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PETROLOGY AND GEOCHEMISTRY OF NEOGENE CONTINENTAL BASALTS AND RELATED ROCKS IN NORTHERN TAIWAN (III): ALKALI BASALTS AND THOLEIITES FROM SHITING-YINKO AREA

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ABSTRACT

Basaltic rocks exposed in the Shiting to Yinko area in northern Taiwan are considered to represent a member of the products of the Neogene intraplate volcanism in the Fujian-Taiwan region of the SE China continental margin. This paper presents new age dating, petrographic (including mineral chemistry) and geochemical data which suggest the existence of two groups of the basaltic rocks: the early Miocene (23 to 20 Ma) alkali basalts and the late Miocene (12 to 9 Ma) tholeiites. The former group distributes mainly in the Chingshuikeng anticlinal area with small outcrops at Shiting and Taliaoti, while the latter group occurs as volcanic bodies widespread in the vicinity of Yinko, including Chienshan, Hengchi, Chulun and Tzelichiao.

Compared with similar volcanic rocks from the Kuanhsi-Chutung area and Penghu Islands, alkali basalts in the Shiting-Yinko area generally have lower Mg-values as well as lower Ni and Cr concentrations, indicative of higher degrees of crystal fractionation involved in the petrogenesis. On the other hand, tholeiites in Shiting-Yinko, as those in the two other regions, have uniform chemical compositions. We propose that tholeiites in the Shiting-Yinko area are the northeastern extension of the Kuanhsi-Chutung volcanics because of their contemporaneous eruption ages and the close spatial relationship and elemental similarities. However, isotope data of these tholeiites (e **Nd around +5) suggest involvement of different magma sources from the Kuanhsi-Chutung volcanics (**e **Nd=+3.5~-1.4) whose generation requires significant contribution by an EM-1 type reservoir in the**

lithospheric mantle (Chung *et al.*, 1995). In the Shiting-Yinko area, as both the older alkali basalt and younger tholeiites have isotopic compositions similar to those of common Fujian-Taiwan Neogene intraplate basalts, the magma generation may be explained by a plum-pudding asthenosphere model proposed in the SE China continental margin.

Key words: Petrology, geochemistry, basalts, Northern Taiwan, Neogene intraplate volcanism

INTRODUCTION

In the study of Neogene basaltic rocks in northern Taiwan, earlier investigators back to the 1920 to 1950 made lots of contributions in petrography (Ichimura, 1929a,b,c, 1932a,b, 1951; Yen, 1950, 1953, 1956, 1957, 1959). Recently, we have re-examined these rocks using more sophisticated analytical techniques to model their petrogenesis largely based on mineral composition, trace element and radiogenic isotope geochemistry (Chen and Chung, 1985; Chen, 1986; Chen *et al.*, 1987, 1989; Chung *et al.*, 1994, 1995).

This article is a continuation of studies on various basaltic rocks occurring in the Shiting to Yinko area in Taipei and Taoyuan County (Fig. 1a), particularly those surrounding the Chingshuikeng Anticline (Ho, 1967), and is a composite presentation of our recent achievements (Hwang, 1987; Chen, 1988; Chung, 1992) and new data obtained afterwards. During our research period, Su (1992) also conducted a geochemical survey on basaltic rocks collected from three tunnels on the route of the Freeway No. 3 in this area. Their results are in good accord with ours, and therefore will not be repeated in this paper. We shall document the ages of relevent volcanic activities, mineralogical and geochemical characters and then discuss the petrogenesis of these rocks, with an emphasis on the origin of these continental tholeiites in northern Taiwan.

GEOLOGICAL BACKGROUNDS

Basaltic rocks are sporadically distributed in the Neogene strata in northern Taiwan. Mostly, they are found as lenticular lava flows in association with basaltic tuffs in late Oligocene to early Miocene Mushan and Taliao Formations (Ichimura, 1929b) and in late Miocene Nanchung and Kueichulin Formations (Ichimura, 1932a,b). However, dikes and sills which intruded the Miocene sedimentary sequences are equally common resulting in the sporadic occurrence of basalts, teschenites and even syenitic rocks (Chen, 1998). Eruption ages for the former group can be bracketed to be early and late Miocene by the stratigraphic control (Wang and Huang, 1953; Ho, 1969), whereas intrusion for the latter group can only be regarded as later than the time of deposition of the thick sediments in northern Taiwan.

Based on sample locations and rock types of these basaltic rocks, five units can be grouped in the Shiting-Yinko area. From east to west, they are (1) Shiting, (2) Chinshuikeng anticlinal area including sectors of Nanshihchiao, Yenliao, Chinghua, and Tucheng, (3) Hengchi, (4) Chienshan and (5) dikes and sills in Chulun, Taliaoti, Tzelichiao and Yinko. Sample locations of these units are shown in Figure 1a with an inset for Chingshuikeng area in greater details (Fig. 1b).

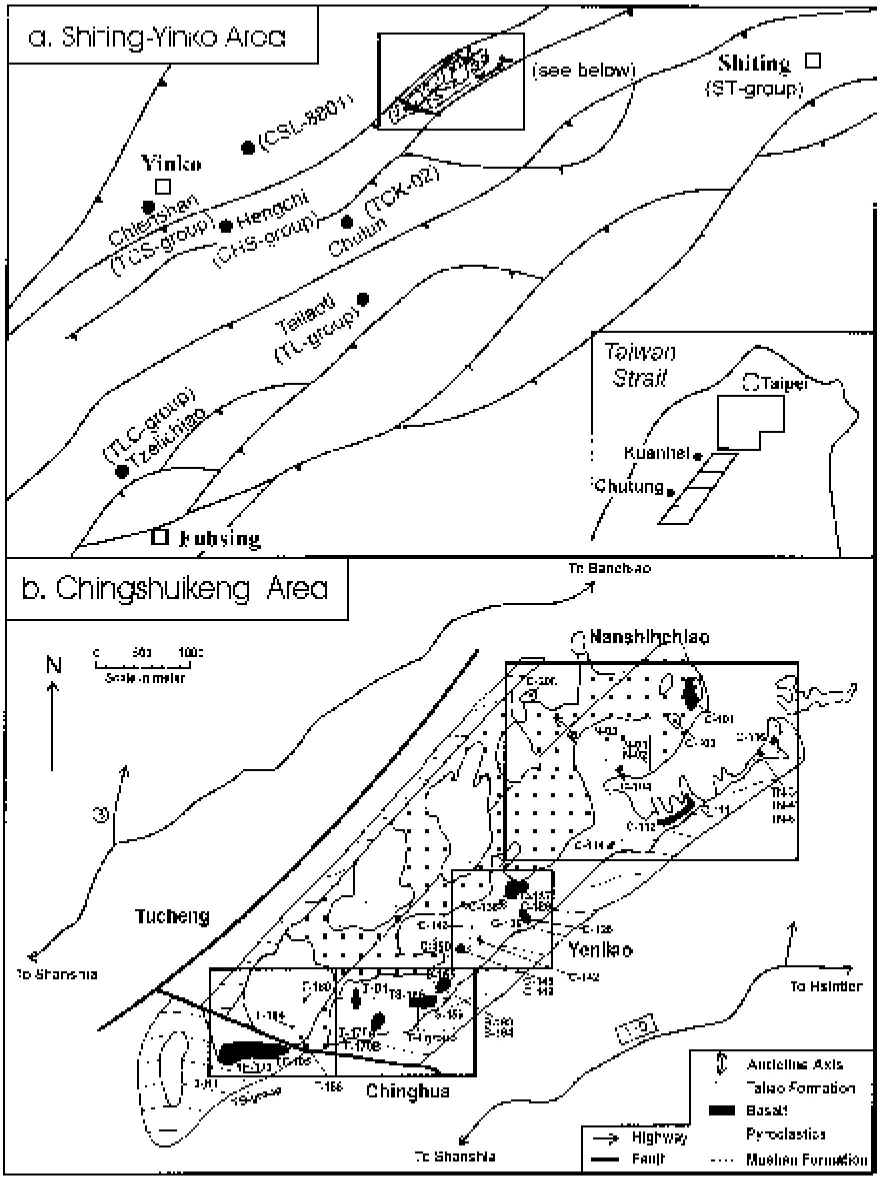

Figure 1. (a) Sample locality map of basaltic rocks between Shiting and Yinko area. (b) The inset is focused on the Chinshuikeng anticlinal area (Ho, 1967).

The largest outcrop of basalt in the studied area is the one exposed near Tucheng (denoted as TB- group) which is a volcanic body consisting of consecutive lava flows of single rock type piling up to about 150 to 200 m thick in total. Others are smaller exposures in several to few tens meter scale scattering in the Chingshuikeng area, mainly including pyroclastic flow deposits in Nanshihchiao and pyroclastic surge deposits in Chinghua (Chung, 1992). Furthermore, there are two separable layers of basaltic lavas in Yenliao, the lower one is an altered, medium-grained and feldspar-rich rock filled with secondary carbonates, and the upper layer is a fine-grained and fresh rock. The total thickness of these two strata may be added up to more than 100 m.

Some larger, independant basaltic bodies aside from the Chingshuikeng area are found in Chienshan (TCS- group) and Hengchi (CHS- group), and smaller ones are the lava flows of Shiting (ST- group), dikes or sills of Taliaoti (TL- group), Chulun (TCK-02), Tzelichiao (TLC- group) and Yinko (CSL-8801).

Lava flows of Hengchi are underlain by a layer of blackish lapilli tuffs (~ 10 m) and then a layer of light sandy tuffs (~20 m). The thickness of lava flow itself is about 10 m with obvious columnar joints at the top. Fine- and coarse-grained rocks have been found.

Basaltic rocks of Chienshan occupy the entire small hill near the junction of two major highways (Nos. 101 and 114) and could be a lava dome in occurrence. Rocks are coarse-grain and somewhat oxidized or altered as reflected by the high degree of opacitization and the complete serpentinization of olivines all over the volcanic body.

In Shiting, there are two thin layers of basaltic lava (2 to 3 m) setting in a thick layer of sandy to shaly tuffs (slightly over 10 m in total thickness). They are typical lenticular bodies in field occurrence.

For the dike and sill rocks, those in Taliaoti (TL- group) represent different portion of the dike about 30 m thick with an attitude of strike=N4^{o}W and dip=10^{o}W set in the sedimentary country rock with an attitide of strike=N84^{o}E and dip=48^{o}S. TCK-02 is collected at the fresh portion from a rather fragmented dike of 15 m thick in Chulun where slickenside is developed in part of this dike. Rocks of TLC- group are collected from a 20 m wide sill by the Tzelichiao Bridge between Wuliao and Shanming. The outcrop of Yinko (CSL-8801) is a >3 m wide dike or sill in the river bed of Tahanchi River near Ganyuan Bridge.

