Volcanism above a subducted extinct spreading center: a reconnaissance study of the North Luzon Segment of the Taiwan–Luzon Volcanic Arc (Philippines)

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Abstract—The aseismic ridge system of the South China Sea, extinct since about 17 Ma, subducts below the central part of the Taiwan–Luzon volcanic arc, North Luzon Segment (NLS). The buoyancy of the relatively young and warm crust of the ridge system may be responsible for the high elevation of the NLS. Volcanism in this part of the arc is characterized by the eruption of small volumes of intermediate to felsic magma (57–65% SiO₂). The eruption products from the volcanic front in the central part of the Cordillera form a low-K, calc-alkaline suite, characterized by high Sr and low HREE and Y contents. Some workers consider these characteristics to be the geochemical fingerprints of magmas generated by slab-melting. However, model calculations require the amount of residual garnet in the source to be small ($\leq 10\%$), in contrast to experimental work that indicates high amounts of residual garnet ($\geq 30\%$). Alternatively, the melts may have been generated by melting of amphibolitic lower crust. The magmas erupted in the eastern and southern parts of the segment are calc-alkaline suites with moderate to high K contents and Sr and Y contents typical for arc suites. The small volume and evolved composition of the erupted magmas may be related to the uplift of the NLS with the crust acting as a density filter, which prevents more mafic magmas from reaching the surface.

Introduction

The subduction of spreading centers may affect magmatism of volcanic arcs in different ways. In some arcs, the impact of the ridge resulted in deep faulting, which provided pathways for the ascent of primitive magmas (e.g. Solomon Islands: Ramsay *et al.*, 1984; Vanuatu: Barsdell and Berry, 1990). Where young ridges are subducted, the dip of the down-going plate may be reduced due to the buoyancy of the still warm crust. As a result, the mantle wedge between subducted slab and crust is shifted far inland, resulting in cessation of arc volcanism, because the subducted crust becomes dehydrated before reaching the mantle wedge (e.g. in the non-volcanic zone of the South American Andes; Mahlburg-Kay *et al.*, 1988). Another consequence of the subduction of young oceanic lithosphere may be the melting of the subducted crust, a process recently investigated by Drummond and Defant (1990) and Defant and Drummond (1990).

The North Luzon Segment (NLS) of the Taiwan–Luzon volcanic arc, which overlies the extinct spreading center of the South China Sea, offers an opportunity to study the magmatic response to subduction of a young ridge. In this contribution we: (1) review the tectonic

setting of late-Miocene to Quaternary volcanism in the NLS; (2) present new petrographic and geochemical data for igneous rocks from different localities along the NLS; and (3) discuss the petrogenesis of the volcanic rocks within their tectonic framework.

Tectonic and Geological Setting

The Luzon arc, formed in response to the subduction of the South China Sea along the Manila Trench, extends for about 900 km from eastern Taiwan to the island of Mindoro in the central Philippines. The arc is composed of five segments, characterized by distinct tectonic setting and magma chemistry (Defant *et al.*, 1989). From north to south, these are: (1) the Taiwan Segment; (2) the Bashi Segment, which includes all the small islands located between Taiwan and Luzon and Cagua Volcano in northeastern Luzon (in contrast to Defant *et al.*, 1989, we include the islands Luta and Lanshu in this segment, because the magmas erupted resemble those of the southern islands in terms of geochemical and isotopic variability, cf. Chen *et al.*, 1990; McDermott *et al.*, 1993); (3) the North Luzon Segment, which extends along the Cordillera Central of northwestern Luzon as far south as the Lingayen–Dingalan Fault; (4) the Bataan Segment; and (5) the Mindoro Segment. The last two are separated by the

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Fig. 1. Tectonic setting of the North Luzon segment (NLS) of the Taiwan-Luzon arc (modified after Lewis and Hayes, 1984; Pautot and Rangin, 1989; Ringenbach *et al.*, 1990; Balce *et al.*, 1980). The cluster of volcanic domes south of the area shown in Fig. 2 and labelled B is the Baguio District. The locations of the Bashi Segment (BAS), the Bataan Segment (BA) and the Macolod Corridor (MC) are indicated. SB is the Steward Bank.

Macolod Corridor, which Defant *et al.* (1988) and Förster *et al.* (1990) suggested to be a "pull-apart" zone (Fig. 1).

Convergence along the Manila Trench is thought to be roughly WSW-ENE (de Boer *et al.*, 1980), i.e. sub-parallel to the strike of the Scarborough Seamount chain (Fig. 1), which is inferred to be the extinct spreading center of the South China Sea (e.g. Taylor and Hayes, 1983; Pautot *et al.*, 1986). North of about 17.5°N, the trench is about 45 km wide and narrows to the south to 10–15 km, where the Scarborough Seamount chain is being subducted (Pautot and Rangin, 1989). As a consequence of the location of the spreading center at the southern end of the NLS, the subducting crust becomes progressively older towards the north (magnetic anomaly 5e to anomaly 10, i.e. 17–30 Ma; Taylor and Hayes, 1983).

East of the Manila Trench, and separated from it by an accretionary prism, the North Luzon Trough contains up to 4 km of sediment (Hayes and Lewis, 1984). Its southern end, the Steward Bank lies roughly along the strike of the Scarborough Seamount Chain. This complex is believed to be composed of a mixture of igneous and sedimentary rocks (Hayes and Lewis, 1984) and is interpreted to be a slice of the South China Sea spreading center accreted to the upper plate (Pautot and Rangin, 1989).

The Ilocos Basin lies east of the North Luzon Trough and is thought to be the northward extension of the Central Valley of Central Luzon (e.g. Hayes and Lewis, 1984), an older sedimentary basin, which probably overlies the northern extension of the Zambales Ophiolite (Hayes and Lewis, 1984). The same sedimentary sequences form the foothills of the Cordillera Central, which, in its core, is largely composed of Early Tertiary volcanic rocks that were intruded by large, composite batholiths during the Oligocene/early Miocene (e.g. Fernandez and Damasco, 1979; Balce *et al.*, 1980; Metal Mining Agency of Japan, 1977, 1981). At least two major strike-slip fault systems (the Vigan-Aggao and Abra River Faults) cut the Cordillera into several longitudinal slices (Fig. 2; Ringenbach *et al.*, 1990).

The NLS differs significantly from typical oceanic arcs and the other segments of the Taiwan-Luzon system by its high elevation with large areas lying at altitudes of 1200–2200 m. Uplift occurred after the deposition of the Kennon limestone in Mid-Miocene time (Balce *et al.*, 1980). Christian (1964), among others, argues for a period of significant uplift in the Pleistocene, based on the sedimentary record in the Cagayan Basin. High elevations are usually found in arcs colliding with crust of increased thickness, but the NLS is not such a collision zone. In this respect the NLS is similar to the South American Andes and a similar mechanism may be responsible for the uplift, i.e. the subduction of young (<25 m.y.) oceanic crust along the Manila Trench. Oceanic crust younger than about 25 m.y. is still warm, hence less dense, and capable to uplift the overlying crust-mantle wedge due to its buoyancy (Uyeda, 1982; Yang *et al.*, 1992). Since the youngest parts of the South China Sea crust have been subducted below northern Luzon, the NLS experienced the most uplift (note that elevations >2000 m occur only at 16°30'–17°30'N, more or less exactly east of the "collision zone"; see Fig. 2 in Ringenbach *et al.*, 1993).

Volcanism in the North Luzon Segment

There are few known preserved young volcanic landforms within the NLS, including three small craters in the Kalinga-Apayao Province (Alvir, 1956). However, Holocene volcanism is indicated by a ¹⁴C-age of 7800 years for an ignimbrite (Ringenbach *et al.*, 1993). This may be due to either a lack of stratovolcanoes in this segment of the Taiwan-Luzon arc or to very rapid erosion resulting from the Pleistocene uplift of this mountain range.

