.6	6.9	8.4	15.4	15.2	17.3	20.5	10.3	12.8
Hy	0.00	0.0	9.5	18.4	15.4	0.0	5.5	12.4	2.3	4.9	0.0	13.9	13.5
Ol	19.90	16.6	13.3	1.8	3.1	10.6	10.9	2.2	4.3	6.3	9.4	0.0	0.0
Mt	3.24	2.9	2.5	3.5	3.5	3.4	5.2	3.4	3.0	4.7	4.9	3.8	3.9
Il	4.30	2.8	3.5	3.3	3.3	4.0	4.1	2.5	3.1	4.3	4.1	5.1	5.4
Ap	0.76	0.5	1.2	1.2	1.2	2.0	0.7	0.7	1.2	1.0	1.2	2.2	1.7
TOTAL	99.99	100.1	100.0	100.0	99.9	100.1	100.0	100.0	100.0	100.1	100.1	100.1	99.9
100 An/Ab+An	61	54	59	48	47	42	41	40	31	44	38	31	30
100 $Mg/Mg+Fe^{2+}$	65	65	64	68	66	60	53	66	59	54	53	59	60

TABLE 1. (*Continued*)

ROCK TYPE	HAWAIITE					MUGEARITE		THOLEIITE
	PS–3	BR–1	K–2	KV–12	CAM526	PS–8	S–3B	BCK–5
SiO_2	51.5	48.9	50.6	48.26	49.00	51.5	52.2	48.9
TiO_2	2.8	2.9	1.6	1.65	2.18	3.0	2.4	1.5
Al_2O_3	14.1	13.5	15.7	17.05*	16.77	14.9	14.5	15.8
Fe_2O_3	4.1	4.1	6.6	11.23*	7.88	5.4	3.8	2.5
FeO	5.1	6.5	4.1	—	3.69	3.4	5.05	9.5
MnO	0.11	0.14	0.07	0.25	0.14	0.10	0.11	0.14
MgO	5.1	6.8	6.0	5.49	3.90	4.2	5.7	8.4
CaO	6.8	7.7	7.1	9.40	8.53	6.0	6.5	8.1
Na_2O	4.0	3.7	3.5	4.17	3.63	4.8	4.9	2.7
K_2O	1.4	1.8	1.5	1.43	1.63	2.3	1.7	0.6
P_2O_5	0.8	0.7	0.4	0.19	0.46	1.1	0.6	0.3
CO_2	0.3	0.1	n.d.	—	—	n.d.	0.2	0.2
H_2O+	1.3	1.1	1.4	—	2.46	1.6	1.5	1.3
H_2O^-	2.4	1.7	1.2	—	0.70	1.5	1.6	0.5
TOTAL	99.8	99.6	99.8	99.12	100.27	99.8	100.8	100.4
Q	3.3	0.0	0.0	0.0	0.00	0.0	0.0	0.0
Or	8.7	11.0	9.2	8.6	9.90	14.1	10.3	3.6
Ab	35.4	32.4	30.6	25.8	31.55	42.1	42.6	23.2
An	17.1	15.4	23.5	23.9	25.32	12.8	12.9	29.7
Ne	0.0	0.0	0.0	5.4	0.00	0.0	0.0	0.0
Di	10.2	15.6	8.3	18.1	12.41	8.6	13.0	7.5
Hy	13.9	5.2	19.1	0.0	5.34	7.5	4.2	22.6
Ol	0.0	8.5	0.9	10.3	5.40	2.7	7.2	6.3
Mt	3.9	4.5	4.4	4.4	4.72	3.7	3.7	3.5
Il	5.6	5.7	3.1	3.2	4.25	5.9	4.7	2.9
Ap	1.9	1.7	1.0	0.4	1.10	2.7	1.4	0.7
TOTAL	100.0	100.0	100.1	100.1	100.0	100.1	100.0	100.0
100 An/Ab+An	33	32	43	48	45	23	23	56
100 Mg/Mg+Fe^2	59	62	59	57	47	55	62	61

*Total iron as Fe_2O_3

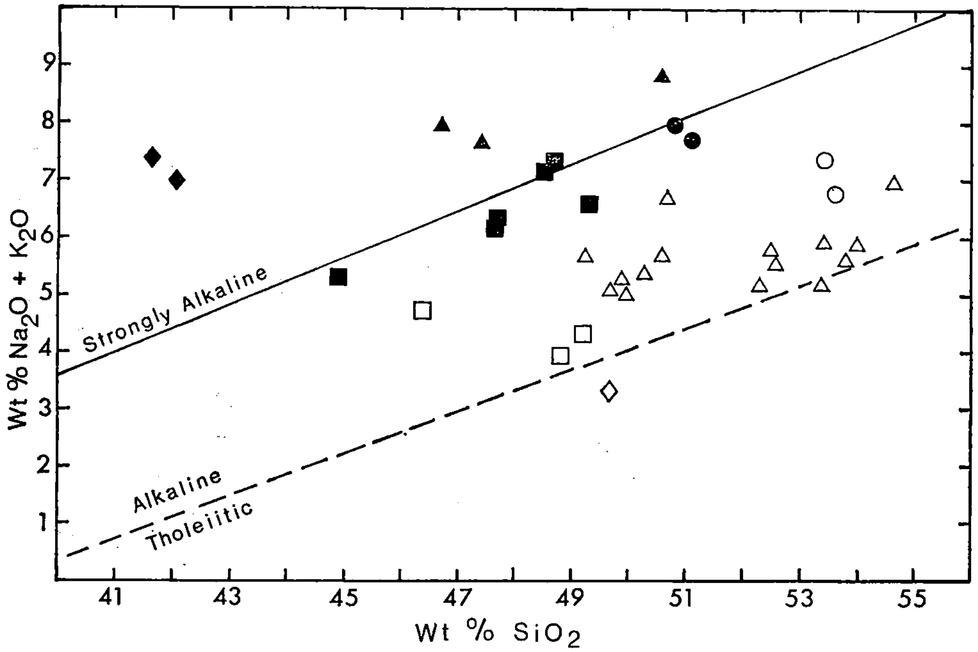

Fig. 3. Alkalies – silica diagram for Thai basalts. Analyses recalculated to 100% before plotting as described in text. Dashed dividing line after Macdonald (1968). Solid dividing line after Saggerson and Williams (1964). Closed symbols = Basanitoid Basalts; diamonds, nephelinites; squares, basanites; triangles, nepheline hawaiites; circles, nepheline mugearites. Open symbols = Hawaiitic Basalts; squares, alkali olivine basalt; triangles, hawaiites; circles, mugearites. Open diamonds = Tholeiitic Basalt. Rock names from figure 7.

Classification of the alkaline rocks is based on their normative compositions, following Coombs and Wilkinson (1969) and Best and Brimhall (1974). Normative nepheline or hypersthene values are plotted against normative plagioclase composition, and subdivisions made on the basis of certain arbitrary values (Fig. 7). The rock types identified by this classification scheme are described below. In general, basalts which were classified as "basanitoid" on the basis of petrography are classified petrochemically as nephelinite, basanite, nepheline hawaiite, and nepheline mugearite, whereas the petrographic group "olivine basalts" includes alkali olivine basalt, hawaiite, mugearite, and tholeiite.

Nephelinites

The norms of nephelinites are characterized by more than 5% nepheline, presence of leucite, and small amounts of very calcic plagioclase. With increasing amounts of normative plagioclase of decreasing calcium content nephelinites are transitional to basanites. Chemically, they show low SiO$_2$ and Al$_2$O$_3$, and high iron, TiO$_2$, MgO, CaO, and P$_2$O$_5$. Both Na$_2$O and K$_2$O are relatively high (Fig. 3) but the nephelinites are not exceptionally potassic (Fig. 4).