ANALYTICAL METHODS

Rock samples are separated into two parts, one for age dating and the other for petrographical and geochemical examination. For the first part, zircon fission track dating (FTD) method was adopted following a standard procedure of mineral separation, mounting, neutron irradiation, chemical etching and track counting (Liu, 1982; Tagami *et al.*, 1988). Conventional K/Ar dating and newly developed Ar/Ar dating equipped with a focused laser beam are used to supplement the samples in case of datable material such as zircon and apatite were eventually not found after mineral separation.

Petrographical observations were conducted by using a LEITZ- Laborlux 12 optical microscope for thin sections and by using electron microprobes model Shimadzu-ARL EMX-SM7 in the Department of Geology, National Taiwan University and model ARL-SEMQ in the Central Geological Survey for polished thin and thick sections under the conditions of 15 KeV accelerating potential and 0.015 μ amp sample current. The data reduction procedure has been described by Chen and Tung (1984).

Geochemical analysis were conducted by using a Rigaku X-ray fluorescence (XRF) spectrometer for 10 major elements (Nesbitt and Stanley, 1980; Lee *et al.*, 1997), a Jobin-Yvon JY38 type of inductively coupled plasma (ICP) atomic emission spectrometer for 7 trace elements including Ni, Cr, V, Zr, Y, Ba and Sr, and an instrumental neutron activation apparatus (INAA) for other trace elements like Rb, Sc, Ta, Hf, Th and some rare earth elements such as La, Ce, Sm, Eu, Tb, Yb and Lu (Chung *et al.*, 1989; Yang *et al.*, 1997). Isotope ratios of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ were carried out for some samples of this study. The isotopic analytical procedures are same as described in the work of Chen (1988).

ROCK TYPES

Determination of rock types is made by examining petrographic slides under the microscope, and then aided by the identification of mineral composition with an electron microprobe and the whole-rock major element chemistry (see later sections). Accordingly, basaltic rocks from the Shiting-Yinko area include three main categories: basanitoid (both primary analcime and alkali feldspar are present in the matrix), alkali olivine basalt (only alkali feldspar is present) and olivine tholeiite (low-Ca pyroxene is present). The first two are collectively called alkali basalts and the last one is referred as tholeiites in this study.

Basically, basanitoids appear in the Nanshihchiao and Tucheng districts and alkali olivine basalt in the other districts of the Chingshuikeng area. Dike rocks in Taliaoti (TL-group), although altered and characterized by the presence of a few secondary apatites, may also be a basanitoid originally. Tholeiites expose mainly in Hengchi and Chienshan, as well as the dike in Chulun and the sill in Tzelichiao (TLC- group). There could be a transitional type appeared as dike rocks in Yinko (CSL-8801).

Certain degree of alteration has taken place in some of these basaltic rocks causing the formation of serpentine after olivine. Therefore, relict olivines with a mesh texture is rather common. Few samples, such as those in Chienshan lava dome and Taliaoti dike rock have even gone to a completion of serpentinization that no olivine are preserved, and are sometimes accompanied by the formation of chlorite after clinopyroxene. In few cases, replacement of plagioclase by epidote and zeolite due to alteration is observed. So alteration can be a consequence of diagenesis or low-grade metamorphism exerted on the basaltic rocks after eruption or injection into the foothill region of northern Taiwan and offshore area (Chen, 1986; Yang, 1986; Chen *et al.*, 1997).

MINERAL CHEMISTRY

Mineral compositions are used to support the classification of rock types. In addition to the general survey of constituent phases, the identification of characteristic minerals such as analcime, alkali feldspar and low-Ca pyroxene are also emphasized. Secondary minerals are not included.

Olivine

Olivines commonly exist in these basaltic rocks, in spite that some have already altered been completely. Frequency distributions of olivines in different units are depicted in Figure 2 reflecting that the peaks may correspond to the most prevailing olivine composition in different units.

Compositions of olivine may vary with different districts. Olivine phenocryst cores in Nanshihchiao samples (e.g. TN-3 and TN-4) are Fo_{86} to Fo_{84}, and become less magnesian to

Fo_{73} in the rims with a normal zoning. The common existence of such kind of Mg-rich olivine cores indicates that the host basalts may represent the products derived from the parental magmas without a major modification by later processes (Juan *et al.*, 1984). This can be manifested by the geochemical results in later sections.

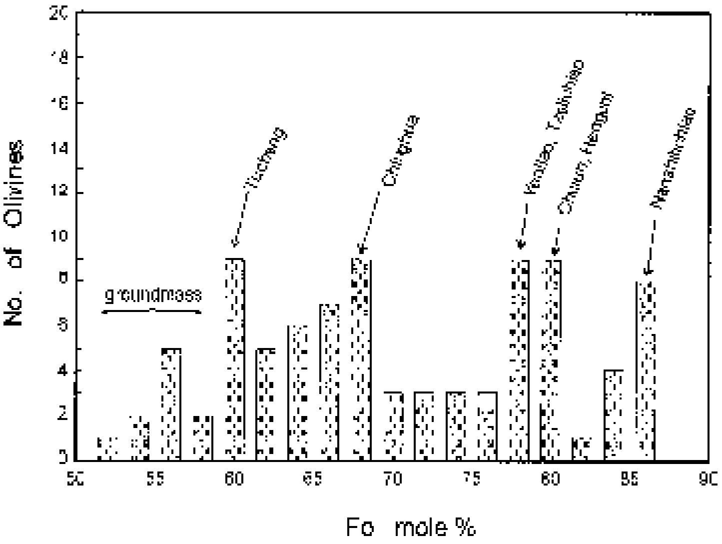

Figure 2. The frequency distribution diagram of olivine compositions of basaltic rocks in the Shiting-Yinko area.

Olivines from rocks of other sectors in the Chingshuikeng anticlinal area are less magnesium. The phenocrysts are mostly Fo_{78} to Fo_{72} in Yenliao (part of C- group), Fo_{68} to Fo_{58} in Tucheng (TB- group), and Fo_{67} to Fo_{52} in Chinghua districts. The groundmass olivines are in general in the range from Fo_{60} to Fo_{51} for these rocks.

For tholeiites, olivine compositions in Hengchi basaltic body vary from Fo_{74} to Fo_{59}, Fo_{76} to Fo_{67} and Fo_{82} to Fo_{77} among different portions in this volcanic body. Chulun dike (TCK-02) from Fo_{80} to Fo_{76}, and Tzelichiao samples (TLC- group) from Fo_{80} to Fo_{67}. They seem to be richer in magnesium than the alkali basalts as a whole, and have rather uniform composition around Fo_{80} for the majority of phenocrysts no matter the wide spread of sample locations.

Pyroxenes

Compositions of pyroxene in these basaltic rocks are present in terms of end members in the Di-Hd-En-Fs quadrilateral (Fig. 3). Like the cases in Penghu Islands and Kuanhsi-Chutung volcanics (Chen, 1990), clinopyroxenes fall largely in the salite field for alkali basalts (more than 150 data points), and in the augite field for tholeiites. Pigeonite and orthopyroxene, as reported to occupy a certain amount in the tholeiitic rocks (Yen, 1953), are mainly found in Hengchi and Tzelichiao.

It is worthy to note that clinopyroxene megacrysts, although rarely occurred, have been found in few alkali basalts from Nanshihchiao. Judging from the Mg-values (70 to 72), Na_2O (~1.1 wt%), FeO (~9 wt%) and Al_2O_3 (~7 wt%) contents, they are closer to the Al-augite than the Fe-Na salite (Chung and Chen, 1990), but are plotted in the salite cluster of Figure 3 as well.

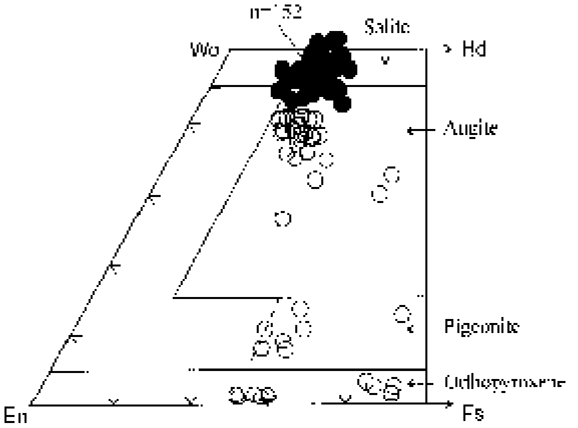

Figure 3. The Di-Hd-En-Fs quadrilateral diagram (Deer *et al.*, 1992) of pyroxenes of basaltic rocks in the Shiting-Yinko area. Solid dots denote alkali basalts, and open circles, tholeiites.

Amphibole

Amphibole is not a common phenocrystal phase present in the basaltic rocks in Taiwan region, but occurs as megacrysts associated with Al-augite in some Kuanhsi-Chutung volcanics (Chen *et al.*, 1987). However, it appears as phenocrysts in rocks of few outcrops of the studied area, particularly in the Yenliao district of the Chingshuikeng area. Reaction rim of opaques on the amphiboles is a common feature, indicative of non-equilibrium state with respect to the host magma.

According to the chemical compositions, they all belong to kaersutitic amphiboles in the nomenclature of Leake (1978) for their Mg-values are greater than 50 and TiO_2 contents are inevitably higher than 5 wt% (in fact, 5.6 to 6.6 wt% for 12 analysis). As kaersutitic amphiboles have also been found in some other alkaline rocks in northern Taiwan (Chen, 1986; Chen *et al.*, 1989; Chung and Chen, 1990), all their compositions are plotted together for comparison in terms of Ti and Al atomic proportions (Fig. 4). It shows that the kaersutitic amphiboles in the Yenliao rocks have intermediate compositions between megacrysts in the pyroclastic rocks from Kuanhsi-Chutung area (Chung and Chen, 1990) and phenocrysts in teschenites from Luku area (Chen, 1986). Further compared with those derived from the crust and upper mantle (Best, 1974), they most probably represent captured lower-crust xenocrysts, i.e. the fragmented high-pressure megacrysts, in the course of magma ascending.

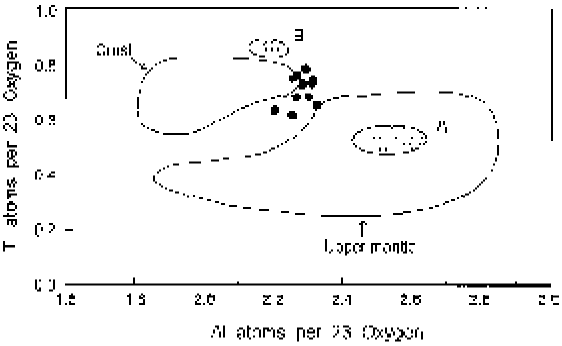

Figure 4. The Ti vs. Al atom plot for amphiboles of basaltic rocks in the Yenliao district of the Shiting-Yinko area. The same type of amphiboles appeared in the other petrological provinces in Taiwan is included for comparison, in which A=phenocrysts in Luku teschenites (Chen, 1986) and B= megacrysts in Kuanhsi-Chutung pyroclastics (Chen *et al.*, 1987). The fields encircled for those derived from crust and upper mantle (Best, 1974) are also dipicted.