Only a limited amount of work has been carried out on the magmatic rocks from the NLS, restricted mainly to the Baguio District located at the southern end of the NLS and some additional data for the Cervantes-Lepanto area (Balce, 1979; Shannon, 1979; Divis, 1983; Lo, 1981; Defant *et al.*, 1990; Ringenbach *et al.*, 1990). Unfortunately, Lo (1981) and Defant *et al.* (1990) do not provide any details about sampling localities, and thus, the geological context of their samples is uncertain.

The available geochemical data indicate compositional variety in the NLS with most published analyses falling into the field of common calc-alkaline rocks and few into the low-K field (Peccerillo and Taylor, 1976). Sr-isotopic

Fig. 2. Tectonic map of the central part of the North Luzon Segment based on a Landsat-photo (Metal Mining Agency of Japan, 1981; Ringenbach *et al.*, 1990; Winter, unpublished data). Only those faults indicated on the maps of Metal Mining Agency of Japan (1981) and Ringenbach *et al.* (1990) seen on the Landsat-photo are shown here. Stars are volcanic domes and plugs (MI = Minlawi Plug, BAN = Banawue Plug, BA = Batog Knob, QU = Quinali dome). Ruled areas are outcrops of Oligocene plutons.

data for the Baguio area (0.7032–0.7037, Divis, 1983; Defant *et al.*, 1990) indicate that $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the NLS are lower than in the southern segments of the Taiwan–Luzon arc and are in the same range as most volcanic rocks of the Taiwan Segment, older volcanics of the Bashi Segment (Calayan, Camiguin, Mt Cagua;

Chen *et al.*, 1990; McDermott *et al.*, 1993), Pliocene to Recent volcanic rocks from the Bicol arc in southern Luzon ($^{87}\text{Sr}/^{86}\text{Sr}$: 0.7035–0.7040; Divis, 1980; Knittel-Weber and Knittel, 1990) and pre-Miocene plutonic rocks from Luzon ($^{87}\text{Sr}/^{86}\text{Sr}$: 0.7035–0.7041, Knittel and Defant, 1988; Winter *et al.*, unpublished data).

1. *Cervantes–Lepanto area*

The geology of the Cervantes–Lepanto area, located in the western part of the Cordillera Central, is dominated by the Cervantes Trough, developed east of the Abra River Fault, where it makes a sharp westward bent before returning to its “normal” N–S direction (Ringebach *et al.*, 1990) (Fig. 2). The trough is thought to have formed in relation to movements along the Abra River Fault, which is considered to be the median branch of the northern horsetail-like ramification of the strike-slip Philippine Fault (Ringebach *et al.*, 1990). A thick volcanoclastic sequence, mildly folded and faulted, fills the trough.

Clusters of small volcanic edifices occur at the northeastern and southeastern ends of the trough (Fig. 2) in the Quirino and Lepanto areas. Other eruption centers thought to be scattered throughout the basin (Ringebach *et al.*, 1990) have subsequently been identified to consist of reworked material (Ringebach *et al.*, 1993, and written communication, 1992).

The northeastern eruption centers are located about 5–10 km east of the township Quirino (Ilocos Sur), at the

northeastern margin of the trough along the Balasian River, a tributary of the Abra River. Four of the five dacitic plugs, having diameters of 500–1000 m, were sampled: the Minlawi, Banawue, Batog and Mt Quinali Plugs.

The plugs intruded altered volcanic flows (predominantly amygdaloidal basalts and andesites) with locally intercalated sediments, considered to be part of the Eocene Licuan Group of Formation I (Metal Mining Agency of Japan, 1981). West of the intrusive bodies, towards the Abra River, unaltered volcanoclastic rocks crop out and represent the Miocene–Pleistocene basin fill of the Cervantes Trough.

No radiometric age determinations have been carried out on the plugs of the Quirino area. An andesite dike, exposed in the lower Balasian River and compositionally similar to the plugs (Table 1), has been dated at 9.8 ± 2.0 Ma (Metal Mining Agency of Japan, 1981). Ringebach *et al.* (1990) give similar ages for several dikes in the area. Andesitic to dacitic clasts in monogenic conglomerates in the Cervantes Trough yield younger K–Ar ages of 3.7–4.9 Ma (Ringebach *et al.*, 1990; Ringebach, 1992), raising the possibility of a younger

Table 1. Chemical and Sr isotope composition of volcanic rocks from the Quirino and Lepanto areas (major elements in wt%, trace elements in ppm)

Sample	Quirino area					Lepanto area					Tirad 329
	Batog P1-76	Dyke B 3350	Quinali P1-77	Minlawi P1-78	Banawue P1-72	TTP216	TTP245D	Posdo TTP169	TTP42	TTP245H	
SiO ₂	57.99	60.08	61.33	61.66	64.72	57.01	61.62	62.65	62.50	63.83	62.06
TiO ₂	0.55	0.50	0.43	0.39	0.44	0.58	0.35	0.52	0.48	0.35	0.38
Al ₂ O ₃	18.00	17.64	17.52	17.61	16.58	19.94	17.83	17.06	18.82	17.16	15.46
Fe ₂ O ₃	6.41	2.76	5.12	4.39	4.38	6.23	3.73	4.94	4.97	4.06	5.43
FeO	—	3.81	—	—	—	—	—	—	—	—	—
MnO	0.15	0.17	0.32	0.12	0.06	0.13	0.10	0.07	0.12	0.11	0.02
MgO	3.24	2.75	2.57	1.89	1.75	1.66	1.48	1.39	1.24	1.44	2.14
CaO	7.40	7.02	6.89	6.05	4.71	4.23	6.11	4.96	6.16	5.84	5.03
Na ₂ O	3.48	3.35	3.73	3.71	4.01	2.93	4.05	3.55	4.17	3.64	4.39
K ₂ O	0.76	0.58	0.38	1.13	1.65	0.90	0.37	2.85	0.95	0.75	1.00
P ₂ O ₅	0.18	0.21	0.15	0.16	0.22	0.19	0.13	0.29	0.16	0.11	0.10
Loss	1.72	1.07	1.54	2.92	0.99	5.49	4.31	0.86	0.56	2.47	1.11
Total	99.88	99.94	99.98	100.03	99.51	99.29	100.08	99.14	100.13	99.76	97.12
Rb	10	n.a.	4	26	24	7	8	78	20	14	25
Sr	461	n.a.	579	716	590	436	518	612	589	509	410
Ba	188	n.a.	216	582	527	529	140	536	293	225	306
Th	1.76	n.a.	1.20	1.24	5.24	2.72	2.73	n.d.	1.72	2.05	1.69
U	0.71	n.a.	0.48	0.60	0.76	0.68	1.16	n.d.	0.58	1.00	0.55
Nb	3	n.a.	1	2	5	4	3	3	4	2	2
Ta	0.13	n.a.	0.27	0.11	0.27	0.17	0.15	n.d.	0.12	0.14	0.22
Zr	70	n.a.	86	71	100	92	78	98	78	73	64
Hf	2.27	n.a.	2.39	1.73	2.43	2.73	3.09	n.d.	2.50	2.19	2.01
Y	11	n.a.	12	12	13	8	12	14	12	10	7
Ni	11	n.a.	11	7	5	8	10	15	19	7	13
Cr	12	n.a.	31	17	15	10	2	7	17	12	16
La	10.4	n.a.	7.87	7.90	24.4	10.6	10.7	n.d.	8.22	8.50	6.10
Ce	19.0	n.a.	15.6	15.8	40.7	23.0	23.3	n.d.	16.8	17.8	12.0
Nd	11.2	n.a.	10.0	9.69	18.9	13.1	11.6	n.d.	9.57	10.2	6.99
Sm	2.39	n.a.	2.19	2.27	3.34	2.81	2.50	n.d.	2.31	2.33	1.61
Eu	0.81	n.a.	0.73	0.68	0.76	0.81	0.79	n.d.	0.68	0.63	0.48
Tb	0.56	n.a.	0.45	0.48	0.62	0.42	0.42	n.d.	0.35	0.36	0.32
Yb	1.48	n.a.	1.69	1.49	1.33	1.14	1.21	n.d.	1.28	1.06	0.85
Lu	0.23	n.a.	0.25	0.22	0.22	0.18	0.19	n.d.	0.19	0.17	0.14
⁸⁷ Sr/ ⁸⁶ Sr	0.70357	n.a.	0.70354	0.70382	0.70363	0.70372	0.70377	n.d.	n.d.	n.d.	n.d.