Our present sampling indicates that nephelinites occur only in the Chantaburi region in the vicinity of a volcanic vent near Tha Mai (TM) where they are closely

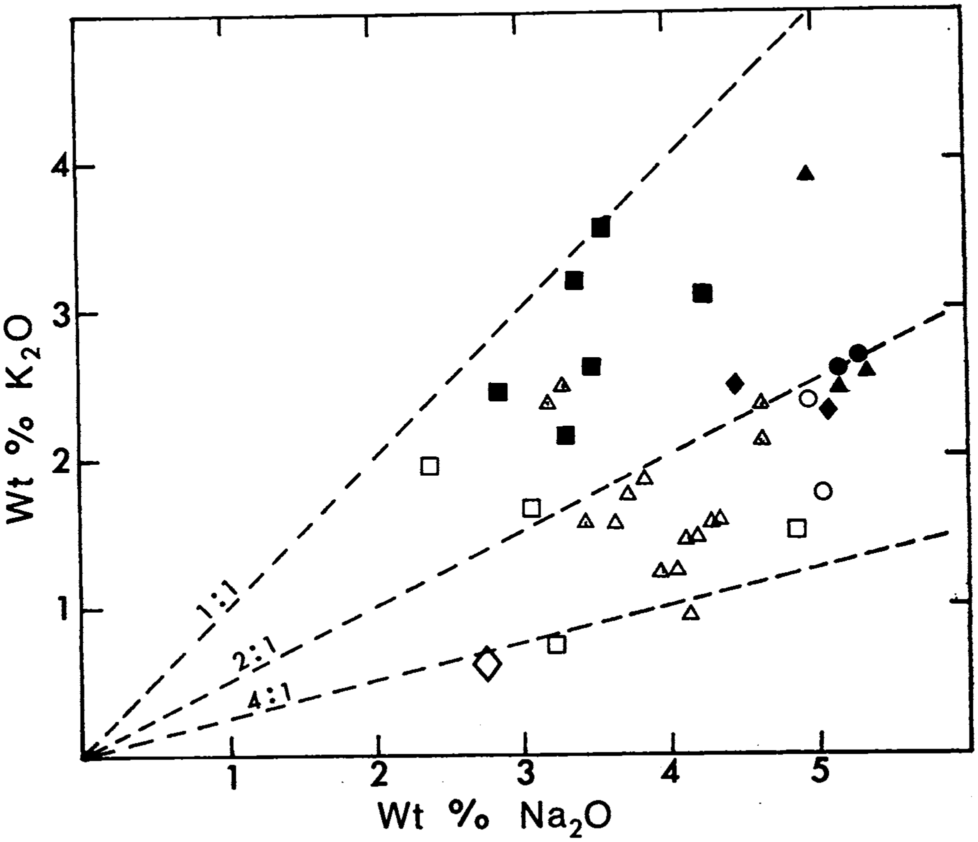

Fig. 4. K_2O–Na_2O diagram for Thai basalts. Analyses recalculated to 100% before plotting as described in Text. Symbols as in figure 3.

associated with corundum and zircon (Fig. 2). However chemically similar basalts (Vichit, 1975) may also occur in Trat Province (T, Fig. 2).*

In hand specimen nephelinites are very dark fine-grained rocks containing small olivine phenocrysts. Megacrysts and ultramafic nodules are abundant very close to vents. In thin section, nephelinites are characterized by abundant phenocrysts of olivine (Fo_{90}) and minor clinopyroxene (with reaction rims) in a groundmass of opaque minerals, clinopyroxene, nepheline, and analcime. Plagioclase is absent.

Basanites

Basanites are characterized by more than 5% normative nepheline and by normative labradorite. Chemically they are rather variable, showing a range in SiO_2 and other oxides (Fig. 5). They verge on strongly alkaline (Fig. 3) and tend to be potassic (Fig. 4). Sample PNR–1 appears transitional between nephelinite and basanite, but

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*This has been confirmed by recent analyses of basalts from Ban Ta Bat and Ban Nong Bon in eastern Trat Province.

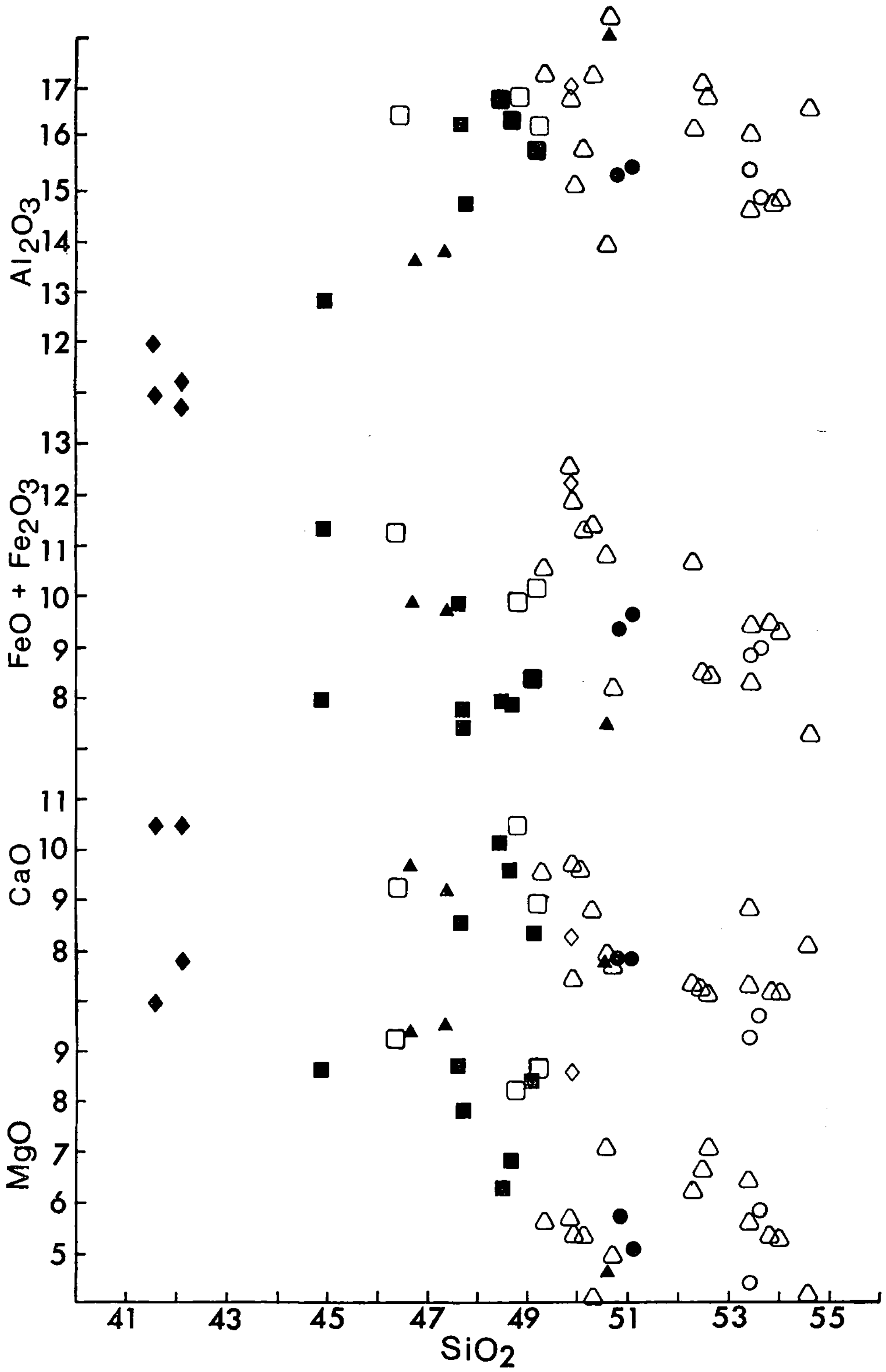

Fig. 5. Silica variation diagram for Thai basalts. Analyses recalculated to 100% before plotting as described in Text. Symbols as in figure 3.