Feldspar, Analcime and Zeolite

Plagioclase is the most abundant constituent mineral of phenocrysts and in the groundmass of these basaltic rocks. Coexisting alkali feldspars are commonly present in the alkali basalts and a few are found in some tholeiitic rocks. The composition range of feldspars in such rocks from different localities is listed in Table 1, and conventional An-Ab-Or triangular diagrams are constructed for depicting the over-all distribution among alkali basalts and tholeiites (Fig. 5). It is noted that some slightly altered Ba-rich alumino-silicates (BaO up to 12.8-13.7 wt% with insignificant Na_2O and K_2O) have been probed in one sample from Chinghua district in Chingshuikeng area (S-155), the most probable mineral would be celsian–the barium feldspar.

Compositions of phenocrystic plagioclases seem to be consistently varying from An_{68} to An_{50}, and those for the majority of the plagioclases in the groundmass fall into An_{46} to An_{40} for rocks of each district, no matter the type is alkali basalt or tholeiite. However, there is a tendency showing that K_2O contents of plagioclases in the alkali basalts are slightly higher than those in the tholeiites (Fig. 5). One particular feature distinguished from the Kuanhsi-Chutung and Penghu Islands volcanics is the existence of alkali feldspars in few tholeiites, although not as voluminous as in the alkali basalts. Most of these alkali feldspars are concentrated in the range of Or_{60} to Or_{45} (sanidines), with some less potassic ones (e.g. Chienshan and Shiting) varying from Or_{30} to Or_{17} (anorthoclases). The latter type could be of xenocrystic origin as viewed from the generality of anorthoclase megacrysts appeared in the rocks of same affinity in northern Taiwan (Chen, 1990). For few highly altered samples, albites are present in association with epidote and zeolites.

Table 1. Feldspar compositions of basbltic rocks in Shiting-Yinko area, N. Taiwan.

Locality	$Pl_{(phen)}$	$Pl_{(gdms)}$	$Pl_{(Ab)}$	Alk. F.
1. Alkali Basalts				
Shiting	An_{60}-An_{50}	An_{41}		Or_{24}-Or_{17}
Nanshihchiao	An_{64}-An_{58}	An_{49}-An_{26}	Ab_{94}-Ab_{100}	Or_{54}
Yenliao	An_{67}-An_{55}			Or_{52}-Or_{44}
Chinghua	An_{61}-An_{54}	An_{46}-An_{32}	Ab_{99}-Ab_{100}	Or_{55}-Or_{44}
Tucheng	An_{66}-An_{53}	An_{37}-An_{35}		Or_{55}-Or_{41}
Taliaoti	none	An_{48}-An_{36}		Or_{57}-Or_{45}
2. Tholeiites				
Hengchi	An_{68}-An_{52}	An_{46}-An_{40}		Or_{59}-Or_{50}
Chienshan	An_{63}-An_{51}			Or_{30}-Or_{26}
Tzelichiao	An_{64}-An_{48}	An_{42}		none
Chulun	An_{68}-An_{48}	An_{40}		Or_{31}
Yinko	An_{67}-An_{50}	An_{46}-An_{41}		none

$Pl_{(phen)}$: plagioclase occurred as phenocrysts; $Pl_{(gdms)}$: plagioclase occurred in the groundmass; $Pl_{(Ab)}$: albitized plagioclase; Alk. F.: alkali feldspar.

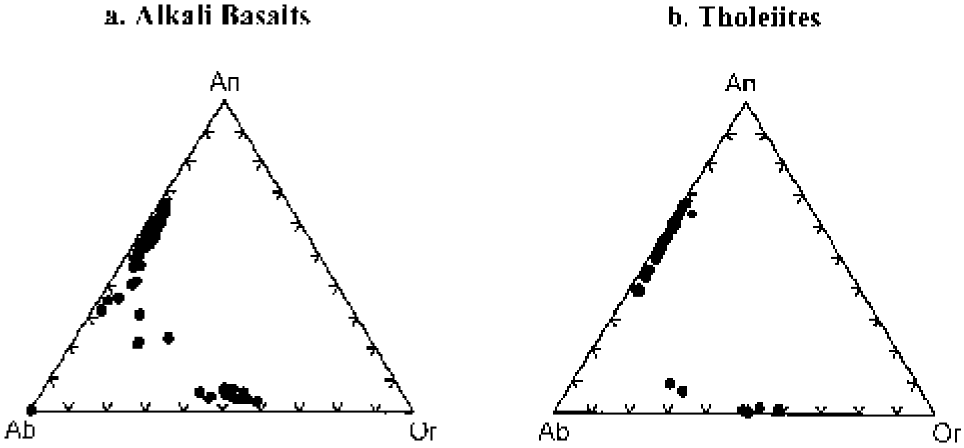

Figure 5. The An-Ab-Or diagram (Deer *et al.*, 1992) of feldspars of basaltic rocks in the Shiting-Yinko area. (a) alkali basalts, (b) tholeiites.

Analcime may present either as primary crystals in basanitoids or as a secondary interstitial phase in alkali olivine basalts pertaining to the intraplate products in northern Taiwan (Chen, 1990). Primary analcimes appear in few fresh rocks from Nanshihchiao (TN-3 and TN-4) and Tucheng (TB- group) making them to be typical basanitoids. Secondary ones are found to associate with Ca-rich hydrous felsics, most probably Ca-zeolites, in Taliaoti samples (TL-group) as a consequence of plagioclase alteration under very low-grade metamorphism (Frey and Robinson, 1999).

Fe-Ti Oxides

Fe-Ti oxides only include magnetite (mostly titanomagnetite) and ilmenite and are present about 1-3% in these rocks. There seems to have a general but not absolute tendency that magnetites predominate ilmenites in alkali basalts whereas elongated ilmenites predominate magnetites in tholeiites. In many cases, there is only one kind of these Fe-Ti oxides in the sample. Using the magnetite-ilmenite pairs as the geothermometer (Powell and Powell, 1977, derived from Buddington and Lindsley, 1964) and the Mg/Mn test for the possible equilibrium pairs (Bacon and Hirschmann, 1988), their equilibration temperatures and oxygen fugacities are calculated and listed in Table 2.

The results indicate that the fine-grained lava flows of alkali basalts from Nanshihchiao (e.g. TN-3) have the highest temperature up to 1100°C and oxygen fugacity to $10^{-9.1}$ atm, and others are generally equilibrated in the range from 910 to 975°C with oxygen fugacities from $10^{-11.2}$ to $10^{-13.5}$ atm. It is not surprising that the tholeiitic dike in Chulun (TCK-02) has the lowest temperature and oxygen fugacity around 820°C and $10^{-14.9}$ atm for a small-scale intrusion.

Table 2. Ulvospinel and hematite components in the coexisting ilmenite and titanomagnetite and their equilibration temperatures and oxygen fugacities of basaltic rocks in Shiting-Yinko area, northern Taiwan.

Samp. no.	Usp %	Hem %	Temp(℃)	$\log f_{O_2}$
1. Alkali basalts				
TN-3	77.1	3.8	1100	-9.1
TB-05	71.4	4.7	940	-12.3
TB-07	72.0	4.8	955	-12.0
TB-09	70.6	4.4	925	-12.7
TB-25	71.7	3.8	910	-13.2
TA-06	75.9	3.1	910	-13.5
2. Tholeiites				
TCS-04	58.6	6.9	920	-12.2
CHS-01	70.3	5.3	960	-11.8
CHS-24	62.0	7.4	960	-11.4
CHS-28	65.6	7.0	975	-11.2
CHS-29	57.1	5.4	950	-11.9
TCK-02	58.1	4.0	820	-14.9

Usp%= calculated ulvospinel mole percent in the magnetite.

Hem%= calculated hematite mole percent in the ilmenite.

ERUPTION AGES

Fission Track Age Dating

Although numerous samples have zircon separates available for fission track dating (FTD), many yield ages too old (> 100 Ma) to be adopted as the record of their eruption time, especially the relatively smaller-scaled lavas (Shiting and Hengchi), dikes and sills (Taliaoti, Chulun, Tzelichiao and Yinko). This phenomenon strongly suggests that these zircons are mostly of xenocrystic origin and may represent the near-surface contaminants of crustal sediments which did not subject to the complete thermal reset after being trapped into the volcanic bodies. On the other hand, another mineral commonly used for FTD—apatite can only be found as needle-like crystals in the altered dike of Taliaoti in sufficient amount. So available fission track age determinations are basically restricted in the Chingshuikeng anticlinal area and the results are listed in Table 3.

For most of the samples from the Chingshuikeng anticlinal area, there are double- or even poly-peak distributions in the zircon FTD age-frequency plots reflecting that there is a severe partial annealing effect on the zircons included in the basaltic rocks (Chung, 1992). Therefore, either the single peak mean age or the youngest peak mean age is taken to document the time of volcanic eruption responsible for producing these rocks.

Table 3. Fission track age dating of basaltic rocks in Shiting-Yinko area, northern Taiwan.

Sample No.	DM	Nt, Nc	ΣN_s	ρ_s $(\times 10^6 cm^{-2})$	ΣN_i	ρ_i $(\times 10^6 cm^{-2})$	Neutron flux (neutrons/cm²)	age±1σ (Ma)
CT-101 (1)	2π	11, 5	275	1.6153	725	7.1330	1.579×10^{15}	21.8±1.6
CT-101 (2)	2π	10, 4	305	1.4663	730	5.8800	1.408×10^{15}	21.3±1.7
CT-101 (Ave.)								21.5±1.6
CL-101	2π	17, 6	214	1.5207	923	6.6770	1.579×10^{15}	22.1±1.5
C-104	2π	9, 1	480	1.5408	1455	6.5065	1.403×10^{15}	20.3±3.0
C-112	4π	4, 4	1206	1.5911	1637	3.2746	1.579×10^{15}	21.6±0.9
C-116	2π	29, 5	446	1.4527	1049	5.7997	1.403×10^{15}	21.3±1.4
C-116	4π	8, 7	1005	2.2740	2604	5.2395	1.579×10^{15}	21.2±0.9
CT-116	2π	33, 9	610	1.7099	2742	6.7392	1.403×10^{15}	22.0±1.0
CT-116	4π	12, 11	1500	1.8369	3894	4.1896	1.579×10^{15}	21.3±0.7
C-143	2π	12, 6	157	0.7793	523	3.2691	1.408×10^{15}	20.1±2.0
T-C1	2π	23, 12	675	1.1641	813	1.5992	5.011×10^{14}	23.0±1.3
T-F1	2π	25, 9	576	1.6745	813	2.3107	5.088×10^{14}	22.2±1.3
T-G2	2π	10, 4	195	1.5387	286	2.2785	5.088×10^{14}	20.9±2.0
TN-6 (1)	4π	4, 4	3104	4.6919	6614	11.2003	5.920×10^{15}	20.7±1.2
TN-6 (2)	4π	6, 6	1071	3.1837	920	2.7348	5.389×10^{14}	19.3±1.0
TN-6 (Ave.)								20.0±1.1
TL-21 (1)	2π	3, 3	61	1.0702	79	1.0983	3.648×10^{14}	20.7±3.5
TL-21 (2)	2π	9, 1	37	2.2914	57	3.6539	3.648×10^{14}	21.1±4.5
TL-21 (Ave.)								20.9±4.0
TL-21 (ap)#	4π		36	0.0836	278	0.7009	2.232×10^{15}	14.9±2.7

DM: detector method, in which 2π: external, 4π: internal.