n.a. = not available, n.d. = not determined. Analysis B3350 is from Metal Mining Agency of Japan (1981), the K–Ar age of the sample is 9.8 ± 2.0 Ma. ⁸⁷Sr/⁸⁶Sr ratios have in-run statistical errors of ± 0.00002 – 0.00003 and are considered to be accurate to ± 0.00005 relative to NBS SRM 987 ⁸⁷Sr/⁸⁶Sr = 0.71025 based on duplicate analyses.

age for the main phase of volcanism in this area. On the other hand, the younger "ages" may be due to argon-losses in the reworked material.

The plugs are composed of porphyritic amphibole dacites. The Banawue Intrusion and Batog Plug are composed to very similar dacites, as are the Mt Quinali and the Minlawi Plug. The former contain few (<15%) phenocrysts of plagioclase containing ubiquitous glass inclusions, and phenocrysts of amphibole in a matrix of tiny, box-shaped plagioclase crystals, magnetite and glass. Phenocrysts in Mt Quinali and Minlawi dacites are more abundant (>35%) and larger (often more than 1 mm across), and plagioclase only rarely contains glass inclusions. In addition, the samples contain quartz phenocrysts with embayments.

The Lepanto area, Benguet Province, is located at the southeastern end of the Cervantes Trough (Fig. 2). The stratigraphy of the area (Gonzales, 1956; Sillitoe and Angeles, 1985; Garcia, 1990) consists of a lowermost unit, the Lepanto Metavolcanics, unconformably overlain by the Balili Sequence. The Lepanto Metavolcanics, possibly of late Cretaceous age (Fernandez and Pulanco, 1967), are composed of massive basalts and some evolved rocks, intercalated with minor turbidites and cut by mafic dikes; they have been metamorphosed to greenschist facies and are weakly deformed. Recently, Maletierre *et al.* (1988) suggested that this unit is part of an ophiolite underlying the Cordillera.

This sequence is intruded by the Bagon Intrusion (Knittel *et al.*, 1990), a composite batholith radiometrically dated at 12–13 Ma by Sillitoe and Angeles (1985), while Ringenbach *et al.* (1990) cite an unpublished date of 24 Ma. Work in progress by Winter suggests that the Bagon intrusive complex is part of the Oligocene to Early Miocene(?) suite of batholiths intruding the axis of the Cordillera Central range. The Bagon Intrusion consists mainly of quartz diorite with minor gabbroic, dioritic and granodioritic phases.

The mid-Miocene Balili Sequence is subdivided into two units (Baker, 1983): the Lower Clastic Unit consists of conglomerates with intercalated silt- and sandstone horizons, and the Upper Volcaniclastic Unit is composed of andesitic lavas and volcaniclastic rocks.

Small quartz diorite porphyry stocks intrude the Balili Sequence; one of them, the Tirad Stock (sample 329), located in the south of the Lepanto area, is spatially and genetically associated with the porphyry Cu–Au mineralization of the Tirad prospect (Sillitoe and Angeles, 1985; Trudu, 1992). A K–Ar age of 3.5 ± 0.9 Ma from sericite associated with this mineralization is reported by Sillitoe and Angeles (1985). Another small quartz diorite porphyry stock underlies the epithermal Au–Cu–As deposit of Lepanto (Sillitoe, 1983). Emplacement of the stocks was followed by a series of phreatomagmatic explosions which produced diatreme/maar complexes (2.9 ± 0.4 Ma from K–Ar dating reported by Sillitoe and Angeles, 1985). One of them, named Posdo Diatreme complex by Trudu (1992), is described in some detail by Sillitoe and Angeles (1985). It consists of peripheral tuffs and breccias of dacitic composition and of a central subvolcanic dacitic dome. This complex postdates the Tirad mineralization and was not affected by hypogene alteration. The latest event may have been volcanism at Mt Tayebo, located south of Lepanto, which produced ash dated at 0.9 ± 0.2 Ma and 7700 year b.p. (Ringenbach, 1992).

Our samples of the Posdo Diatreme complex contain plagioclase, quartz and hornblende phenocrysts. Plagioclase phenocrysts are tabular, show oscillatory zoning, and have a zone rich in glass-inclusions near the margins. Quartz phenocrysts are rounded and show embayments. Amphibole phenocrysts are characterized by brown pleochroism. The groundmass ranges from a microcrystalline intergrowth of plagioclase and quartz to glass. Crystal-rich and crystal-poor tuffs are recognized; their phenocryst assemblage differs from that of Posdo dacite described above in: (1) pleochroism of the hornblende (green–yellow in the tuffs and brown–pale yellow in the dacite); (2) higher contents of quartz and lower contents of plagioclase; and (3) the occurrence of rare deformed biotite. The groundmass of the tuff is composed of devitrified glass and a microcrystalline intergrowth of quartz and plagioclase. Lithic fragments are more abundant in the crystal-poor than in the crystal-rich tuff.

The Tirad Stock is not exposed but has been intersected by drill cores at depths ranging from 250 to 500 m below the surface during the exploration of the Tirad porphyry Cu–Au mineralization. It is about 1000 m long and 500 m wide with steeply dipping sides. The subvolcanic rocks are composed of phenocrystic quartz, plagioclase, hornblende and biotite set in a groundmass of quartz with minor plagioclase. Similar porphyry–Cu mineralization occurs north of the Tirad prospect (Sillitoe, 1983; Conception and Cinco, 1989).

The samples analyzed for this study are fresh or, at most, very weakly altered (minor chlorite $\pm$ epidote), as in the case of the Tirad Stock and the tuff of the Balili Formation.

2. The Tabuk area

The Tabuk area, Kalinga–Apayao Province, is located along the Chico River about 5–13 km east of the township of Tabuk. Three small intrusions occur along the Chico River Valley: these are, from east to west, the Naneng, Dalimuno and Mambucayan intrusions (Fig. 2). The largest of these, the Naneng intrusion, has a diameter of about 3000 m and is associated with a group of radial tension faults (Durkee and Pederson, 1961). The plugs intruded the turbidites of the Late Miocene to Pliocene Cabagan Formation (Caagusan, 1980) [the Cabagan Formation corresponds to the Buluan Formation of the Mabaca River Group of Durkee and Pederson (1961), the different names having been introduced by different oil companies working in the same general area (Christian, 1964)]. In the area between the Naneng and Dalimuno intrusions the sediments comprise siltstones with cm to dm thick intercalations of fine to medium grained impure sandstones. The detrital components of the sandstone (feldspars, quartz, rock fragments and opaque minerals) are subangular to angular, suggesting short transport distances. The siltstones are characterized by clay-rich, cross-laminated compositions.