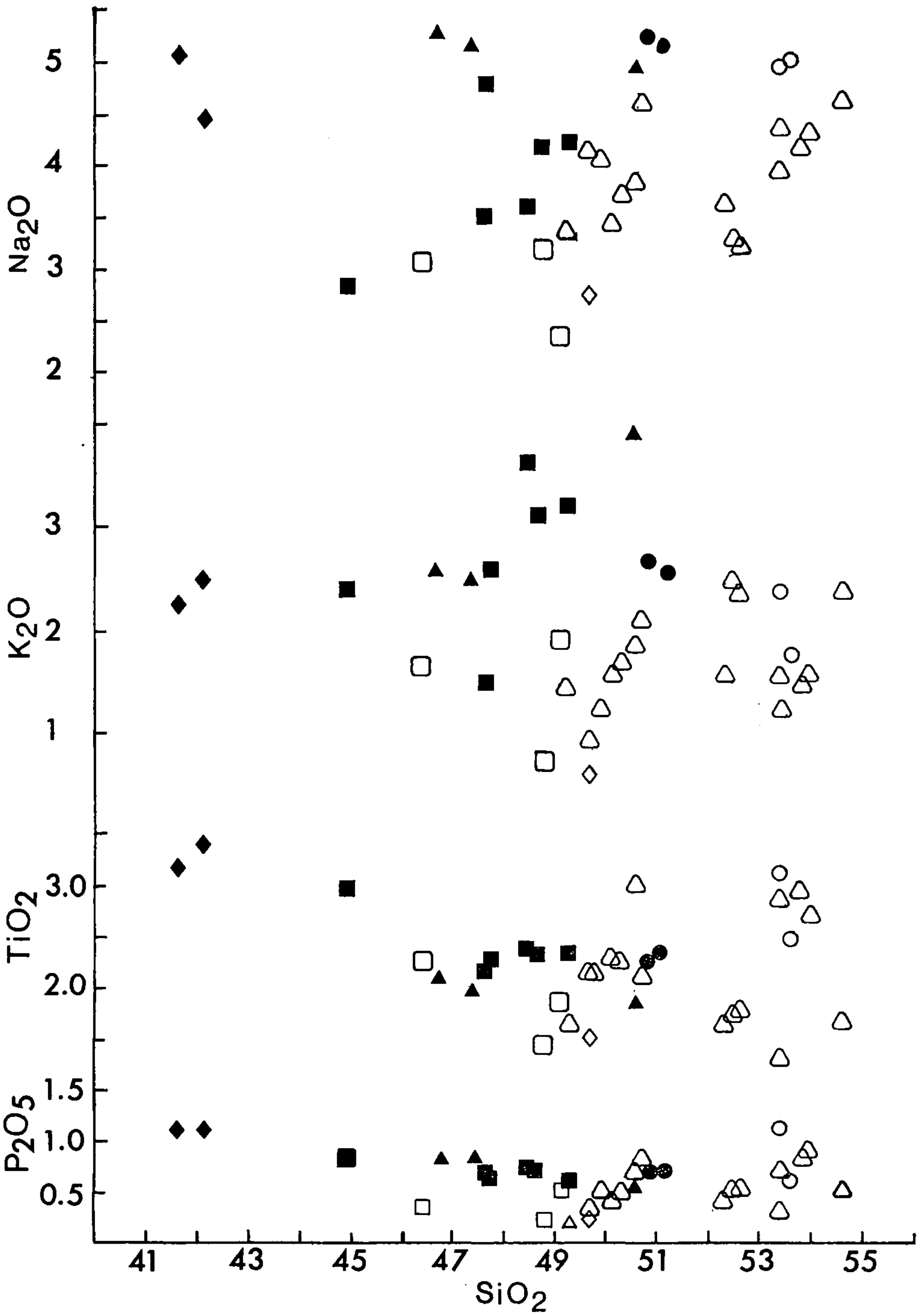

Figure 5. (*Continued*)

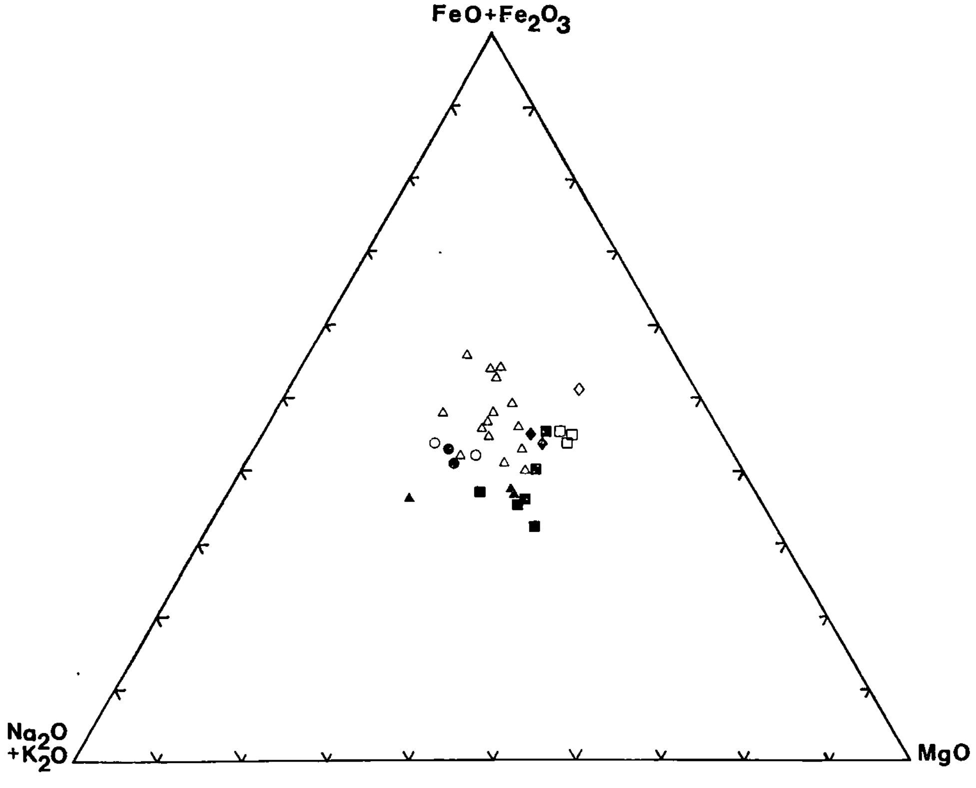

Fig. 6. AFM diagram for Thai basalts. Symbols as in figure 3.

on the basis of the norm calculated free of H_2O and $CaCO_3$ (Fig. 7), and petrography, it is classified with the basanites.