Nt= total counted grain number, Nc= age-calculated grain number.

ΣN_s: Spontaneous track number, ρ_s: Spontaneous track density,

ΣN_i: Induced track number, ρ_i: Induced track density.

by using of apatite as the dating material; otherwise, zircon.

It is obvious that fission track age dating on zircons in the Chingshuikeng area are confined to be 23 to 20 Ma, conformable with the stratigraphic control of so-called "Kungkuan Tuff" associated with these volcanics (Wang and Huang, 1953; Ho, 1967). There seems to have a discrepency on FTD results in the dike of Taliaoti (TL-21) showing that the ages dated to be 20.9 ±4.0 Ma on zircons but 16.1 ±3.0 Ma on apatites. This will be discussed below in combination of other dating data.

K-Ar and Ar-Ar Age Dating

Two tholeiitic samples of Hengchi lava (CHS-24 and CHS-28) have been determined with the K-Ar method (Tab. 4) although there already have some dating data in the literature (Miki, 1991; Tsao *et al.*, 1992). Because Hengchi is only a small volcanic body, the average of these data (ca. 9.3 Ma) is taken to represent the most probable age for the eruption of Hengchi basalts. Two more samples are further determined with Ar-Ar method: the tholeiitic sample of

Chulun dike (TCK-02) gives a result of 11.8 ±0.4 Ma, and the alkali basalt sample of Taliaoti dike (TL-31) is 18.3 ±1.9 Ma which is in fair agreement with the fission track dating on zircons (20.9 ±4.0 Ma) in the different portion of the same dike (TL-21). As the Taliaoti dike has been slightly altered , the older ages reflected by the system with higher blocking temperatures (Ar-Ar on whole rock and FTD on zircons) are considered to represent the time of injection, whereas the younger age (FTD on apatites), is the time of subsequent alteration probably due to the burial or very low-grade metamorphism.

Combining the fission track, K-Ar and Ar-Ar age data, it can be concluded that the eruption time of tholeiitic magmas in the Shiting-Yinko area was confined to a span in late Miocene (12 to 9 Ma), whereas alkali basalts were most active in early Miocene (23 to 20 Ma). These two time spans may be used to better define the so-called Chiaopanshan and Kungkuan volcanic stages respectively in northern Taiwan (Yen, 1956), and to indicate that there may be an eruption gap about 10 My as the volcanic activity changed from alkali basaltic to tholeiitic magmas in this area.

Table 4. The K-Ar and Ar-Ar age dating results of some basaltic rocks in the Shiting-Yinko area, northern Taiwan.

Sample No.	K %	Age (Ma)
1. Hengchi*		
CHS-24	0.497±0.025	9.54±0.97
CHS-28	0.491±0.021	8.34±0.77
N124	0.580	7.91±0.45[a]
KK04(1)	0.554	10.2±0.6[b]
(2)		9.5±0.6[b]
HC9109	0.630	10.2±0.5[b]
Average		9.3±0.6
2. Chulun**		
TCK-02	0.573	11.8±0.4
3. Taliaoti**		
TL-31	1.934	18.3±1.9

a: Miki, 1991; b: Tsao *et al.*, 1992.

* by conventional K-Ar method. ** by laser sourced Ar-Ar method.

WHOLE-ROCK GEOCHEMISTRY

The results of whole-rock analysis are listed in Table 5. In terms of major elements, tholeiites are obviously distinguished from the alkali basalts by the normative compositions as revealed from the calculated CIPW components plotted in Figure 6. This is conformable with the tholeiite series and the basanitoid-alkali olivine basalt series commonly observed in northern Taiwan intraplate products (Chen, 1990). If further examining the distribution field encircled for basanitoids and alkali olivine basalts, there seems to have a discontinuity of data points between these two groups in the entire range of alkali basalts (connected by the dashed lines in Figure 6). However, such grouping is not obvious in the trace element behavior as shown in later sections. Mineralogically, tholeiites are characterized by the presence of augites and low-Ca pyroxenes (Fig. 3).

The most striking feature of basaltic rocks in the Shiting-Yinko area is the existence of many basanitoids with low Mg-values and high alkalinities when compared with those from the Penghu Islands and Kuanhsi-Chutung area (Fig. 7). The undisrupted spread of Mg-values from 68 to 32 is an indication of high-degree crystal fractionation during the evolution of the magmatic stage. As the rocks of low Mg-values are mostly dated to be older (23 to 20 Ma) than the rocks of Penghu Islands (16 to 8 Ma, Lee, 1994) and Kuanhsi-Chutung area (10 to 9 Ma, Chen, 1990), it seems to suggest that the rift system in northern Taiwan at early Miocene time was still not yet developed to an extent as the Penghu and Kuanhsi-Chutung areas in middle to late Miocene, thus preventing the creation of more conduits for magmas to ascend in a shorter time.

Another feature is the non- to poor-coherence of incompatible trace elements (e.g. Rb, Sr and Ba) but a more positive correlation of high field strength elements (e.g. Hf, Ta, Th and perhaps Zr and Y) with the increasing La concentrations among these rocks (Fig. 8). Considering that some alkali basaltic samples have been subjected to various degree of alteration, concentrations of incompatible trace elements, Rb in particular, could have been modified to higher extents owing to their greater mobilities under the process of alteration relative to the high field strength elements. However, distribution trends of Hf and Y in tholeiites are somewhat deviated from those of alkali basalts among the high field strength elements and shall be discussed later.

It should be mentioned that three data points in the Ta vs. La plot are abnormally high in Ta concentrations (Fig. 8), this could be resulted from the contamination ascribed to the use of tungsten carbide miller during the sample grinding stage. To avoid ambiguity, these particular samples are not included for the further discussion when Ta concentrations are mentioned. Determinations of Ta values (1-7 ppm) for other samples are comparable with Neogene intraplate basalts in Taiwan (Chung *et al.*, 1995), so the concern about Ta contamination can be ignored. Furthermore, some Yenliao samples with high Ba concentrations may be a reflection of alteration.

The normalized REE distribution patterns are present in total ranges for alkali basalts and tholeiites respectively (Fig. 9). In fact, there are no big differences between Shiting-Yinko, Penghu Islands and Kuanhsi-Chutung volcanics (Chen, 1990) in terms of the overall shapes and relative abundances of alkali basalts and tholeiites.Under this scheme, minor degree of Eu anomaly in some individuals are wiped out. In general, the alkali basalts have LREE concentrations about 60 to 300 times, while the tholeiites have about 50 to 100 times, and both types have close HREE concentrations about 10 to 30 times of the chondrite value. According to the trace element data (Tab. 5), spidergrams for the studied rocks would be similar to those appeared in Chung *et al.* (1995), so they are not repeated here.

Table 5. Major and trace element compositions of basaltic rocks in the Shiting-Yinko area, northern Taiwan.

Wt %	ST-01	ST-02	ST-03	ST-22	ST-25	TN-3	TN-4	N-01	N-02	N-03	C-101	C-103	C-104A	C-111
SiO_2	43.95	45.07	45.92	44.64	46.22	44.79	44.60	47.71	48.35	49.36	45.66	48.43	44.68	45.62
TiO_2	3.41	3.78	3.01	3.13	2.80	2.85	2.73	2.36	2.45	2.58	2.70	2.71	3.91	2.67
Al_2O_3	14.67	14.33	14.18	14.17	13.60	13.24	13.35	15.79	16.42	16.74	12.85	15.53	13.67	12.44
tFe_2O_3	10.61	10.90	10.15	10.21	10.06	12.10	12.04	10.64	8.10	10.88	11.48	11.89	11.67	11.24
MnO	0.33	0.28	0.15	0.19	0.15	0.18	0.19	0.19	0.14	0.15	0.17	0.15	0.14	0.15
MgO	8.63	8.69	9.62	6.73	9.19	9.20	9.65	2.42	2.58	4.41	9.42	5.69	8.58	8.85
CaO	10.69	10.10	8.78	11.07	9.01	8.83	8.90	7.36	7.85	7.23	9.96	7.59	10.29	10.76
Na_2O	1.64	2.12	3.12	1.24	3.00	3.63	3.49	4.26	3.60	3.15	4.00	3.41	2.51	2.08
K_2O	0.78	0.87	0.96	0.73	1.06	1.12	1.10	2.53	3.50	3.03	1.34	1.47	1.40	0.84
P_2O_5	0.99	0.96	0.94	1.01	0.94	0.64	0.65	1.03	1.04	1.00	0.62	0.60	0.70	0.62
LOI	6.41	5.07	4.81	6.87	2.29	4.47	3.65	6.29	5.58	2.45	2.51	1.62	3.21	4.59
	102.10	101.61	101.64	99.99	98.32	101.00	100.25	100.58	99.61	100.98	99.51	99.10	100.79	99.86
Mg'	63	64	67	59	67	63	64	33	41	47	62	49	59	61
tAlk	2.42	2.99	4.08	2.97	4.06	4.75	4.59	6.14	5.72	6.18	4.14	4.88	3.91	2.92
ppm														
Ni	210	196	230	220	233	206	225	33	55	45	179	65	134	178
Cr	253	236	283	282	312	275	285	35	42	47	192	71	156	243
V	173	195	168	199	194	237	233	120	119	139	221	195	282	212
Sc	21	20	20	19	26	21	21	11	23	14	21	18	29	23
Rb	7	14	5	14	6	17	12	41	61	55	19	52	bdl	12
Sr	1558	1938	969	1292	932	657	749	931	940	722	716	993	732	998
Ba	1358	630	680	976	679	889	883	1879	2105	896	855	642	853	1310
Zr	297	300	298	324	300	284	299	357	319	331	337	264	315	310
Y	30.5	30.8	30.6	31.5	28.1	26.0	25.0	32.9	31.8	32.2	32.7	30.9	32.6	30.2
Ta	4.8	4.7	9.2	2.4	4.8	5.6	4.8	8.4	5.0	4.9	4.2	2.3	4.1	1.5
Hf	8.1	7.7	8.2	7.7	7.3	6.1	6.8	8.2	8.1	8.7	6.2	5.3	6.2	5.9
Th	7.0	6.9	8.3	6.9	7.2	5.4	6.0	9.6	9.4	7.2	5.2	4.7	5.0	5.1
La	66	69	70	67	63	49	53	67	64	64	48.1	35	44.0	45.9
Ce	114	129	138	142	142	97	105	123	121	135	99	69	96	96
Sm	10.7	11.1	11.4	8.6	8.9	9.7	9.0	8.9	9.6	10.0	8.7	7.0	9.4	8.9
Eu	3.2	3.2	3.1	3.5	3.1	2.9	2.8	3.1	3.5	3.5	2.9	2.3	3.0	2.8
Tb	1.7	1.4	1.2	1.2	1.0	1.2	1.1	1.1	1.2	1.0	1.7	1.2	1.1	1.2
Yb	1.7	1.7	1.8	2.4	2.0	2.3	2.1	2.1	2.1	1.7	2.13	2.13	2.54	2.18
Lu	0.28	0.28	0.28	0.44	0.30	0.37	0.29	0.35	0.34	0.26	0.26	0.27	0.24	0.28

Mg': mg number of the rocks; tAlk: total alkalies; bdl: below detection limit.