The plugs are composed of porphyritic dacite and andesite (Table 2) with plagioclase and amphibole phenocrysts. Plagioclase phenocrysts usually contain zones or cores with glass patches. All samples are holocrystalline. Close to the contacts, the rocks are fine grained.

While Durkee and Pederson (1961) observed no particular relationship between the intrusions and adjacent structural elements, it appears from maps published by the Philippine Bureau of Mines (1974) and Caagusan

Table 2. Chemical and Sr isotope composition of volcanic and sedimentary rocks from the Tabuk and Bokod areas (major elements in wt%, trace elements in ppm)

Area	Tabuk area						Bokod area			Baguio
Subgroup	Dalimuno	Naneng	Graywacke	Shale						Black Mtn
Sample	TBK1	TBK2	TBK4	TBK3sa	TBK3sh	BOK10	K152	K149	B251	P1-71
SiO ₂	63.09	64.14	58.16	48.84	53.90	58.10	58.66	59.29	63.11	55.87
TiO ₂	0.39	0.40	0.54	0.69	0.74	0.57	0.59	0.52	0.44	0.74
Al ₂ O ₃	16.66	16.83	18.91	16.69	18.46	17.27	17.79	17.79	16.83	16.44
Fe ₂ O ₃	3.88	3.79	5.67	5.85	8.83	6.00	2.39	2.11	2.43	7.07
FeO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3.81	3.77	2.55	n.d.
MnO	0.10	0.11	0.18	0.10	0.10	0.11	0.13	0.14	0.09	0.14
MgO	1.60	1.76	1.99	2.65	4.56	2.38	2.66	2.52	2.01	4.82
CaO	5.20	4.80	7.32	8.48	1.79	5.88	5.37	4.56	2.89	8.17
Na ₂ O	3.82	4.16	3.50	2.98	3.35	4.14	4.61	4.70	4.67	3.29
K ₂ O	1.78	1.82	1.42	1.55	1.45	2.31	2.26	2.17	2.10	1.41
P ₂ O ₅	0.12	0.14	0.27	0.20	0.21	0.30	0.26	0.26	0.19	0.17
Loss	3.28	1.97	2.38	11.40	6.78	2.07	0.74	1.41	2.36	0.33
Total	99.92	99.92	100.34	99.43	100.17	99.13	99.27	99.24	99.67	98.45
Rb	48	54	33	35	34	44	n.a.	n.a.	n.a.	32
Sr	639	562	590	884	316	1010	n.a.	n.a.	n.a.	429
Ba	599	610	354	168	106	564	n.a.	n.a.	n.a.	235
Th*	6.32	6.18	0	0	5	4.55	n.a.	n.a.	n.a.	n.d.
U	1.60	1.60	n.d.	n.d.	n.d.	1.24	n.a.	n.a.	n.a.	n.d.
Nb	9	8	7	2	2	3	n.a.	n.a.	n.a.	4
Ta	0.64	0.63	n.d.	n.d.	n.d.	0.19	n.a.	n.a.	n.a.	n.d.
Zr	132	134	130	70	82	134	n.a.	n.a.	n.a.	96
Hf	3.1	3.18	n.d.	n.d.	n.d.	3.47	n.a.	n.a.	n.a.	n.d.
Y	15	16	19	15	12	17	n.a.	n.a.	n.a.	19
Ni	7	7	8	28	20	10	n.a.	n.a.	n.a.	19
Cr	18	14	9	98	57	21	n.a.	n.a.	n.a.	n.d.
La	23.6	24.7	n.d.	n.d.	n.d.	20.8	n.a.	n.a.	n.a.	n.d.
Ce	40.5	46.6	n.d.	n.d.	n.d.	41.6	n.a.	n.a.	n.a.	n.d.
Nd	18.0	17.1	n.d.	n.d.	n.d.	23.4	n.a.	n.a.	n.a.	n.d.
Sm	3.21	3.14	n.d.	n.d.	n.d.	4.55	n.a.	n.a.	n.a.	n.d.
Eu	0.75	0.79	n.d.	n.d.	n.d.	1.19	n.a.	n.a.	n.a.	n.d.
Tb	0.56	0.59	n.d.	n.d.	n.d.	0.76	n.a.	n.a.	n.a.	n.d.
Yb	1.59	1.55	n.d.	n.d.	n.d.	1.92	n.a.	n.a.	n.a.	n.d.
Lu	0.24	0.25	n.d.	n.d.	n.d.	0.28	n.a.	n.a.	n.a.	n.d.
⁸⁷ Sr/ ⁸⁶ Sr	n.d.	0.70413	0.70396	0.70545	0.70614	0.70362	n.a.	n.a.	n.a.	0.70372

n.d. = not determined, n.a. = not available. *INNA data for TBK1, TBK2, BOK10. Analyses K152, K149, B251 are from Metal Mining Agency of Japan (1977). Sample P1-71 was analyzed in Aachen by Winter and the Sr isotopic composition was determined by Albrecht in Albuquerque. ⁸⁷Sr/⁸⁶Sr ratios have in-run statistical errors of ± 0.00002 – 0.00003 and are considered to be accurate to ± 0.00005 relative to NBS SRM 987 ⁸⁷Sr/⁸⁶Sr = 0.71025 based on duplicate analyses.

(1980) that they actually intruded the Upper Chico River Fault (Fig. 2), which displaces the N–S running fault at the western margin of the Cagayan Basin (Santiago and Chico River Faults) about 10 km in a left-lateral sense. The displacement has affected the Miocene to Pliocene Cabagan Formation, but has left Pleistocene gravels undisturbed, suggesting a pre-Pleistocene age for the fault (Caagusan, 1980) and a post-Pleistocene age for the small plugs.

About 25 km west of the Naneng Plug and probably still on the trace of the Upper Chico River Fault (which may be traced on a Landsat-photo into the Quirino area) the Batong Buhay porphyry–Cu deposit lies approximately in the center of a 12 × 10 km wide volcanic field (Metal Mining Agency of Japan, 1981). The cluster of volcanic vents described by Alvir (1956) lies south of Batong Buhay in the center of that field and may be the source of the volcanic rocks. Durkee and Pederson (1961) refer to the volcanic deposits as Awidon Mesa Formation, which they describe as being “composed of welded tuffs and tuffaceous sediments of a dacitic type ... characterized by the presence of bipyramidal quartz

phenocrysts (generally less than 5%) and euhedra of hornblende and sodic feldspar” (p. 159). They found that the volcanic deposits form a valley-filling deposit which attains a maximum thickness of at least 300 m. West of the volcanic field a major pluton of the Oligocene to early Miocene suite of calc-alkaline batholiths is exposed (Metal Mining Agency of Japan, 1981).

3. The Bokod area

Very little is known about the local geology of the Bokod area, Benguet Province, located about 25 km ENE of the Baguio area (Figs 1 and 2), except for unpublished data by the Benguet Corp., which explored the Tawi-Tawi porphyry–Cu–Au prospect from 1969 until 1975, and a few chemical analyses and K–Ar data from the Metal Mining Agency (1977). The most important geological feature of the area is the occurrence of one large and at least two smaller diorite porphyry stocks, the largest of which extends 5 km NS and 2 km EW and hosts several porphyry copper ore bodies.

The Bokod area is underlain by metamorphosed sedimentary and volcanic rocks (pre-Cretaceous?) overlain by unmetamorphosed volcanic units (Oligocene?). These rocks were intruded by the mineralized diorite porphyries and by hornblende diorite porphyry dikes, which postdate the mineralization. The pluton is estimated to have been emplaced at about 3–6 Ma, based on K–Ar data (Metal Mining Agency of Japan, 1977). Two major faults intersect the area: one trends north–south and defines the contact between the diorite and the unmetamorphosed volcanic units.