Basanites show wider distribution than the nephelinites, occurring in the Chantaburi region (PNR), near Denchai (DC), and near Lampang (LMP) where they appear to be the only basalt type present, and are not restricted to the vicinity of vents. In hand specimen, basanites are generally similar to nephelinites, and may contain ultramafic nodules (as near Denchai). However, few megacrysts are observed in the basanites, although they appear to be associated with gem-deposits near both Denchai and Chantaburi. In thin-section, the basanites consist of olivine phenocrysts (Fo_{80-90}) and smaller clinopyroxene grains (augite ?) in an intergranular (or intersertal) groundmass of plagioclase laths (An_{42-55}), clinopyroxene, titaniferous magnetite, and, in some flows, glass. Alkali feldspar and/or nepheline may also occur but only in accessory amounts.

Nepheline Hawaiite

Nepheline hawaiite is characterized by more than 5% normative nepheline and by normative andesine.

The occurrence of nepheline hawaiite at Bo Phloi has the form of a subcircular plug, about 300 m in diameter, around which gem-stones (mainly sapphire and spinel)

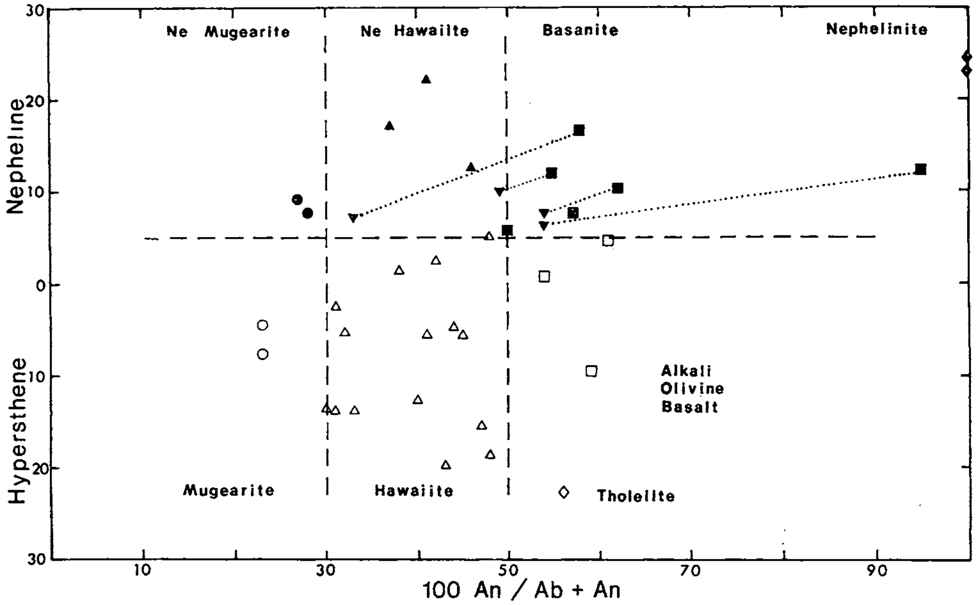

Fig. 7. Plot of normative hypersthene or nepheline against normative plagioclase composition. Symbols as in figure 3. Samples high in CO_2 which are recalculated to 100% free of H_2O and $CaCO_2$ before calculating norms are shown as inverted triangles, joined by dotted lines to the volatile-free normative mineralogy. Field boundaries after Best and Brimhall (1974) and Coombs and Wilkinson (1969).

are concentrated from gravels. The rocks themselves are dark and fine-grained, and very similar to the basanitoid types already described. But they contain a spectacular number of ultramafic nodules (spinel lherzolite), megacrysts, and inclusions of many types. In thin section, olivine (Fo_{90-95}), clinopyroxene, orthopyroxene, plagioclase, and occasional spinel phenocrysts are observed in a fine-grained groundmass of aegerine-augite, nepheline, andesine, alkali feldspar, titaniferous magnetite, and analcime. The most common megacrysts are black clinopyroxene, spinel, nepheline, plagioclase, sanidine, and anorthoclase. The Bo Phloi nepheline hawaiite is strongly alkaline (Fig. 3) and high in Na_2O (Fig. 4) and MgO, but low in SiO_2 and Al_2O_3 (Fig. 5).

In chemistry some basalts from east of Kantharalak (KV–11, KV–12) are also nepheline hawaiites. KV-12 plots close to the arbitrary boundary with hawaiite (Fig. 7) and seems to have closer chemical affinities with hawaiites than nepheline hawaiites (Figs. 3,4). However KV-11 has higher K_2O, TiO_2, and P_2O_5, and lower total iron, characteristic of nepheline hawaiites.

Nepheline Mugearite

This type is characterized by more than 5% normative nepheline and by normative oligoclase. The only known Thai occurrence (KH) of nepheline mugearite is an intrusive plug 500 m in diameter forming a prominent hill (elevation 262 m) 50km south of Sisaket. This plug is located near, but separate from, poorly exposed flows of hawaiite composition (K). The intrusion is assumed to be significantly older than these flows.

The nepheline mugearite of the plug is a medium-grained grey rock, rather homogeneous in appearance except for local pegmatoid patches of similar mineralogy. No megacrysts or ultramafic nodules occur. In thin section, the rock consists of euhedral olivine (Fo_{80}), subhedral clinopyroxene (subcalcic augite), and large finely zoned plagioclase laths (An_{40-60}) together with abundant titaniferous magnetite and apatite needles, minor alkali feldspar and biotite, and interstitial carbonates and zeolites. The texture is intergranular.

Alkali Olivine Basalt

Alkali olivine basalt is characterized by normative plagioclase more clacic than An_{50}, and by normative nepheline less than 5% or low normative hypersthene. Occurrences of these rocks are not common, but they occur as flows in association with hawaiites near Kok Samrong (KSR), and with hawaiite and basanite near Denchai (DC). These rocks are typical fine-grained, grey olivine basalts composed of olivine (Fo_{80-85}), clinopyroxene, plagioclase (An_{40-44}), and titaniferous magnetite, with intergranular to subophitic textures depending on the habit of the clinopyroxene. Ultramafic nodules were found only in the flow sampled near Denchai.

Chemically, some basalts in Trat Province (Vichit, 1975) and in the Mekong River at Ban Huai Sai (BHS 132, Table 1) are also alkali olivine basalts. The latter is described as "glassy, aphyric basalt" (Lacroix, 1933). These areas were not sampled during the present study.

Hawaiites

Hawaiites are characterized by normative andesine, and by less than 5% normative nepheline or normative hypersthene. Hypersthene values in Thai hawaiites may be as high as 19%, but their alkaline character is indicated by high total alkalies (Fig. 3) and by ubiquitous sodic plagioclase occurring with olivine and clinopyroxene. Compared to basalts described above, they generally have higher SiO_2, and Al_2O_3 and lower MgO, CaO, total iron, and alkalies (Fig. 5).

Hawaiites are by far the most abundant and widespread of the alkaline basalts of Thailand. Most occur on the Khorat Plateau of eastern Thailand, but they also occur in association with alkali olivine basalt near Kok Sam Rong (KSR) just west of the Khorat Plateau, and with alkali olivine basalt and basanite near Denchai (DC) further to the north (Fig. 2).

They are fine-grained, sparsely porphyritic olivine basalts, petrographically similar to alkali olivine basalts. They are composed of small olivine phenocrysts (Fo_{75-85}), plagioclase laths (An_{35-55}), interstitial to subophitic clinopyroxene (augite), and titaniferous magnetite. Plagioclase may also occur as large zoned phenocrysts (labradorite-bytownite). Plagioclase laths commonly show flow alignment. Alteration is common, with olivine altering to iddingsite and to serpenitine and magnetite, and magnetite altering to hematite. Interstitial and amygdaloidal carbonate are common.