Table 5. (cont.)

Wt %	C-126	C-129	C-142	C-143	C-148	C-150	TH-01	TH-01A	TH-02	TH-03	TH-05	TH-06	S-155	S-164
SiO_2	50.06	46.92	48.63	46.67	50.46	50.02	47.57	47.58	50.51	49.40	50.57	49.40	49.83	48.25
TiO_2	2.41	3.10	2.48	2.92	2.61	2.33	2.61	2.56	2.41	2.39	2.44	2.39	2.59	2.59
Al_2O_3	16.73	16.37	17.02	15.49	17.03	16.78	13.90	13.51	17.20	16.59	17.57	17.53	16.66	16.83
tFe_2O_3	9.20	10.86	9.55	10.53	10.67	9.69	11.80	11.99	9.77	10.20	8.90	8.74	10.32	10.42
MnO	0.17	0.15	0.16	0.15	0.16	0.18	0.15	0.14	0.12	0.15	0.13	0.10	0.17	0.18
MgO	2.97	5.76	2.32	7.07	3.52	2.52	5.56	6.34	2.86	2.85	2.72	3.41	3.71	3.94
CaO	7.42	8.15	7.16	8.33	7.41	6.88	9.04	8.98	6.86	6.60	6.60	6.65	7.37	6.68
Na_2O	3.41	3.20	3.65	3.24	2.85	3.87	2.70	2.74	3.10	3.73	3.22	3.21	3.30	3.24
K_2O	3.06	1.58	2.72	1.72	2.93	3.20	1.76	1.73	3.16	3.14	3.51	3.40	2.66	3.23
P_2O_5	1.01	1.02	1.02	0.99	0.98	0.98	0.74	0.71	1.04	1.06	1.07	1.02	0.98	1.02
LOI	4.69	4.21	4.70	4.63	3.21	3.48	3.29	3.39	4.81	4.32	3.41	3.11	2.40	3.17
	101.13	101.32	99.61	101.69	101.83	99.93	99.12	99.67	101.84	100.43	100.14	98.96	99.99	99.56
Mg#	39	51	37	57	40	40	51	54	39	38	40	46	42	43
tAlk	6.47	4.78	5.41	4.96	5.78	7.07	4.42	4.47	5.77	6.87	5.52	5.15	5.96	6.04
ppm														
Ni	28	55	20	32	29	24	165	160	50	42	42	50	34	26
Cr	45	51	26	38	37	28	131	131	34	25	35	31	46	29
V	122	187	126	141	132	104	175	172	174	117	116	113	136	113
Sc	11	15	9	12	12	10	16	16	11	14	13	13	12	11
Rb	52	16	bdl	27	59	bdl	32	33	45	40	31	77	54	58
Sr	881	740	1478	892	760	840	725	829	879	1745	1029	855	874	769
Ba	1608	2663	3692	1108	1312	964	575	553	745	1392	1352	931	949	1323
Zr	446	364	563	393	371	412	223	229	268	391	376	395	399	418
Y	35.8	32.6	36.5	33.6	32.5	32.2	29.0	29.2	32.8	26.0	33.4	36.6	35.0	36.0
Ta	6.3	5.0	5.4	5.5	5.6	5.7	3.7	3.8	6.8	6.0	5.2	6.3	5.7	6.5
Hf	10.2	6.8	8.6	7.7	8.0	8.4	5.2	5.4	7.8	7.7	8.0	8.2	8.2	10.5
Th	9.0	6.2	7.2	6.6	6.6	7.7	4.1	4.4	7.6	7.4	7.3	7.7	7.0	9.1
La	69.5	58.6	69.7	63	64.9	67.5	38	39	73	67	66.5	68.5	64.7	71.[illegible]
Ce	120	111	132	120	123	122	75	82	79	131	153	128	121	120
Sm	12.1	9.6	10.6	10.3	10.5	10.3	6.4	7.4	6.5	9.2	9.7	10.2	10.6	11.1
Eu	3.2	2.3	3.4	3.3	3.5	3.2	2.8	2.7	3.8	3.7	3.3	3.4	3.4	3.8
Tb	1.3	1.5	1.4	1.3	1.6	1.4	1.3	1.2	2.1	1.6	1.3	1.3	1.5	1.3
Yb	3.74	2.47	2.68	3.21	2.27	2.73	1.9	2.1	2.4	3.1	2.4	2.7	2.46	2.54
Lu	0.39	0.32	0.34	0.34	0.33	0.34	0.35	0.32	0.37	0.36	0.36	0.42	0.35	0.38

Table 5. (cont.)

Wt.%	TSB169	T170A	TB176A	TB175B	T-B1	TB-02	TB-06	TB-07	TB-10	TB-11	TB-21	TB-23	TB-24	TB-27
SiO_2	47.95	46.47	48.62	49.37	46.36	47.12	46.44	48.75	46.61	47.95	47.39	47.27	47.93	46.78
TiO_2	2.79	3.36	2.75	2.58	3.34	2.95	2.96	2.94	2.91	2.96	2.78	2.82	2.84	3.01
Al_2O_3	17.31	15.54	17.73	16.85	15.08	15.50	15.29	16.00	15.51	15.85	15.02	15.19	15.54	15.57
tFe_2O_3	9.15	10.43	8.65	10.38	11.39	12.00	12.21	12.09	12.19	12.12	11.98	11.91	11.76	12.09
MnO	0.13	0.13	0.12	0.16	0.14	0.17	0.12	0.17	0.17	0.17	0.17	0.17	0.16	0.17
MgO	3.80	5.40	3.57	4.10	5.80	4.76	4.62	4.98	4.73	4.62	5.56	5.44	5.20	4.47
CaO	7.46	9.60	8.88	7.45	9.30	7.65	7.25	7.53	7.56	7.74	8.42	8.51	8.37	7.59
Na_2O	4.79	3.18	3.95	3.00	3.22	3.83	3.80	3.62	3.66	3.44	3.28	2.93	2.83	3.34
K_2O	1.98	1.03	2.47	2.86	1.57	2.27	2.28	2.24	2.21	2.32	2.16	2.19	2.19	2.38
P_2O_5	0.98	1.05	1.00	0.98	0.97	0.89	0.89	0.89	0.89	0.92	0.81	0.81	0.84	0.92
LOI	5.01	4.00	2.60	2.91	3.66	2.30	2.90	2.47	2.68	2.0	1.79	1.97	2.03	2.98
	101.33	100.20	100.30	00.84	100.83	99.44	98.76	101.68	99.12	100.09	99.36	99.21	99.69	99.30
$Mg^{\#}$	45	51	45	41	50	46	45	47	46	45	50	50	49	45
ΣAlk	6.77	4.21	6.40	5.86	4.79	6.10	6.08	5.86	5.87	5.76	5.44	5.12	5.35	5.72
ppm														
Ni	42	82	40	63	71	46	74	44	53	55	44	70	70	52
Cr	37	104	33	174	91	31	84	34	34	40	71	81	78	38
V	173	193	181	210	199	174	162	157	173	156	142	163	167	167
Sc	13	19	13	22	16	18	18	15	16	15	14	13	14	13
Rb	27	bdl	29	25	20	43	38	41	45	42	24	42	41	46
Sr	1358	855	944	927	1008	1007	950	817	931	855	817	855	922	953
Ba	1030	1001	775	1222	1139	704	654	665	711	672	528	676	696	729
Zr	347	332	359	451	303	274	238	243	278	261	209	238	242	267
Y	32.3	33.2	31.4	38.6	30.0	31.5	31.2	29.4	33.4	28.9	25.4	29.6	30.0	32.5
Ta	4.6	4.8	4.8	5.4	4.0	4.8	4.5	4.0	3.4	4.1	3.9	4.0	4.0	4.6
Hf	6.2	7.1	7.0	8.4	5.8	6.8	5.4	6.7	6.2	5.6	5.6	5.4	6.0	6.3
Th	6.4	5.8	6.6	8.4	4.7	5.3		5.4		4.5	5.9	4.2	4.5	4.9
La	54.3	54.3	54.5	62.5	49.0	53	46	53	53	45	46	40	44	51
Ce	105	108	104	116	94	117	93	101	94	91	82	118	104	123
Sm	12.5	9.6	12.7	10.8	9.3	9.4	9.5	10.6	7.8	8.6	6.2	8.6	8.5	7.1
Eu	2.8	2.9	2.8	3.5	3.0	3.3	2.5	3.2	3.5	3.0	3.2	2.9	3.1	3.3
Tb	1.2	1.4	1.2	1.3	1.0	0.9	0.9	1.4	1.2	1.3	1.2	1.0	1.2	1.3
Yb	2.34	2.43	2.60	2.34	2.17	1.8	2.1	2.4	2.1	2.3	1.7	1.7	2.0	1.9
Lu	0.25	0.30	0.23	0.31	0.29	0.27	0.32	0.35	0.29	0.34	0.37	0.17	0.23	0.36

Table 5. (cont.)