Metal Mining Agency of Japan (1977) has distinguished two phases of quartz diorite in the main stock: one characterized by abundant quartz phenocrysts and the other by few or no quartz phenocrysts. The one sample studied by us is very similar in major element composition to several samples analyzed by Metal Mining Agency of Japan (1977) and is considered to be representative of the plutonic units of the area (Table 2). It is a porphyritic microdiorite with large phenocrysts of plagioclase (<2 mm), amphibole (<1 mm), magnetite, and a few biotite crystals, which reflect the high potassium content of the rock.

4. The Baguio district

The Baguio district is located at the southern end of the Cordillera Central (Fig. 1). The geology of the area has been documented in several studies (Fernandez and Damasco, 1979; Balce *et al.*, 1980; United Nations, 1987), but many important aspects are still unclear or contentious, e.g. the distribution and ages of the various units.

The eastern part of the area is underlain by several large plutons which form a composite batholith. There is no agreement on the age of this complex. K–Ar data suggest ages of 12–18 Ma (Wolfe, 1981), but Balce *et al.* (1980) maintain, on the basis of geological mapping, that it is older than the Miocene Zigzag Formation. This discrepancy is probably due to the continued magmatic and hydrothermal activity in this area, which resulted in a resetting of the radiometric clocks. Recently, part of the plutonic complex has been re-interpreted as part of an ophiolite complex (United Nations, 1987).

To the west of the batholith several smaller plutons and dikes intrude the younger sedimentary formations, several of which have associated porphyry–Cu mineralization (e.g. Bryner, 1969; United Nations, 1987). The stocks appear to be younger than 15 Ma (Wolfe, 1981). Though some data are available for these rocks, we do not discuss them in any detail, because neither the locations nor age relationships of most samples are known. In Table 2 we provide a new chemical analysis and Sr isotope determination for one of the young plugs, the Black Mountain complex (United Nations, 1987).

Analytical Methods

We have analyzed the samples for major, minor and trace elements by a low dilution XRF method (Thomas and Haukka, 1978). REE, Ta, U, Th and Hf concentrations were determined at the National Taiwan University (Taipei) by neutron activation analysis. Mineral compositions were determined in wavelength dispersive mode with a Cameca SX50 electron microprobe using mineral

and metal oxide standards and correction procedures given by Pouchou and Pichoir (1984). Sr isotope analyses were carried out at La Trobe University following the procedures described by Gray (1987), except that the analyses were done on unspiked samples.

Bulk Rock Geochemistry

The new analytical data are given in Tables 1 and 2, which also include several analyses from the literature. All samples have similar FeO^*/MgO ratios and thus form a calc-alkaline suite as defined by Miyashiro (1974, see Fig. 3a). The samples from the Posdo complex and the Quirino area (with the exception of Banawue sample P1-72 and sample TTP169 from the Posdo complex, characterized by unusually high K_2O , Rb, Sr, Ba, Y and Zr contents, Table 1) fall into the field of low-K suites (Peccerillo and Taylor, 1976). The clasts from the Cervantes Trough (Ringebach *et al.*, 1990, 1993) appear to be slightly enriched in K_2O and related trace elements (Ringebach *et al.*, 1990) and fall into the field of “normal” calc-alkaline suites. The Tabuk and the Banawue samples fall into the same field, while the Bokod samples straddle the boundary to the high-K suites (Fig. 3b). The low-K samples from the Posdo and Quirino areas show considerable scatter, in contrast to the often quasi-linear oxide– SiO_2 relationships seen in many volcanic suites from destructive plate boundaries (here illustrated by the low-K suite of Mt Natib; Defant, 1985).

The volcanic rocks from the Quirino area and Posdo complex are notable for their low abundances in K_2O , Rb, Y and Zr. This is illustrated in Fig. 4, which compares the Rb and Y contents of these rocks with the low-K calc-alkaline suite of the Natib volcano in the Bataan Segment (cf. deBoer *et al.*, 1980; Defant, 1985) and the low-K lavas of the Coastal Range of Taiwan

Fig. 3. (a) K_2O vs SiO_2 and (b) FeO^*/MgO vs SiO_2 for Late Miocene volcanic rocks from the Northern Luzon Segment. Boundary lines are from Peccerillo and Taylor (1976) and Miyashiro (1974), respectively. Data are from Tables 1 and 2, Maletierre, *et al.* (1988) and Ringebach *et al.* (1990). Fields for Mt St Helens (Smith and Leeman, 1987) and Pinatubo dacites (Bernard *et al.*, in press) are shown for comparison.

Fig. 4. Rb, Sr and Y contents of Late-Miocene rocks from the Northern Luzon Segment as compared to the low-K series of Natib in the Bataan Segment (data from Defant, 1985) and the low-K volcanics from the Coastal Range of Taiwan (data from Chen, 1975). Average Y-values for orogenic andesites from the SW Pacific arcs are also shown (Ewart, 1979). Symbols as in Fig. 3.

Fig. 5. REE values for the analyzed samples, normalized to the chondritic values of Nakamura (1974) following the suggestions of Rock (1987).

(Chen, 1975). However, several samples are strongly enriched in Ba. The medium-K calc-alkaline suite of the Tabuk Plugs and the intrusives of the Bokod area are enriched in all trace elements relative to the Quirino and Posdo samples.

REE concentrations show enrichment in the light REE (LREE) relative to the heavy REE (HREE) (Fig. 5) for all samples. Dacites from the western centers, excluding P1-72, i.e. the low-K samples have $La(n) = 20-35$ and $Yb(n) = 4-8$. The Tabuk, Bokod and Banawe samples are more LREE enriched [$La(n) = 65-75$], but have similar low HREE as the low-K samples, consistent with the low Y abundances. In addition, they exhibit distinct Eu-anomalies.

Mineral Chemistry

1. Amphibole

Amphibole, which is ubiquitous in our samples, is relatively Ca-rich with 1.8–1.9 Ca per formula unit (on the basis of 23 O), except for the Posdo amphiboles, which may contain as little as 1.6 Ca (Table 3). There are distinct compositional differences between amphiboles from the low-K and K-rich suites and between amphiboles from the western and eastern centers, respectively. The amphiboles from the western centers are Mg-rich [$Mg/(Mg + Fe) > 0.65$] as opposed to those of the eastern centers [$Mg/(Mg + Fe) < 0.65$] (Fig. 6). The low-K suites contain amphiboles with less than 0.08 K per formula unit, while the normal and high-K suites contain amphiboles with 0.08–0.22 K (Fig. 6). The high K content in the Banawe amphiboles is good evidence that the relatively high potassium content in the whole rock analysis is a primary feature.

The Al-content is quite variable within individual samples even if only rim compositions are considered. Al^{IV} and Al^{VI} correlate with the total Al-content, but in an Al^{VI}/Al^{tot} plot the individual complexes show different trends. The amphiboles from the Posdo complex are distinctly low in Al, Ca and Ti. The small number of phases present in the lavas (plagioclase, amphibole and spinel) precludes the use of the Al contents in the amphiboles as a geobarometer (see discussion in Hollister *et al.*, 1987).

Fig. 6. K vs $Mg/(Mg + Fe)$ for amphiboles (on the basis of 23 O) illustrating the relationships between K-contents in amphibole and in the host rock.