Mugearites

Mugearites resemble hawaiites but contain normative oligoclase. They occur as flows associated with hawaiite at two localities on the Khorat Plateau (PS and S).

At PS, the mugearite occurs on the top of a sequence of hawaiite flows exposed on a hill (volcanic vent ?). Mugearites are petrographically very similar to hawaiites.

Olivine Tholeiite

The only Thai basalt occurrence which has been found to be distinctly non-alkaline is the tholeiite occurring near Thoeng in Chiang Rai province, northern Thailand (BCK). These are distinctive light grey basalts containing zoned phenocrysts of plagioclase (labradorite) and microphenocrysts of clinopyroxene in a groundmass of plagioclase laths, clinopyroxene (augite), minor olivine, magnetite, and calcite. Clinopyroxene microphenocrysts commonly show narrow reaction rims, and plagioclase phenocrysts exhibit spongy or skeletal growth zones, and some reverse zoning. Textures are generally intergranular.

The small occurrence (PMS) in northwest Thailand has only been sampled from float material. However, it is petrographically very similar to BCK basalt, and may also be tholeiitic.

COMPARISON OF GEM-BEARING AND NON-GEM-BEARING BASALTS

As gems were not found actually within any of the analyzed basalts, direct correlation of gem occurrence with basalt type has an element of uncertainty. However, at Bo Phloi (BP) and Tha Mai (TM) only one type of basalt occurs. In these two cases, it seems clear that the gems are derived from nepheline hawaiite and from nephelinite respectively, in both cases adjacent to vents.

At another gem occurrence near Denchai (DC) more than one type of basalt occurs, with two basanite flows (DC–10) overlying flows of alkali olivine basalt (DC-15) and hawaiite (DC–3,5). The basanite flows appear to be restricted to a relatively small area in the vicinity of the inferred vent. Zircons and sapphires are mined from alluvial deposits on valley floors radiating outwards from this vent area, and are presumed to be derived from weathering of the basanite flows.

Some 20 km east of Chantaburi, gems are mined at several localities in Trat Province (T, Fig. 2), at the western and southern margins of lobate north-trending lava fields (Hughes and Bateson, 1967). Four analyses reported by Vichit (1975) indicate that these basalts are low in silica and high in iron, ranging from alkali olivine basalt through basanite or nephelinite. The gems are described as being derived from basalts by weathering of the edges of the flows, and relationships with source vents are unknown. Our sample PNR–1 from the extreme northern end of these lava fields is transitional between basanite and nephelinite.*

The other known gem occurrence in Thailand is southeast of Kantharalak, where corundum and zircon are found over a wide area in potholes on the surface of a plateau sloping down to the north from the Cambodian border (Aranyakanon and Sampatawanit, undated report). "Olivine basalt" cobbles are reported in association with these gems but outcrops are not observed. Analysis KV–12 (from Vichit, 1975) represents a basalt occurrence northeast of these gem fields and, in view of the regional

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*Recently completed analyses of basalt samples from Ban Nong Bon Ta Bat east of the main coccurrenes in Trat Province confirm that these gem-bearing basalts are basanitoid.

drainage, is an unlikely source of the gems (a conclusion in accord with the chemistry of the basalt). On the basis of its chemical composition, KV–11 (nepheline hawaiite) could be a source of gems, but the exact locality from which this sample was collected is not known to the authors. However, a plug of nepheline hawaiite (KH) in the area (Fig. 2) indicates that extensive erosion of basalt of basanitoid chemistry has occurred.

On plots shown in figures 3 to 7, the distinction between these gem-bearing basalts and the non-gem-bearing basalts is clear. All gem-bearing basalts are nephelinite, basanite, or nepheline hawaiite. They tend to be strongly alkaline, with high TiO_2, P_2O_5, CaO, MgO, and total iron. They are low in SiO_2 and Al_2O_3 relative to non-gem-bearing basalts. They generally occur near vents and contain a variety of nodules, megacrysts, and inclusions.

On the basis of these characteristics, the Lampang Basalt (LMP) should also be gem-bearing, although gems have not been found. This may be related to the relatively undissected nature of the Lampang Basalt which is confined to a flat valley floor.

PETROGENESIS OF THE BASALTS

Alkaline basalt magmas are generally agreed to have originated by partial melting of the mantle at relatively deep levels. A variety of alkaline magmas may be produced by varying the amount and depth of both partial melting and fractional crystallization during ascent. Green and Irving (1976) suggest that the Mg-value (100 Mg/Mg + Fe^{2+}) may be an indication of magma history. Values higher than 66 indicate primary magmas in equilibrium with mantle olivines of composition Fo_{86-90}, whereas values lower than 66 imply some history of fractional crystallization. As pointed out by Irving and Green (1976), this parameter is not ideal because of the necessarily rather subjective estimation of pre-eruptive Fe_2O_3 contents. However, in the absence of other criteria, the Mg-value may provide a guide to petrogenesis. On this basis, Thai basalts have undergone varying degrees of crystal fractionation (Table 1, Figure 8). However the basanitoid Lampang Basalts, the basanites and hawaiites of the Denchai Basalt, and the nepheline hawaiites of the Bo Phloi plug may be primary magmas (although the possibility of forsteritic olivine accumulation cannot be ignored in any of these). Alkali olivine basalts are also close to being primary. Other nepheline hawaiites, nepheline mugearites, and most hawaiites are clearly derived magmas. Nephelinites

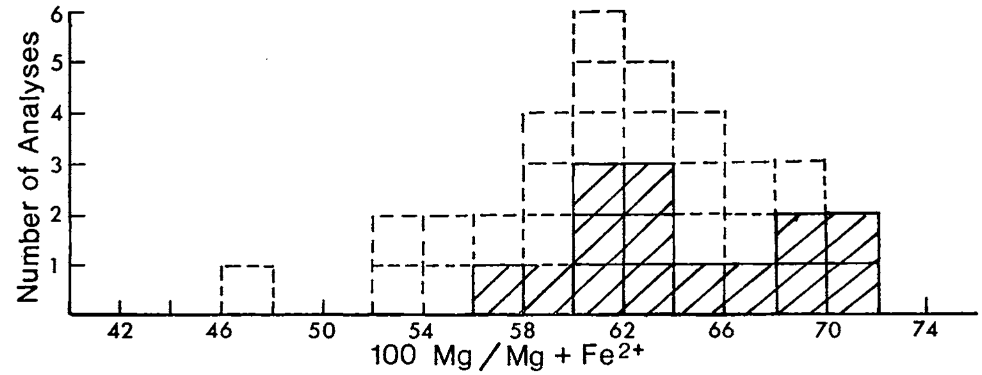

Fig. 8. Histogram of Mg-Values for Thai basalts. Cross-hatched squares are basanitoid basalts; open squares are hawaiitic basalts. Mg-values after Irving and Green (1976).