Wt.%	TB-28	TB-29	TB-42	TB177	T180	TB180B	T184	T185	TB188	TF101	TL-01	TL-04	TL-05	TL-21
SiO_2	47.15	47.03	47.51	48.13	44.32	47.74	45.06	46.15	48.11	49.02	45.40	43.76	44.43	45.10
TiO_2	2.97	3.01	3.23	3.09	3.02	2.90	2.91	3.29	2.64	3.01	2.56	2.57	2.51	2.93
Al_2O_3	15.75	15.65	16.20	16.08	14.63	15.32	14.84	16.04	14.94	16.27	13.31	13.06	13.04	14.37
tFe_2O_3	12.18	12.27	12.22	10.75	10.36	10.10	10.64	12.26	10.31	11.62	10.67	9.34	10.84	10.49
MnO	0.17	0.17	0.17	0.15	0.13	0.15	0.15	0.17	0.03	0.16	0.11	0.21	0.15	0.10
MgO	4.58	4.61	4.78	6.87	5.73	5.61	6.74	4.71	7.42	4.61	6.33	6.54	7.49	6.16
CaO	7.72	7.49	7.69	8.34	9.71	5.81	8.61	7.17	8.99	7.88	7.49	11.18	9.36	7.05
Na_2O	3.43	3.74	3.91	2.68	3.19	4.91	3.37	3.71	2.43	3.07	3.66	2.59	2.26	3.91
K_2O	2.34	2.33	2.36	2.37	2.48	1.94	2.30	2.30	2.17	2.14	2.49	2.29	2.25	2.33
P_2O_5	0.93	0.93	0.93	1.02	0.98	0.92	0.88	0.91	0.85	0.88	0.84	0.91	0.84	0.91
LOI	2.22	1.83	2.03	2.41	2.17	2.74	3.80	2.50	3.05	1.37	7.76	8.89	8.06	8.22
	99.44	99.06	101.03	101.79	96.72	100.14	99.36	99.21	100.94	100.03	100.62	101.34	101.23	101.57
Mg#	45	45	46	56	61	52	56	44	59	44	56	60	60	56
tAlk	5.77	6.07	5.63	5.05	4.45	5.85	5.15	5.11	4.60	5.21	6.15	4.88	4.51	6.24
ppm														
Ni	40	52	40	85	103	77	193	36	206	32	164	140	140	106
Cr	22	29	36	140	146	89	162	16	191	21	219	196	236	215
V	164	160	184	205	250	198	193	219	183	179	147	151	140	165
Sc	14	13	14	21	25	18	23	16	21	14	15	17	18	20
Rb	43	41	52	74	40	bdl	37	53	58	31	50	46.5	34	54
Sr	893	912	872	913	813	840	921	733	1370	928	874	1359	1235	813
Ba	723	696	773	857	888	682	1136	911	1435	733	1731	941	846	1950
Zr	261	251	264	408	447	341	381	413	350	342	256	253	266	271
Y	32.2	30.6	29.0	35.8	35.1	30.3	38.9	38.7	35.1	35.8	26.6	28.2	26.6	25.0
Ta	4.6	4.2	4.1	4.9	4.5	4.4	5.0	4.6	4.5	4.3	3.6	3.5	4.1	4.5
Hf	6.6	5.9	5.7	7.89	6.93	6.2	8.4	7.8	7.4	6.3	5.8	5.8	7.0	6.3
Th	6.3	6.3	4.3	7.1	6.5	5.8	7.6	5.2	6.6	4.1	6.7	5.9	6.9	6.8
La	53	49	51	58.9	52.5	53	57.3	52.3	50.9	47.1	55	50	64	52
Ce	115	114	146	116	92	98	103	97	90	97	110	111	146	90
Sm	7.2	7.0	10.6	10.5	8.9	6.3	9.3	9.7	8.1	10.6	11.9	8.1	10.3	9.2
Eu	3.5	3.3	3.4	2.9	2.7	2.7	3.3	3.7	2.9	3.1	2.5	2.7	3.2	2.9
Tb	1.5	0.9	1.5	1.3	1.1	1.2	1.2	1.4	1.1	1.3	0.77	0.73	0.89	1.09
Yb	2.4	1.9	2.8	2.12	2.37	2.39	2.55	2.60	2.08	2.59	2.5	2.2	2.2	2.3
Lu	0.38	0.23	0.44	0.32	0.32	0.21	0.31	0.24	0.33	0.28	0.29	0.24	0.39	0.30

Table 5. (cont.)

Wt %	CSL 8801	CHS-01	CHS-13	CHS-24	CHS-28	TCS-01	TCS-02	TCS-04	TCS-13	TCK-02	TLC-2	TLC-3	TLC-33
SiO_2	46.86	50.78	50.34	49.52	49.45	51.28	51.74	52.03	51.54	50.43	50.72	51.39	52.02
TiO_2	2.73	2.20	2.18	2.15	2.20	2.38	3.01	2.67	2.45	2.09	1.53	1.69	1.50
Al_2O_3	13.05	14.22	14.56	13.95	13.95	14.89	14.74	15.20	14.77	14.01	13.85	14.09	14.00
tFe_2O_3	11.18	11.48	10.92	11.44	11.60	10.53	11.39	10.27	10.75	11.56	10.07	9.86	10.06
MnO	0.15	0.15	0.12	0.14	0.14	0.12	0.14	0.12	0.12	0.14	0.14	0.14	0.14
MgO	9.38	6.76	6.42	7.27	7.41	6.04	4.66	3.97	5.63	7.38	8.05	7.47	7.75
CaO	8.90	9.64	9.68	9.48	9.66	9.59	8.94	8.59	9.26	9.48	8.68	8.57	8.52
Na_2O	2.31	2.86	2.67	2.71	2.66	2.83	3.17	3.36	3.02	2.77	2.89	3.08	3.10
K_2O	1.46	0.60	0.58	0.58	0.47	0.19	0.83	1.27	0.71	0.69	0.44	0.48	0.47
P_2O_5	0.68	0.37	0.30	0.36	0.37	0.40	0.52	0.54	0.46	0.35	0.32	0.29	0.33
LOI	3.29	1.80	1.99	2.28	1.19	2.59	7.10	1.85	0.78	2.89	3.64	2.64	3.17
	99.99	100.86	99.76	99.88	99.10	101.34	101.24	100.77	99.49	101.79	100.33	99.70	101.11
Mg'	64	57	56	58	58	55	47	45	53	58	64	62	61
tAlk	3.77	3.46	3.25	3.29	3.13	3.32	4.00	4.63	3.73	3.46	3.33	3.56	3.57
ppm													
Ni	200	73	115	162	160	120	66	76	129	131	216	206	180
Cr	241	205	178	200	209	162	49	95	154	184	326	295	273
V	163	242	214	184	187	190	229	229	185	162	140	145	138
Sc	24	22	21	22	23	21	22	21	19	23	17	18	16
Rb	40.5	14	11	19	12	16	15	28	15	16	22	16	22
Sr	576	652	438	381	414	511	502	496	489	384	338	377	404
Ba	372	617	145	159	115	200	255	284	193	149	254	212	386
Zr	204	80	126	170	173	128	160	167	224	128	128	177	101
Y	23.1	16.5	20.5	26.8	26.6	20.5	28.4	20.8	28.2	21.6	18.1	22.1	15.0
Ta	3.5	1.2	1.2	1.2	1.4	1.9	2.2	2.1	2.1	1.7	1.1	1.5	1.9
Hf	5.8	3.9	3.8	4.2	4.6	4.6	5.3	5.5	4.6	3.5	3.0	3.8	3.0
Th	4.8	2.4	2.1	2.5	2.3	3.4	3.9	3.8	3.2	2.4	1.8	3.2	2.2
La	39.2	18.3	14.6	18.8	19.8	20.0	24.8	24.8	23.2	17.4	15.9	21.4	15.6
Ce	82.4	33.8	44.7	38.7	40.1	49.3	53.3	70.6	40.4	39.0	32.6	41.0	35.2
Sm	7.7	5.6	4.9	5.4	5.6	5.7	7.0	7.1	6.6	5.2	4.14	4.79	4.3
Eu	2.7	1.9	1.8	1.9	1.9	2.1	2.4	2.4	2.1	1.9	1.42	1.66	1.5
Tb	1.07	0.70	0.99	0.94	0.93	1.04	1.20	1.17	0.94	0.9	0.62	0.74	0.7
Yb	1.94	1.72	1.67	1.89	1.90	1.57	2.19	1.96	1.86	1.9	1.24	1.46	1.4
Lu	0.37	0.24	0.35	0.26	0.25	0.34	0.38	0.42	0.26	0.23	0.18	0.21	0.17

Note: sample CHS-01 and those in its right-hand side are tholeiites (12 in total); otherwise, alkali basalts.

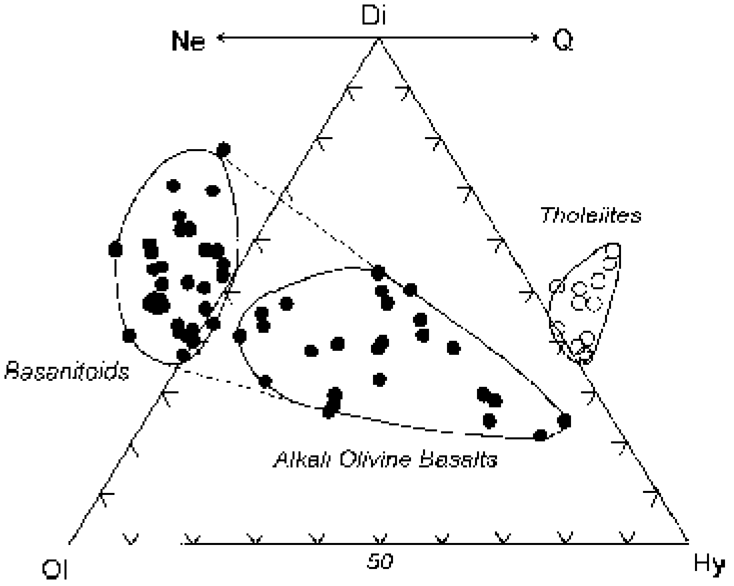

Figure 6. The normative CIPW compositions of basaltic rocks in the Shiting-Yinko area. Symbols are the same as in Figure 3.

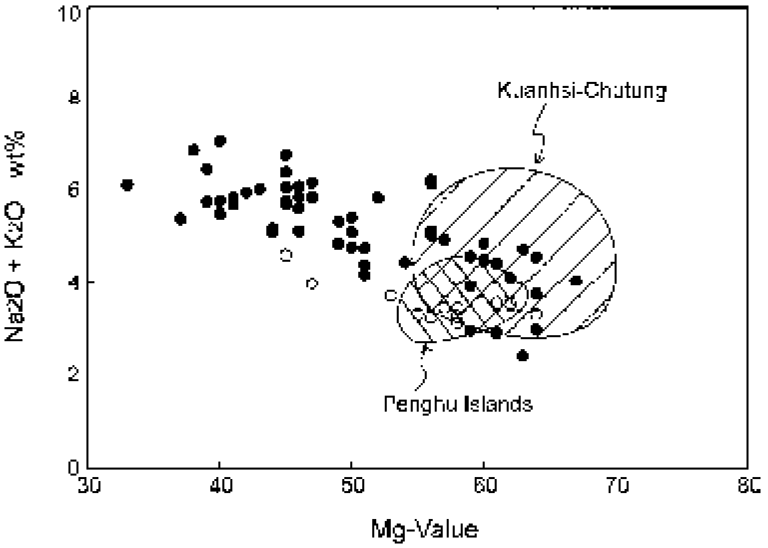

Figure 7. The total alkalies (Na_2O+K_2O) vs. Mg-value plot of basaltic rocks in the Shiting-Yinko area. Note that there is a wide spectrum of Mg-values as compared with the Kuanhsi-Chutung and Penghu Islands volcanics. Symbols are the same as in Figure 3.