Table 3. Selected amphibole analyses for Late-Miocene volcanic rocks from the Northern Luzon segment

Complex Sample	Batog		Posdo		Banawue		Naneng		Bokod	
	P1-76	P1-76	TTP216	TTP216	P1-72	P1-72	TBK4	TBK4	BO10	BO10
SiO ₂	40.90	40.85	45.59	48.15	43.15	41.48	41.90	42.64	41.75	44.11
TiO ₂	1.63	1.38	0.88	0.94	1.64	1.15	1.99	1.64	2.07	1.68
Al ₂ O ₃	13.36	12.05	8.62	6.72	11.69	13.42	10.85	9.61	10.49	8.34
MgO	13.60	12.74	14.66	15.70	16.56	13.70	11.22	10.87	12.92	13.52
CaO	10.84	12.34	10.53	10.48	11.16	11.28	11.31	11.68	11.42	11.71
MnO	0.25	0.38	0.59	0.52	0.07	0.12	0.43	0.60	0.42	0.48
FeO	13.41	15.08	13.38	12.35	9.17	12.27	15.60	16.77	14.19	13.81
Na ₂ O	2.13	1.66	1.42	1.21	2.21	2.30	2.00	1.66	2.15	1.78
K ₂ O	0.20	0.19	0.31	0.18	0.65	0.52	0.57	0.62	0.81	0.72
F	0.01	0.02	0.05	0.13	0.11	0.15	0.09	0.04	0.08	0.14
Cl	0.00	0.02	0.07	0.05	0.02	0.02	0.15	0.11	0.07	0.06
H ₂ O _{calc}	1.99	1.97	1.97	1.96	1.98	1.93	1.89	1.91	1.92	1.90
Total	98.32	98.68	98.07	98.39	98.41	98.33	98.00	98.15	98.29	98.25
Si	6.134	6.183	6.803	7.085	6.342	6.201	6.400	6.539	6.338	6.660
Al ^{IV}	1.866	1.817	1.197	0.915	1.658	1.799	1.600	1.461	1.662	1.340
Al ^{VI}	0.495	0.333	0.318	0.251	0.367	0.465	0.354	0.276	0.214	0.144
Ti	0.184	0.158	0.099	0.104	0.181	0.129	0.229	0.189	0.236	0.190
Mg	3.040	2.874	3.261	3.444	3.627	3.052	2.555	2.484	2.924	3.044
Ca	1.741	2.001	1.684	1.653	1.757	1.807	1.850	1.919	1.858	1.895
Mn	0.032	0.048	0.075	0.065	0.009	0.015	0.056	0.078	0.054	0.062
Fe	1.682	1.909	1.670	1.520	1.127	1.533	1.993	2.150	1.801	1.744
Na	0.618	0.486	0.410	0.344	0.630	0.667	0.593	0.494	0.632	0.520
K	0.038	0.037	0.059	0.034	0.122	0.099	0.112	0.121	0.157	0.138

Structural formulae based on 23 O, Fe calculated as Fe²⁺.2. *Pyroxene*

Clinopyroxene is very rare and appears to be of xenocrystic origin. Its compositional similarity to the clinopyroxenes, that occur as relicts in the Lepanto Metavolcanic rocks, suggests their derivation from these rocks (Table 4).

3. *Biotite*

Biotite is found in only two of the Posdo samples and in the Bokod sample investigated here. In one of the Posdo samples the biotite is clearly xenocrystic as indicated by the fragmented nature of the flakes. In the second sample (TTP169), enriched in K₂O relative to

Table 4. Composition of clinopyroxenes from sample TTP 46 from the Lepanto Metavolcanics and sample P1-72 from the Quinali Plug

Sample Analysis	TTP 46					P1-72	
	2	8	12	13	14	2	3
SiO ₂	50.71	51.99	51.77	50.20	49.76	50.33	52.28
TiO ₂	0.56	0.17	0.20	0.61	0.75	0.50	0.37
Fe ₂ O ₃	2.34	1.86	2.20	3.34	3.16	3.76	2.03
Al ₂ O ₃	3.40	3.08	2.43	2.52	2.76	3.26	2.07
Cr ₂ O ₃	0.04	0.55	0.16	0.01	0.02	0.22	0.17
MgO	16.12	17.47	17.15	14.88	14.89	15.42	16.38
FeO	4.63	1.76	2.90	6.67	6.52	3.43	3.56
MnO	0.19	0.08	0.14	0.24	0.22	0.13	0.12
CaO	20.81	22.42	21.62	20.09	19.92	21.87	22.56
Na ₂ O	0.20	0.13	0.17	0.30	0.30	0.34	0.23
Total	98.99	99.52	98.75	98.87	98.30	99.25	99.79
Si	1.884	1.900	1.915	1.890	1.883	1.867	1.923
Ti	0.016	0.005	0.006	0.017	0.021	0.014	0.010
Al ^{IV}	0.116	0.100	0.085	0.110	0.117	0.133	0.077
Al ^{VI}	0.033	0.033	0.021	0.002	0.006	0.031	0.011
Fe ³⁺	0.065	0.051	0.061	0.095	0.090	0.091	0.057
Cr	0.001	0.016	0.005	0.000	0.001	0.006	0.005
Mg	0.893	0.952	0.945	0.835	0.840	0.853	0.898
Fe ¹⁺	0.144	0.054	0.090	0.210	0.206	0.106	0.110
Mn	0.006	0.002	0.005	0.008	0.007	0.004	0.004
Ca	0.828	0.878	0.856	0.811	0.807	0.869	0.889
Na	0.015	0.009	0.012	0.022	0.022	0.025	0.016

Structural formula on the basis of six oxygen.

Table 5. Selected core/rim analysis of plagioclase phenocrysts and some matrix crystals

Volcano Sample Analysis	Batog P1-76			Quinali P1-77			Banawue P1-72			Dalimuno TBK2			Bokod BO10		
	46 core	45 rim	44 matrix	50 core	49 rim	17 core	16 rim	30 matrix	6 i.core	5 o.core	1 rim	32 i.core	31 o.core	30 i.rim	28 o.rim
SiO ₂	48.50	52.48	50.78	48.96	58.86	52.79	54.39	54.68	53.15	57.87	56.03	53.23	57.43	56.52	58.50
TiO ₂	0.03	0.04	0.05	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.03	0.00	0.00
Al ₂ O ₃	31.27	27.95	29.86	31.89	25.31	28.99	27.59	27.76	28.83	25.69	26.84	27.47	24.78	25.57	24.55
Fe ₂ O ₃	0.26	1.47	0.66	0.34	0.32	0.37	0.35	0.46	0.40	0.26	0.29	0.26	0.25	0.22	0.29
MnO	0.04	0.08	0.00	0.00	0.07	0.01	0.00	0.01	0.00	0.01	0.03	0.03	0.02	0.02	0.00
MgO	0.01	1.17	0.07	0.01	0.02	0.02	0.03	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00
CaO	15.71	12.31	14.03	15.50	8.05	12.62	11.09	10.97	12.15	8.48	10.14	10.87	7.60	8.36	6.99
Na ₂ O	2.71	4.13	3.61	2.64	6.75	4.46	5.23	5.35	4.27	6.21	5.57	5.30	7.03	6.76	7.39
K ₂ O	0.03	0.08	0.03	0.02	0.43	0.09	0.18	0.16	0.12	0.23	0.19	0.27	0.51	0.47	0.59
SrO	0.06	0.04	0.00	0.04	0.05	0.08	0.10	0.12	0.06	0.09	0.11	0.30	0.11	0.15	0.17
BaO	0.12	0.04	0.11	0.00	0.12	0.06	0.07	0.00	0.02	0.00	0.00	0.06	0.00	0.02	0.03
Total	98.73	99.78	99.19	99.39	99.99	99.48	99.03	99.55	99.03	98.84	99.22	97.79	97.76	98.09	98.51
Si	2.253	2.397	2.337	2.253	2.639	2.410	2.484	2.484	2.431	2.610	2.544	2.470	2.637	2.594	2.663
Al	1.712	1.504	1.620	1.729	1.337	1.560	1.485	1.486	1.554	1.371	1.436	1.503	1.341	1.383	1.317
Fe	0.009	0.050	0.023	0.012	0.011	0.013	0.012	0.016	0.014	0.009	0.009	0.009	0.009	0.008	0.010
Ca	0.782	0.602	0.691	0.764	0.387	0.617	0.543	0.534	0.596	0.411	0.493	0.540	0.374	0.411	0.341
Sr	0.001	0.001	0.000	0.001	0.001	0.002	0.003	0.003	0.002	0.002	0.003	0.008	0.003	0.004	0.005
Ba	0.002	0.001	0.002	0.000	0.002	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001
Na	0.244	0.366	0.322	0.235	0.587	0.395	0.463	0.471	0.389	0.545	0.491	0.477	0.626	0.601	0.652
K	0.002	0.004	0.002	0.001	0.024	0.005	0.010	0.009	0.007	0.013	0.011	0.016	0.030	0.027	0.034