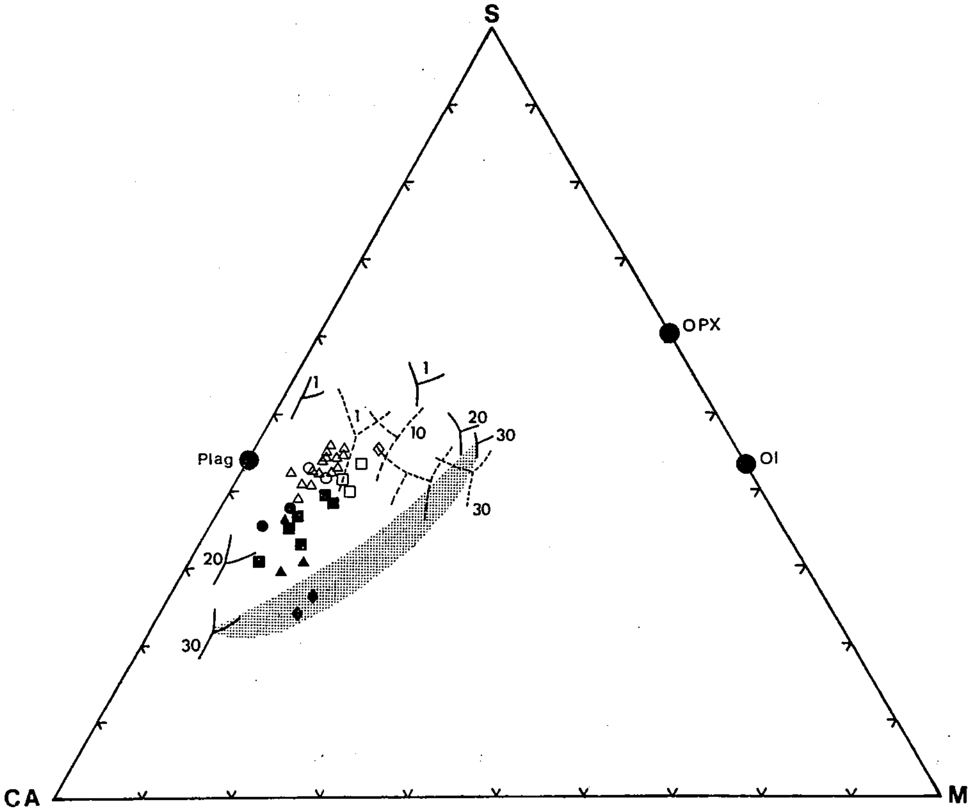

Fig. 9. Liquidus relations and Thai basalt analyses, plotted in the CMAS system projected from CMS_2 (clinopyroxene) onto CA–M–S. Dashed lines show approximate positions of primary phase boundaries involving olivine, orthopyroxene, and aluminous phases at 1 atm., 10, 20, and 30 kb deduced from experimental data. Solid lines are analogous boundaries at 1 atm., 20, and 30 kb in the systems $CaAl_2O_4$–Mg_2SiO_4–SiO_2 (centre of diagram) and $NaAlSiO_4$–Mg_2SiO_4–SiO_2 (near CA–S edge). Phase boundaries from Best and Brimhall (1974). Symbols for Thai basalts as in figure 3.

and basanites of the Chantaburi area (TM and PNR) apparently have anomalously low Mg-values because of their unusually high total iron contents and therefore are probably not derived magmas. More detailed geochemical studies of these unusual rocks are in progress.

Additional insight into the petrogenesis of the basalts is gained by recalculating the analytical data in terms of the CMAS system, CaO–MgO–Al_2O_3-SiO_2 (O'Hara, 1968). These data can then be plotted on the CMAS tetrahedron, and can be projected onto any of a number of planes within the tetrahedron. Following Best and Brimhall (1974) the data for Thai basalts were projected from CMS_2 (diopside) onto the plane CA-M-S, which they consider to be most suitable (subject to a number of constraints) for alkaline basalts. In this projection (Fig. 9) Thai basalts form two "groups": nephelinites, basanites, nepheline hawaiites, and nepheline mugearites form a scattered group separate from alkali olivine basalts, hawaiites, and mugearites which form a cluster. This pattern can be interpreted using experimentally derived primary phase boundaries and invariant points involving: (i) liquid, pyroxenes, olivine, and an aluminous phase at 1 atm., 10 kb, 20 kb, and 30 kb deduced for rocks containing little or no components other than the CMAS oxides (significant concentrations of other elements would shift phase boundaries and cause possible appearance of new phases); (ii) liquid, olivine, orthopyroxene, and an aluminous phase at 1 atm., 20 kb, and 30 kb in the systems $CaAl_2O_4$–Mg_2SiO_4–SiO_2 and $NaAlSiO_4$–Mg_2SiO_4–SiO_2 taken from Kushiro (1968). This demonstrates the effect of alkalies in the system. Many constraints on the use of this diagram are discussed in detail by Best and Brimhall (1974). However, used in a general sense, the diagram seems valid. The shaded band schematically represents the range of liquids produced by variable degrees of partial melting at 30 kb. As degree of melting increases, liquid compositions shift from a point near the CA-S join (where incompatible elements are highly concentrated) toward a point in the interior of the projection (where incompatible elements are more diluted). The spread of the basanitoid group parallel to this shaded band may correspond to increasing amounts of partial melting under high pressure conditions whereas the spread parallel to the trend from 30 kb to 20 kb pressure may indicate that chemical variation is caused by different depths of partial melting as well as degree (although the absolute pressures indicated by the diagram cannot be considered accurate). This is in agreement with the common association of ultramafic nodules and high-pressure megacrysts with these basalts, indicating pressures in excess of 20 kb (Binns *et al*, 1970; Irving, 1974; Ellis, 1976). The survival of these heavy inclusions in the magma suggests rapid ascent to the surface, which precludes extensive crystal fractionation or accumulation. This is in agreement with the generally high Mg-values of the basanitoid basalts. However, experimental work (Ellis, 1976; Irving and Green, 1976) has demonstrated that nepheline hawaiite and nepheline mugearite can be produced from a basanite parent by fractional crystallization of amphibole (and other minerals) under hydrous, high-pressure conditions. This process may have been operating prior to final ascent of the magmas to cause the observed range in Mg-values.

The grouping of alkali olivine basalt, hawaiite, and mugearite analyses at the silicic end of the basanitoid trend lies closest to the 1 atm. invariant points, suggesting equilibration at low pressures. Fractionation of olivine and possibly also accumulation of plagioclase probably explain the trend within this group from alkali olivine basalt to hawaiite and mugearite. The general absence of ultramafic nodules and megacrysts suggests slow ascent of magma permitting significant degrees of crystal fractionation and accumulation.

Production of hawaiites from basanite is not considered to be possible by any reasonable fractionation process (Best and Brimhall, 1974; Irving and Green, 1976). Alkali olivine basalts produced by 5–15% melting of the mantle under hydrous conditions are generally considered parental to hawaiites. The pressure at which partial melting occurs cannot be deduced but is assumed to be lower than those at which the basanite melts form. The apparently small volume of alkali olivine basalt compared to hawaiite in Thailand is not in support of this idea. It may be that under some conditions hawaiite is the direct result of partial melting (for example DC-3, DC-5, and KSR-2 which have high Mg-values). However, alkali olivine basalt is also present at both Denchai (DC-15) and Kok Sam Rong (KSR-7). At Denchai, the alkali olivine basalt and hawaiite flows are overlain by basanite flows, which invites speculation concerning relationships between the two groups in spite of experimental evidence to the contrary.

Tholeiitic magmas are generally thought to originate by relatively large amounts of melting (20%) at relatively shallow levels in the mantle (Green and Ringwood, 1967). The Mg-value (Table 1) and the CA-M-S plot (Fig. 9) indicate that some shallow crystal fractionation occurred prior to eruption of tholeiitic magmas in Thailand.

Variations in the ratio K_2O/Na_2O observed in Thai basalts (Fig. 4) may be explained by varying amounts of partial melting, inhomogeneous source material, and/or fractionation of clinopyroxene (as suggested by Ellis, 1976).