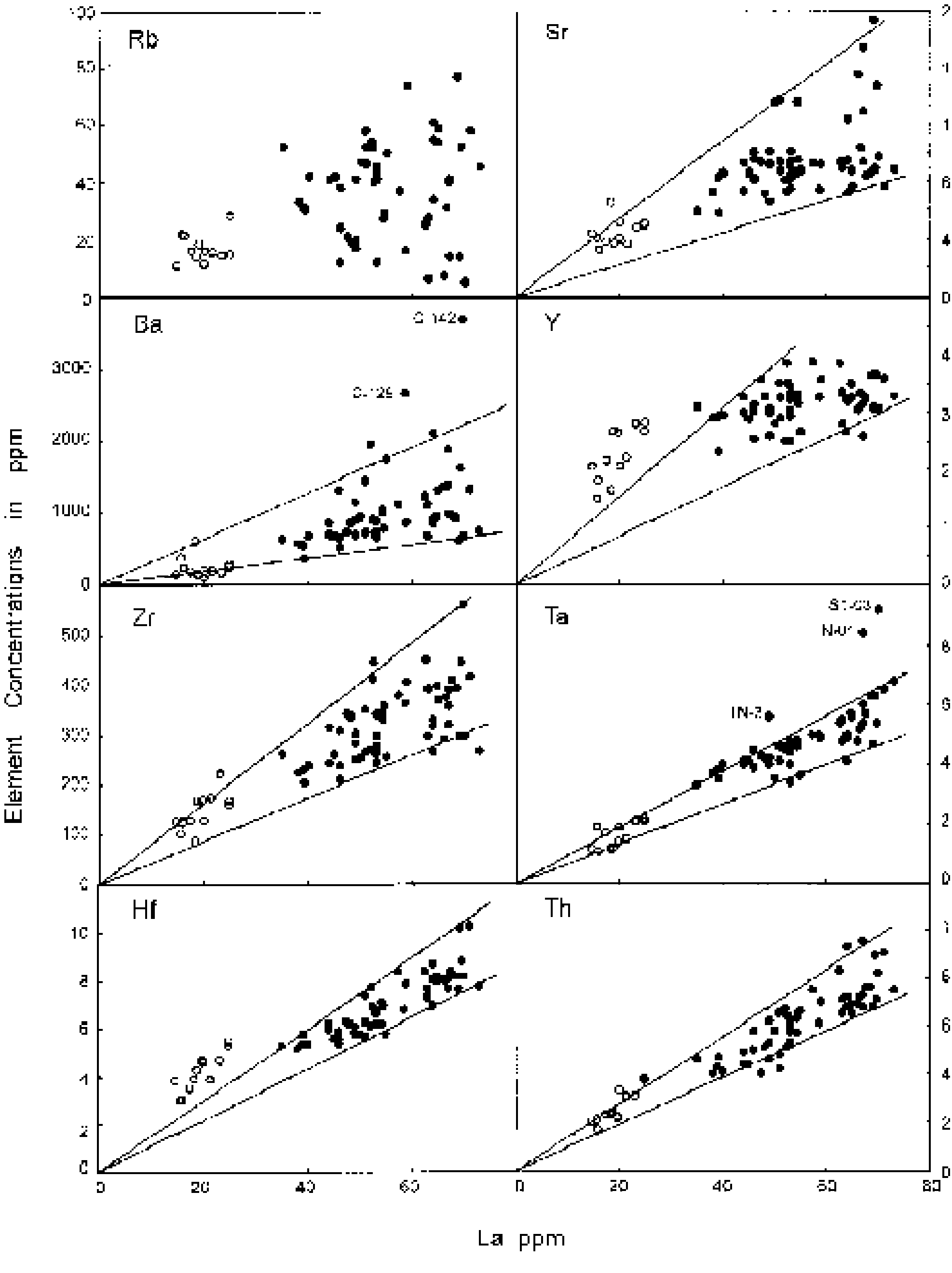

Figure 8. The trace element vs. La plot of basaltic rocks in the Shiting-Yinko area. Symbols are the same as in Figure 3. The degree of coherence between trace element and La can be revealed by the spread of angle for data points.

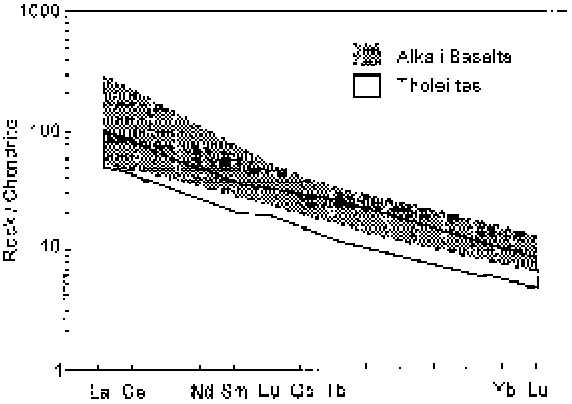

Figure 9. The chondrite normalized distribution patterns of basaltic rocks in the Shiting-Yinko area. Chondrite values for normalization are those of McDonough and Sun (1995).

Sr- and Nd-isotopic compositions among alkali basalts and tholeiites are rather uniform. For instance, ^{87}Sr/^{86}Sr ratios concentrate in 0.7036 for alkali basalts and 0.7039 to 0.7041 for tholeiites; εNd values vary in a narrow range from +4.3 to +6.0 for both types of basalt (Tab. 6), indicative of insignificant crustal contamination during magma generation. All these data are indistinguishable from the common Neogene intraplate basalts in Fujian-Taiwan region, with the only exception of the Kuanhsi-Chutung area where basaltic rocks possess much higher ^{87}Sr/^{86}Sr and lower ^{143}Nd/^{144}Nd ratios (Fig. 10). The Kuanhsi-Chutung basalts, moreover, exhibit an EM-1 type Pb isotopic compositions (Chung *et al.*, 1995). Whereas the generation of Kuanhsi-Chung basalts requires involvement of an EM-1 type mantle source thought to reside in shallow lithospheric levels, the isotopic compositions of other Fujian-Taiwan Neogene basalts can be accounted for by a plum-pudding asthenosphere model under the lithospheric extension condition (Chung *et al.*, 1994, 1995). In the latter scheme, most of the Fujian-Taiwan intraplate volcanics were derived from various degrees of partial melting of a heterogeneous asthenosphere (mantle source) that had been previously influenced by an EM-2 type component (i.e., the plum) resulting from thermal and/or mechanical erosion of the lower part of lithospheric mantle during the continual extension around the Taiwan strait (Chung *et al.*, 1994).

DISCUSSION

Petrogenesis

In the Shiting-Yinko area, basaltic rocks can mainly be divided into early Miocene (23-20 Ma) alkali basalts and late Miocene (12-9 Ma) tholeiites separated by a time gap of about 10 My. By contrast, nearly contemporaneous eruptions of alkali basalts and tholeiites from 16 to 8 Ma have been observed in adjacent areas like Penghu Islands (Lee, 1985) and Kuanhsi-Chutung (Chen and Chung, 1985). Therefore, a model involving different degree of partial melting at different depths from a rather homogeneous mantle source was proposed to account for their petrogenesis with the evidence that all kinds of basalt in single area have indistinguishable isotopic compositions (Chung *et al.*, 1994).

Table 6. Isotopic compositions of basaltic rocks in Shiting-Yinko area, N.Taiwan.

Sample no.	Rx Type	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	εNd
1. Shiting				
ST-02	AB	0.70363	0.51293	−5.3
2. Nanshihchiao				
TN-4	AB	0.70362	0.51291	+5.3
		0.70359*	0.51292*	+5.5
3. Tucheng				
TB-07	AB	0.70361	0.51293	+5.6
		0.70358*	0.51294*	+5.7
TB-08	AB	0.70352	0.51293	+5.7
TB-11	AB	0.70365	0.51288	+4.7
		0.70362*	0.51289*	+4.9
4. Chienshan				
TCS-01	TH	0.70387	0.51288	−4.5
TCS-02	TH	0.70405	0.51286	−4.3
5. Hengchi				
CHS-01	TH	0.70385	0.51292	−5.5
CHS-13	TH	0.70408	0.51295	−6.0

Rock types: AB= alkali basalt; TH= tholeiite.

* Data from Chung *et al.*(1995); $\varepsilon Nd=\{(^{143}Nd/^{144}Nd)_{samp}/0.512638-1\}x10^4$

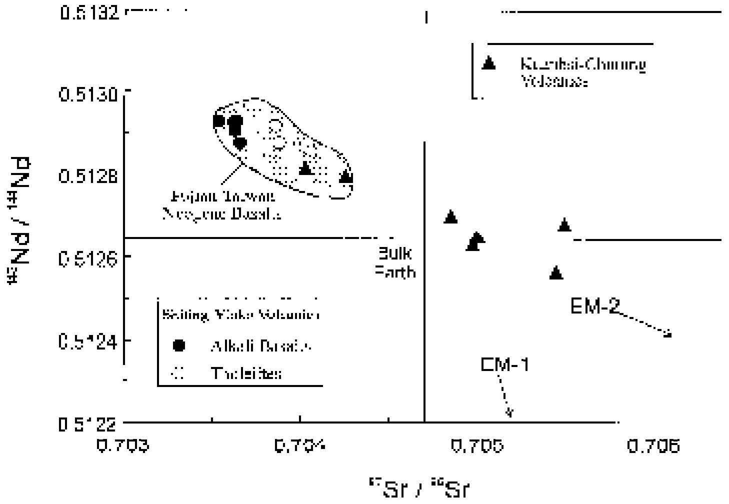

Figure 10. The Sr-and Nd-isotopic variations of basaltic rocks in the Shiting-Yinko area are compared with the Neogene Fujian-Taiwan basalts and Kuanhsi-Chutung volcanics (Chung *et al.*, 1995).