i.core = inner core, o.core = outer core; i.rim = inner rim, o.rim = outer rim.

Fig. 7. Or plotted vs An for core compositions of plagioclase phenocrysts.

other Posdo samples, the biotite forms large, well defined tabular crystals, suggesting primary crystallization from the melt (secondary biotite, which is ubiquitous close to the porphyry mineralization forms aggregates of fine biotite flakes, which bear no similarity to the primary crystals of sample TTP169).

4. Plagioclase

Phenocrystic plagioclase exhibits a wide range in composition in all samples (Table 5, Fig. 7), except those of the Posdo complex, where phenocrysts within a single sample have a compositional range of only 5 mol% An. Samples from the Naneng and Dalimuno Plugs with An_{42-60} show moderate variation in core composition and relatively uniform groundmass plagioclase compositions with An_{36-40} in the Naneng samples and An_{57-60} in the Dalimuno sample. The greatest variations are found in the low-K Batog sample (An_{40-76}) and the Bokod sample (An_{31-67}). Compared to plagioclase from other low-K suites, the plagioclase in the lavas from the Mankayan and Quirino areas is relatively sodic (e.g. plagioclase in Tonga dacites has An_{60-80} , Ewart, 1979).

There are notable differences with regard to the Or contents in plagioclase cores from the low-K, medium-K, and the high-K rocks, respectively, though plagioclase in the low-K Posdo and medium-K Tabuk samples have similar compositions (Fig. 7). For rim compositions the distinction among the series becomes less clear, because rims are often distinctly more Or-rich than the cores (except in the Batog sample) and evolve towards the field of the Or-rich Bokod plagioclase. A similar crude correlation between the potassium contents in plagioclase and the potassium contents in the host rock was described for medium-K and high-K series from the Marianas arc (Bloomer *et al.*, 1989). Among the Quirino samples, the Banawue sample plagioclase is notable for its high K contents (similar to the amphibole) and confirms the high K_2O contents found for the whole rock analysis.

5. Spinel

Spinel is a ubiquitous phase in all of our samples. It is nearly pure magnetite in the Bokod and Tabuk samples with 0–10% Fe^{3+} replaced by Ti and V, while in the Posdo and Quirino samples an additional amount of Fe^{2+} (up to 17%) may be replaced by Mg and Zn (Fe^{2+}/Fe^{3+} calculated on the basis of three cations and four oxygens).

Sr Isotopic Compositions

Twelve new $^{87}Sr/^{86}Sr$ ratios are given in Tables 1 and 2. In view of the very low Rb/Sr ratio of most samples and their young age, no age corrections are required.

The low-K rocks from Mt Quinali, the Banawue Plug, and the Batog Plug in the Quirino area have the lowest $^{87}Sr/^{86}Sr$ ratios (0.70354–0.70363) of all samples studied. Sample P1-78 from the Minlawi Plug, which contains somewhat more radiogenic Sr (0.70382), is the most altered sample, and thus the measured value may not reflect the Sr-isotopic composition of the magma. The two samples from the Posdo complex have slightly more radiogenic Sr (0.70372–0.70377) compared to the Quirino samples (excluding P1-78). The reported values for the Baguio area (Divis, 1983; Defant *et al.*, 1990), including a new analysis (Table 2), fall into the same range.

In contrast, the medium-K rocks from the Dalimuno and Naneng Intrusions ($^{87}Sr/^{86}Sr$: 0.70396 and 0.70413, respectively), contain distinctly more radiogenic Sr than the low-K volcanics from the western part of the Cordillera. On the other hand, our sample from the Bokod area, which is even more enriched in LILE and also comes from the eastern part of the Cordillera, has Sr isotopic composition similar to the Quirino samples, i.e. at present it is not clear whether a correlation between $^{87}Sr/^{86}Sr$ and LILE contents exists.

The observed ratios are clearly lower than those reported for the southern segments of the Luzon arc ($^{87}Sr/^{86}Sr$: 0.7042–0.7051, Knittel and Defant, 1988) and confirm the earlier suggestion of Divis (1983) and Defant *et al.* (1990) that NLS volcanism is characterized by relative low $^{87}Sr/^{86}Sr$.

Discussion

1. Regional geochemical variations

The late Miocene volcanic rocks of the NLS are distinct from those of the Bashi and Bataan segments to the north and south in that they are limited to relatively high SiO_2 contents. The mafic mineralogy is dominated by amphibole, while the lavas of the Bataan Segments are dominated by anhydrous phenocryst assemblages (Defant *et al.*, 1991), although amphibole-bearing lavas are present at Mt Pinatubo and Mt Arayat (Bernard *et al.*, in press; Knittel and Bau, unpublished data). Evolved lavas in the Bashi Segment have two pyroxene or clinopyroxene $\pm$ amphibole phenocryst associations (Jacques, 1987). $^{87}Sr/^{86}Sr$ ratios are distinctly lower in the NLS than in the Bataan Segment and less heterogeneous than in the Bashi Segment (see below).

Samples of the western centers (Quirino and Lepanto areas) are characterized by very low K_2O , Rb, Zr and Y concentrations, whereas those from the Tabuk and Bokod areas and some from the Baguio area have elevated LILE. It thus appears that the western centers (closer to the Manila Trench) are characterized by lower LILE concentrations than the eastern centers, except for Sr and sometimes Ba, which are quite enriched. Within the Baguio area, both low-K and medium-K suites appear to be developed (Maletterre *et al.*, 1988). In contrast, there appears to be little evidence to suggest that $^{87}Sr/^{86}Sr$ shows a similar variation (though the

Tabuk centers contain more radiogenic Sr, because no increase in $^{87}\text{Sr}/^{86}\text{Sr}$ is found in either the Bokod or the Baguio samples. The reason for the elevated $^{87}\text{Sr}/^{86}\text{Sr}$ in the Tabuk samples is not clear. The host rocks clearly contain sufficiently radiogenic Sr ($^{87}\text{Sr}/^{86}\text{Sr}$: 0.7055–0.7061, Table 2) to cause increased $^{87}\text{Sr}/^{86}\text{Sr}$ by contamination, but the other plugs probably intrude host rocks containing Sr of similar composition. It might be noteworthy that the Tabuk samples also contain more than twice as much Nb and Ta as the other dacites (including the Bokod sample), suggesting that these magmas are derived from different, more enriched sources.