ORIGIN OF GEMS AND OTHER MEGACRYSTS

Corundum, zircon, and other high-pressure mineral phases appear to be confined to the basanitoid group, magmas of which probably ascended more rapidly and from deeper mantle levels than the hawaiitic magmas. These data (particularly the association with a chemically distinctive group of magmas which is not restricted geographically to any particular area in Thailand) appear to confirm the high-pressure cognate origin of these minerals. As yet, insufficient chemical data are available to assess the chemical and physical conditions which lead to the formation of the various megacryst phases. Detailed geochemical work on these minerals is now in progress.

TECTONIC SETTING AND ORIGIN OF THE BASALTS

Continental alkaline basalts are generally associated with rifting and block faulting (e.g. East African Rifts, Rhine Graben, Basin and Range Province), but in some places the tectonic setting is not clear (e.g. Eastern Australia, North Africa). The latter situation is true for basalts in Southeast Asia. It has been suggested (e.g. Zonenshain *et al*, 1974) that alkaline magmatism is part of the zonal pattern of magmatism associated with subduction zones in the western Pacific region, occurring farthest from the trench behind the zone of calc-alkaline volcanism. This explanation seems untenable for alkaline basalts in Southeast Asia because of their increase in volume to the southeast (Fig. 1), a direction approximately parallel to the nearest appropriate subduction zone (Fig. 10). Also, it is difficult to accept that the Indonesian subduction zone can be responsible for volcanism 1000 km behind the active calc-alkaline volcanism, although it might be a factor in occurrences of alkaline basalt in Malaysia.

An alternative suggestion relating the alkaline volcanism to opening of marginal basins is suggested here. The tectonic map of Southeast Asia showing Late Mesozoic-Cenozoic structural features (Fig. 10) suggests progressive migration of Southeast Asia towards the SSE, as proposed by Rodolfo (1969). Part of this migration is manifested by development of marginal basins, mainly in the eastern half of the region.

Ben-Avraham and Uyeda (1973) in their study of the development of the China Basin show that north-south extensional opening of the basin occurred either during Late Jurassic to Early Cretaceous or Late Cretaceous to Early/Middle Tertiary. The China Basin appears to be a typical marginal basin and a direct analogue of the Japan Sea. Although the mechanism for formation of marginal basins is not clear (Karig, 1971; Packham and Falvey, 1971) lithospheric thinning must be involved and it seems likely that the effects would not be restricted to within the limits of the developing basin, but would be developed in the Indochinese peninsula to the west. It is proposed that those effects include block faulting and alkaline basaltic magmatism.

Isayev and Kkhoan (1976) on the basis of gravity data describe two downwarps trending southeast in the continental crust in Indochina accompanied by crystal thinning and mantle upwelling. Crustal thickness apparently decreases from 35–40 km to 30–35

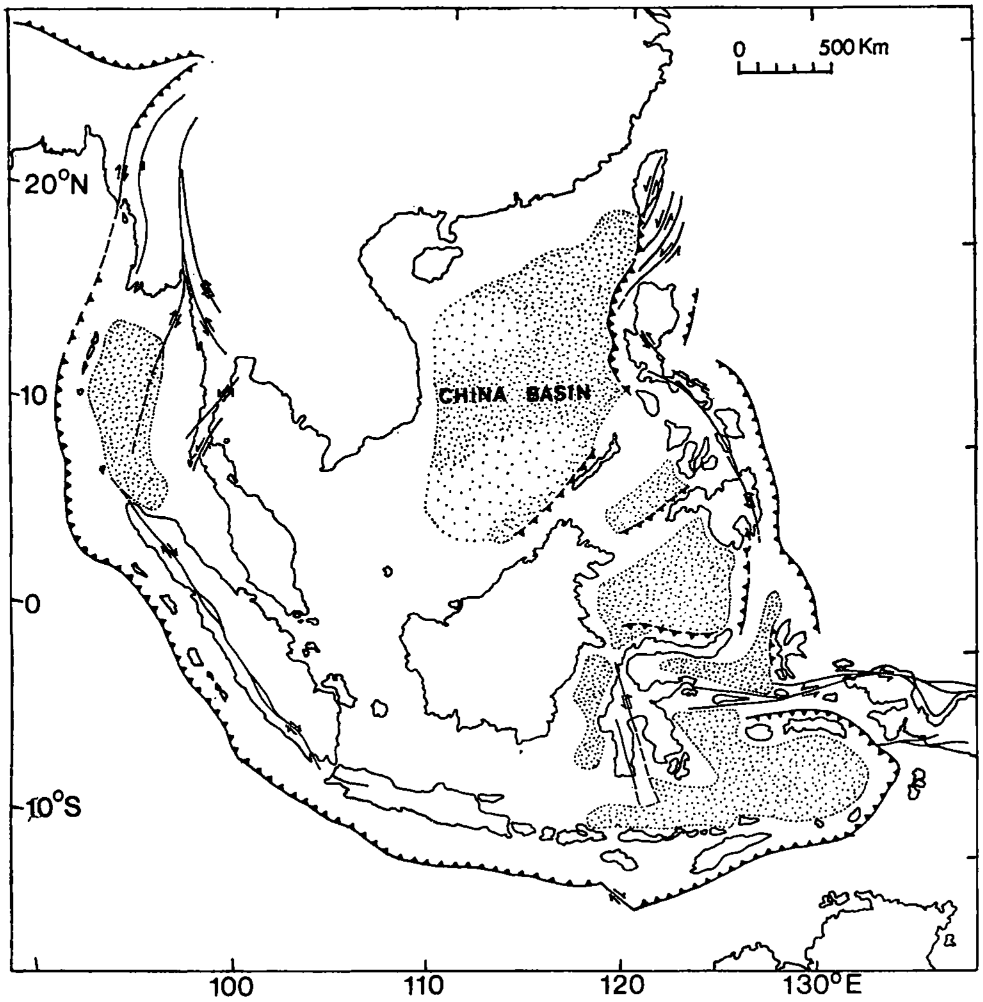

Fig. 10. Late Mesozoic structural features of Southeast Asia. Dotted areas are marginal basins. Hatchured lines are subduction zones. Modified from figure 1 of CCOP–IOC (1974).

km. The "Hanoi Downwarp" was formed at least as early as Palaeocene and has undergone continuous sinking to the present time. It is bounded by faults, and seismic activity still occurs, with hypocentres at depths of 10–15 to 50 km. The crustal thickness decreases and the depth of earthquake foci increases to the southeast. Little is known about the "Mekong Downwarp" but Isayev and Kkhoan (1976) suggest that it is similar to the "Hanoi Downwarp", but with more crustal thinning involving a larger area.