Most of the alkali basalt samples have low Fo contents in the olivine phenocrysts, together with low Mg-values and low Ni and Cr concentrations in the whole rock analysis (Tab. 5), indicating that they could have solidified from more evolved magmas. Among these alkali basalts, the basanitoids from Shiting and Nanshihchiao (e.g. ST-25 and TN-4) are considered to be approximate to the primary melts in equilibrium with the mantle source for deriving alkali basaltic magmas in the Shiting-Yinko area. They are characterized by (1) having the highest Fo contents in olivines (Fo_{86}), (2) crystallizing at the highest temperature about 1100°C as revealed from the Fe-Ti oxide geothermometry, (3) containing high Mg-values (Mg'=67 to 64) as well as high Ni (230 ppm) and Cr (around 300 ppm), but low Rb (12 to 6 ppm) concentrations, and (4) possessing the Sr- and Nd-isotope signatures (εNd=+5) similar to the common Neogene Fujian-Taiwan mantle.

In order to have a better understanding of the major controlling factor for different rock types with various compositions, the diagram constructed by adopting the La element as the incompatible dominator (in this case, the La/Sm ratio versus La concentration plot) is used to delineate the partial melting versus fractional crystallization processes among the studied rocks (Fig. 11). Unlike the cases of Penghu Islands and Kuanhsi-Chutung volcanics which are nearly identical in this respect, larger degrees of fractional crystallization are thought to have taken place in the magmatic evolution for deriving different types of alkali basalts, particularly the low-Mg basanitoids, in Shiting-Yinko area as reflected by the wider spread of data points in Figure 11. It should be mentioned that feldspar may not be an important phase in the course of fractionation because there appear to be invisible Eu anomalies in the normalized REE distribution patterns for these rocks, even for the low-Mg basanitoids (Fig. 9).

Tholeiites in the Shiting-Yinko area are significant in this study. They are characterized by having a rather limited chemical compositions (including Sr- and Nd-isotope ratios) for all rocks from different units and having a span of volcanically active time at 12-9 Ma similar to that of Kuanhsi-Chutung volcanics. This is to say, regarding the eruption time and spatial distribution, Shiting-Yinko tholeiites can be treated as the northeastern extension of the Kuanhsi-Chutung volcanics (the striped area in Figure 1a). On the geochemical ground, although data points displaying in the La/Sm vs. La plot (Fig. 11) do not exclude a common source that can generate tholeiites with a larger degree of partial melting than alkali basalts, the Sr- and Nd-isotopic compositions are not conformable with the Kuanhsi-Chutung volcanics which distribute far away from the field of general Fujian-Taiwan intraplate basalts in Figure 10. Under this circumstance, the nature of mantle source for deriving tholeiites and alkali basalts in the Shiting-Yinko area and for basaltic rocks in the Kuanhsi-Chutung area should be examined in the first place.

It has been demonstrated that high field strength elements vary coherently with La concentrations in the studied rocks (Fig. 8), so they are used to test for the nature of source region. The parameters chosen are Th/Ta and Th/Hf ratios (Fig. 12), for concentrations of these three elements are all at few ppm level in these rocks and analyzed simultaneously using INAA method. In this diagram alkali basalts mostly spread in the field bounded by two slopes of α=1.8 and 1.3, whereas tholeiites have greater slopes with α=2.5 for Chienshan and Tzelichiao samples and α=3.3 for Hengchi samples. The lack of a well-defined linear distribution for alkali basalts and tholeiites from Shiting-Yinko area reflects either a source heterogeneity or different source regions for the generation of these rocks. It is noted that, in the same graphic scheme, alkali basalts are invariably superimposed and extended by tholeiites in a field between α=2.0 and 1.0 (dashed lines in Figure 12) for the case of Penghu Islands and Kuanhsi-Chutung volcanics (Chen, 1990; and unpublished data).

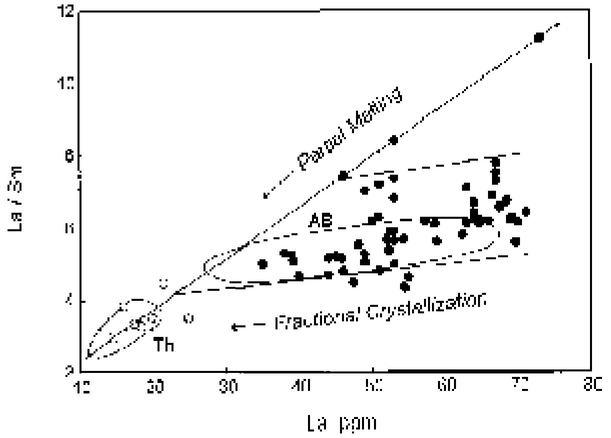

Figure 11. The La/Sm vs. La plot of basaltic rocks in the Shiting-Yinko area in which the distribution fields for Tertiary alkali basalts (AB) and tholeiites (Th) in Kuanhsi-Chutung and Penghu Islands (noted that they are virtually the same and can be present in common fields) are drawn for comparison. Symbols are the same as in Figure 3.

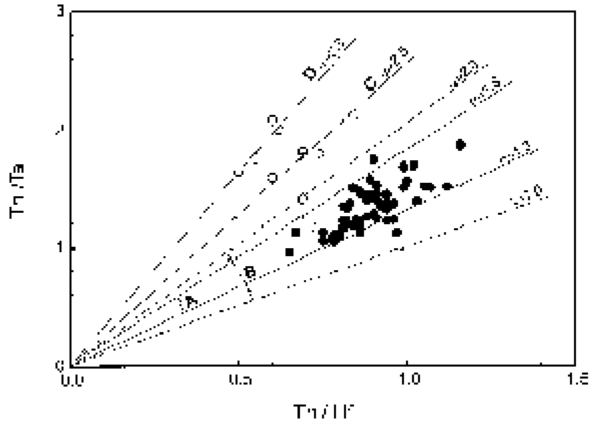

Figure 12. The Th/Ta vs. Th/Hf plot of basaltic rocks in the Shiting-Yinko area. Symbols are the same as in Figure 3. A: the distribution range for alkali basalts in Shiting-Yinko area, B: the distribution range for both alkali basalts and tholeiites in Penghu Islands and Kuanhsi-Chutung area, C: tholeiites in Chienshan and Tzelichiao, and D: tholeiites in Hengchi.

It may be concluded that, unlike the case of Penghu Islands and Kusnhus-Chutung volcanics, tholeiites and alkali basalts in Shiting-Yinko area cannot be derived from a common mantle source as revealed by the high field strength element data. Further judging from the Sr- and Nd-isotopic compositions, the tholeiites in Shiting-Yinko area possess isotopic signature different from basaltic rocks in Kuanhsi-Chutung area, thus precluding the possibility to generate magmas for all the late Miocene tholeiites in northern Taiwan from a common source. To reconcile our earlier plum-pudding model with the discrepancies of the high field strength elements and Sr- and Nd-isotope compositions, we, therefore, propose that the early Miocene alkali basaltic magmas, were mainly derived from the asthenospheric source with the involvement of small amount of the EM-2 type component through small degree of melting, similar to a process responsible for the generation of other Fujian-Taiwan Neogene intraplate basalts (Chung *et al.*, 1994, 1995). On the other hand, the late Miocene tholeiitic magmas could have originated at shallower depths perhaps near the lithosphere-asthenosphere boundary with larger degree of melting. As for the unique Kuanhsi-Chutung volcanics, they were thought to have been influenced by the accidental and unique EM-1 type source residing in the lithospheric mantle to a certain extent (Chung *et al.*, 1995).

Tectonic Implications

Isotopic compositions of basaltic rocks can be used to constrain the magmatotectonics in the SE China continental margin (Lapierre *et al.*, 1997), where basic volcanisms have been prevailing at late Cretaceous (92 to 76 Ma, Lee *et al.*, 1999), Paleogene (56 to 53 Ma, Chen *et al.*, 1997), early Miocene (23 to 20 Ma, this study) and late Miocene (16 to 8 Ma, Chen, 1990; Lee, 1994; this study). Late Cretaceous tectonic evolution in the vicinity of Taiwan Strait is believed to have been under an initial stage of post-orogenic environment (Lee *et al.*, 1999) marking with the beginning of an extensional stretching of lithosphere which resulted in the emplacement of abundant mafic dikes in this area. Such an environment could have lasted for a long time as manifested by the older basic rocks in adjacent region, e.g., late Cretaceous mafic dikes in Fujian coastal area (Lan *et al.*, 1995; Lee *et al.*, 1999) and Paleogene basalts beneath the northern Taiwan offshore area (Chen *et al.*, 1997), which have significantly more enriched magma sources (εNd= -2 to -5).

Isotopic compositions of the early Miocene Shiting-Yinko alkali basalts (εNd= +5) may further indicate the time for a dramatic change of mantle source regions of the intraplate basalts. These values are virtually indistinguishable with those of other early Miocene alkali basalts (for instance the inner Fujian) as well as the general Fujian-Taiwan Neogene intraplate basalts. As the late Miocene Shiting-Yinko tholeiites keep the same isotope compositions, the present data support our earlier inference (Chung *et al.*, 1994) that in the continental extension the lithosphere near northern Taiwan remains rarely stretched until at least early Miocene time when alkali basalts were dominantly emplaced. In the late Miocene, however, tholeiitic magmas derived from the asthenosphere-lithosphere boundary occurred because most likely of larger amounts of lithosphere thinning and asthenosphere upwelling.

CONCLUSIONS

Basaltic rocks occurred in Shiting-Yinko area consist mainly of early Miocene (23 to 20 Ma) alkali basaltic and late Miocene (12 to 9 Ma) tholeiitic lavas with some sporadical dikes and sills of the same ages. Although they appeared to be different rock types and erupted with a gap for about 10 My, both alkali basalts and tholeiites display Sr- and Nd-isotopic variations similar to the common Fujian-Taiwan Neogene intraplate basalts except Kuanhsi-Chutung area.

Fractional crystallization, to some degrees, is suggested to have taken place in some alkali basaltic rocks with smaller Mg-values (for instances, Tucheng samples). Incorporation of fragmented and resorbed kaersutitic amphiboles in Yenliao basalts may indicate the presence of the high-pressure megacrysts, which is consistent with the notion of existence of a basic lower crust resulting from extensive basaltic underplating coupled with crystal accumulation near the crust-mantle boundary underneath northern Taiwan in early Tertiary (Lee *et al.*, 1993). On the other hand, tholeiitic rocks have limited geochemical variations, but show distinct characteristics of the high field strength elements. This precludes the possibility for generating both tholeiitic and earlier alkali basaltic magmas from a common mantle source in the Shiting-Yinko area.

Isotopic compositions for early Miocene alkali basalts in the Shiting-Yinko area marks the earliest time to record a depleted mantle signature in northern Taiwan (including the northern offshore area). This can be explained by the Cenozoic lithospheric extension in this area under which a plum-pudding type asthenospheric mantle source is applied for the generation of these basaltic magmas (Chung *et al.*, 1994, 1995). Subtle involvement of the EM-2 type component (plum) and different degrees of melting in the asthenospheric mantle (pudding) led to the generation of magmas varying from alkali basalt to tholeiite at different depths and times in northern Taiwan.

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