Both downwarps appear on geological maps as sediment-filled basins (Fig. 11), two of many in the region. Although Tertiary deposits are not discriminated from Quaternary on available geological maps, it is known that a number of small inland

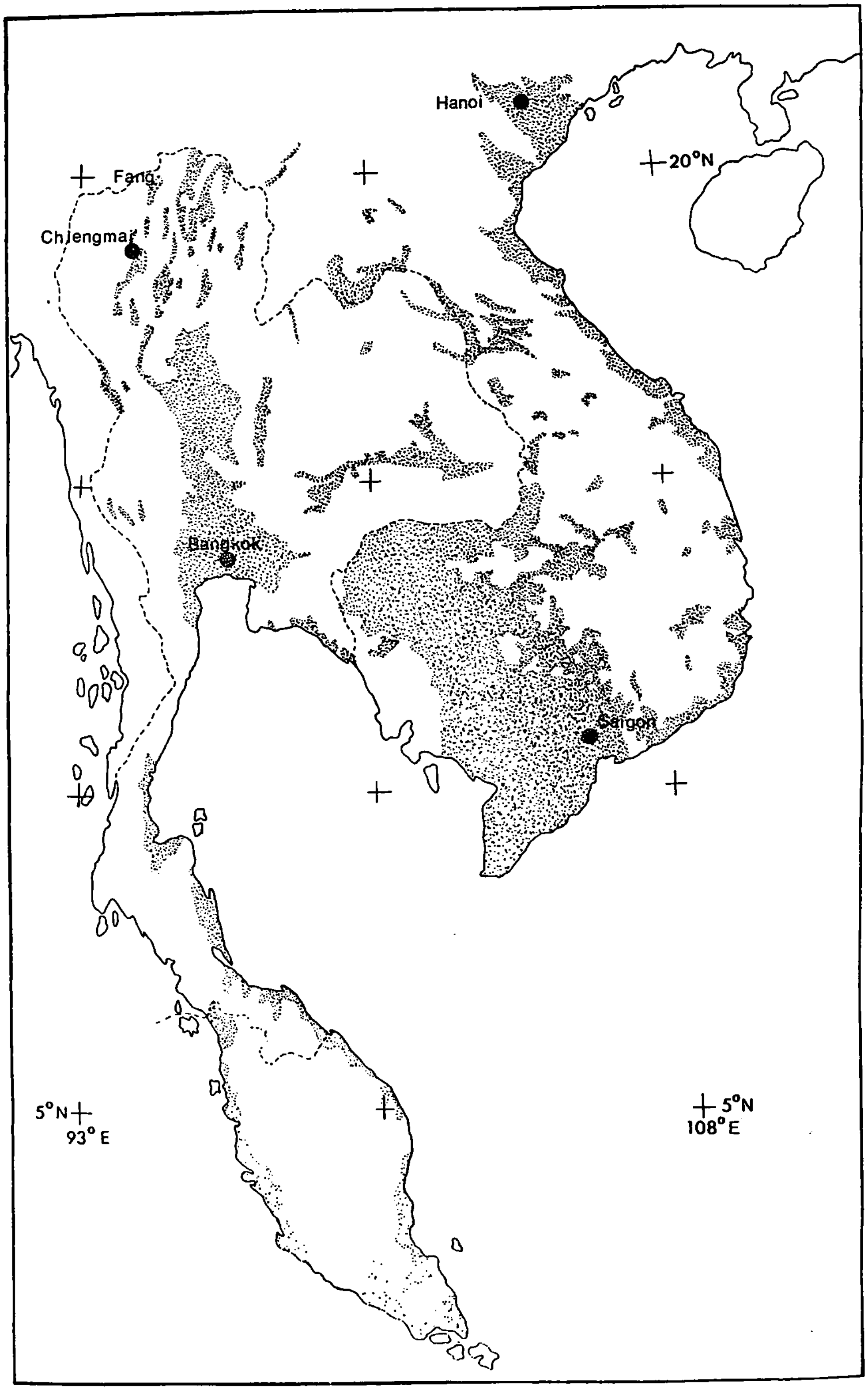

Fig. 11. Cenozoic sediment-filled basins in Southeast Asia. After Geological Map of Asia and the Far East, ECAFE, 1971.

basins contain deposits as old as Palaeocene, for example, Fang and Chiengmai Basins in Northern Thailand (Carbonnel and Saurin, 1975). The distribution and local trends of these inland basins indicate that their formation was controlled by regional structural trends.

Initiation of China Basin development in Late Cretaceous with spreading continuing until Early or Middle Tertiary (one of two alternatives proposed by Ben-Avraham and Uyeda, 1973) would explain synchronous events occurring on the Southeast Asian mainland to the west of the Basin:

1. Late Cretaceous alkaline intrusions in the Red River area of northern Vietnam (D.R. Workman, pers. comm. 1975), formed during initial stages of rifting.
2. Formation of Tertiary basins in Southeast Asia, by tensional exploitation of older structural trends.
3. Initiation of alkaline magmatic activity in Vietnam where basalts as old as Miocene may occur (J.P. Berrangé, written comm., 1976).

Continued migration of the region to the south-southeast during the Cenozoic is assumed to have maintained an essentially extensional tectonic environment in the western part of the region (Indochina and Thailand). This enabled formation and development of the basins and the related alkaline basaltic magmatism to continue to at least the Late Tertiary. Comparison between figure 1 and figure 11 shows that the basins and basalts are closely associated, reflecting their genetic relationship.

To what extent the opening of the Andaman Sea may have affected the regional tectonics is not clear. This NW–SE extension began in Late Miocene (Rodolfo, 1969) or Late Pliocene (Lawver *et al.*, 1975). By analogy with the China Basin, limited block faulting and magmatism could have been initiated in Burma and Thailand. However, these effects may have been negligible as the Andaman Sea now lies mainly within a "structurally disengaged" western margin of Southeast Asia (Fig. 10).

CONCLUSIONS

Late Cenozoic alkaline basalts in Thailand may be divided on the basis of petrography and geochemistry into two main groups:

1. Basanitoid basalts, including nephelinite, basanite, nepheline hawaiite, and nepheline mugearite.
2. Hawaiitic basalts, including alkali olivine basalt, hawaiite, and mugearite.

Zircon, corundum, and other megacrysts and ultramafic inclusions appear to be associated only with basanitoid basalts, which occur at scattered geographic locations in Thailand, in some occurrences in association with hawaiitic basalts. The restriction of megacrysts to one petrochemical group of basalts implies that they are cognate in origin, although the rate of ascent may also be an important factor.

Tholeiitic basalts are known to occur only at one or two isolated localities in northern Thailand.

Basanitoid magmas apparently formed by relatively small (but variable) amounts of partial melting at high (but variable) pressures (20 – 30 kb) followed by rapid ascent to the surface. Differentiation at shallow levels was minor, but high pressure fractionation may have occurred.

Hawaiitic magmas probably also formed by relatively small amounts of partial melting, although evidence concerning pressure has been obscured by relatively low-pressure fractionation. However, the crustal thickness in Thailand is likely to be similar to that in Vietnam (Isayev and Kkhoan, 1976), implying pressures of at least 10 kb in order for melting to take place in the mantle.

Tholeiitic magmas probably originated by larger degrees of partial melting in the mantle.

Current ideas concerning basalt petrogenesis indicate that the basanitoid basalts, hawaiitic basalts, and tholeiitic basalts cannot be related by crystal fractionation processes. Variations in chemistry within each of the main groups may result from varying degrees and depths of partial melting, inhomogeneous source material, crystal fractionation or accumulation, and perhaps minor crustal contamination and weathering (especially in the case of the hawaiitic basalts).

The alkaline igneous activity in Thailand and Southeast Asia as a whole may be related to development of the China Basin in Late Mesozoic – Cenozoic time.

ACKNOWLEDGEMENTS

We are indebted to W.G. Prewitt for setting up the analytical methods at the Department of Geological Sciences, Chiengmai University, and for performing many of the chemical analyses. We thank P. Vichit, Department of Mineral Resources, Bangkok, for providing his chemical data and other useful information. CUSO Thailand helpfully provided a vehicle for field work. Most of this work was completed during our employment as CUSO Volunteers at the Department of Geological Sciences, Chiengmai University, and we appreciate kindness shown to us by staff and students in that Department.

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