Previously, Knittel and Defant (1988) suggested that volcanic rocks related to the subduction of the South China Sea crust (Luzon arc) have generally higher $^{87}\text{Sr}/^{86}\text{Sr}$ (>0.7040) than those related to subduction of the Philippine Sea plate (<0.7040 ; pre-Miocene plutonic complexes in northern Luzon and the Bicol arc in southern Luzon). The data presented here and in Defant *et al.* (1990) show that in the NLS, where volcanism clearly is related to subduction of the South China Sea, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are identical to the initial ratios of the Oligocene batholiths (Knittel and Defant, 1988; Winter *et al.*, unpublished data). On the island of Batan, located in the north of the Bashi Segment, the older volcanic rocks likewise are characterized by low $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7036–0.7040, Richard, 1986), whereas the younger lavas have higher $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7044–0.7048, Richard, 1986).

Knittel and Defant (1988); Knittel *et al.* (1988) and Defant *et al.* (1989, 1990) argue that even higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (>0.7050 and correlated low $^{143}\text{Nd}/^{144}\text{Nd}$ and elevated LILE and LREE concentrations) observed in the Bashi and Mindoro Segments at the southern and northern ends of the Taiwan–Luzon arc reflect the input of continental material in the vicinity of the collision zones between the Asian continent and the Philippine arc (see Stephan *et al.*, 1986, for a review). The change in the isotopic composition observed for lavas erupted on Batan would indicate the arrival of such material in the magma sources. For the Bashi Segment, however, Chen *et al.* (1990) consider sediment input as inadequate to explain the observed isotopic signatures and suggest that the enriched signatures are due to the tapping of an enriched EM1-mantle-component (Zindler and Hart, 1986). McDermott *et al.* (1993) ascribe the unusual isotopic signature to mantle modified by bulk assimilation of sediment and additional contamination by slab derived fluids.

2. Petrogenesis

The youngest phase of volcanism in the North Luzon Segment of the Luzon Arc is characterized by the eruption of siliceous andesites and dacites. Within the Mankayan Mineral District and the Quirino area, these siliceous andesites/dacites, with one exception, belong to the low-K calc-alkaline series. These low-K rocks have unusual trace element contents. Sr is extremely enriched, as shown by comparison with the low-K lavas from the Taiwan Segment and compared to average SW Pacific low-K rocks, which contain about 300 ppm Sr in the range of 60–66% SiO_2 (Ewart, 1979). Y is much lower (7–12 ppm) than in most investigated arc volcanics (20–25 ppm, Lambert and Holland, 1974); Ewart (1979) gives average values of 19–30 ppm Y for low-K suites in the 60–66% SiO_2 range.

Fig. 8. Sr/Y vs Y plot with fields of supposed slab-derived melts and melts generated by fractionation (based on Defant and Drummond, 1990; Drummond and Defant, 1990). Symbols as in Fig. 3.

Siliceous low-K suites have been interpreted as products of fractional crystallization of low-K precursors (e.g. Tomblin, 1979) or as anatectic melts, generated by partial fusion of the lower crust (e.g. Gill and Stork, 1979; Giese *et al.*, 1986; Smith and Leeman, 1987). Recently, Drummond and Defant (1990) proposed that trondhjemitic/dacitic magmas may be generated by partial fusion of metamorphosed basalt in young (<20 m.y.), still “warm”, subducted lithosphere. This model is based on the chemical characteristics of high-Al trondhjemites/dacites ($>15\%$ Al_2O_3 at 70% SiO_2). These rocks generally have high LREE and low HREE contents, suggesting residual garnet in their source. In this model, low K/Rb (<550) indicates either residual amphibole in the source or extensive amphibole fractionation. High Sr contents would result from the lack of plagioclase in the source and lack of extensive plagioclase fractionation.

The geochemistry of the siliceous andesites in the Mankayan District appears to be appropriate for the Drummond and Defant model to be applied. We note that Y and the HREE, which are compatible in garnet, are consistently low in the Mankayan rocks compared to the commonly observed range, as noted above. In particular, in an Sr/Y vs Y plot, the Quirino and Posdo samples clearly plot in the field defined by lavas of inferred slab origin (Fig. 8). Furthermore, since the area is located where the youngest part of the South China Sea ridge is subducted, the subducted lithosphere underlying this area was young (<14 m.y.) at the time of dacite volcanism. On the other hand, Y and HREE are also compatible in amphibole and, thus, extensive amphibole fractionation could also be responsible for the low Y and HREE concentrations and would also account for the low K/Rb ratios.

Calculations of the REE concentrations of eclogite-derived melts do not support an eclogite-melting model. Experiments of Rapp *et al.* (1991) have shown that the residue of melted basaltic compositions at 22 and 32 kbar is composed essentially of garnet and clinopyroxene with minor amounts of rutile, magnetite and rarely plagioclase. The amount of garnet in the residue usually surpasses 30%. Model calculations using high K_d values for $\text{REE}_{(\text{garnet-melt})}$ (we used the values in Martin, 1987) show melts derived from either N- or E-MORB have similar REE patterns as the NLS dacites only if the amount of garnet in the residue is small ($<10\%$) and the degree of partial melting high ($>25\%$) (Fig. 9a, c). $\text{Yb}(n) < 6$

Fig. 9. Calculated chondrite-normalized Sm/Yb, La/Yb and Yb for magmas generated by melting of N- and E-MORB (MORB data from Jahn, 1986) in eclogite facies using the K_d -values of Martin (1987) (A, C) and Kay (1980) (B), respectively. Numbers following "Morb"-labels are residue compositions (gt = garnet, px = clinopyroxene). Ticks at the curves indicate the degree of partial melting.

could be accounted for if the applicable K_d values for $REE_{(garnet-melt)}$ are slightly lower than those chosen by Martin (1987). If low K_d values are applied, e.g. those used by Kay (1978), high amounts of residual garnet ($\geq 50\%$) and high degrees of partial melting are required to produce patterns as observed for the NLS magmas (Fig. 9b). However, such low K_d values appear to be more appropriate for basaltic melts (cf. Irving and Frey, 1978).

There are several features indicating that the NLS low-K rocks do not form a suite related by fractional crystallization to basaltic precursors, the most obvious one being the large scatter in LILE. To explain the unusual low Y and HREE contents it would be necessary that large amounts of amphibole were fractionated, while at the same time the high Sr contents argue against extensive fractionation of plagioclase. Alternatively, the high Sr contents could be due to accumulation of plagioclase, but this is not supported for the Posdo samples,

Fig. 10. Al_2O_3 vs SiO_2 for North Luzon samples (symbols: see Fig. 3) compared to melts experimentally produced by melting of basaltic starting compositions (Helz, 1976; Rapp *et al.*, 1991). Fields for Mt St Helens (light colour, data from Smith and Leeman, 1987) and Pinatubo dacites (dark colour, data from Bernard *et al.*, in press) are shown for comparison. Symbols as in Fig. 3.

in which plagioclase shows only very limited compositional variation (Fig. 7). Furthermore, the amphiboles in the low-K samples have high $Mg/(Mg + Fe)$ (Fig. 6), unlike amphiboles crystallizing from highly fractionated melts.

The third possible genetic model commonly discussed for dacites is melting of amphibolite in the lower crust. This process is difficult to model in detail because the composition of the lower crust and the residue are uncertain. Rapp *et al.* (1991) found various assemblages of plagioclase + amphibole $\pm$ garnet + minor phases at pressures between 8 and 16 kbar. Qualitatively, melting of an amphibolite would account for the low Y and HREE contents of the low-K suite, if a small amount of garnet remains in the residue (see Fig. 9a, c), while the high Sr content is not readily explained. Melting at crustal levels may have been promoted by the tectonic setting of the NLS, because the high elevation of the Cordillera could prevent mafic magmas from rising to the surface resulting in intrusion at crustal levels. Mafic magma stored at lower crustal levels could have heated the host rocks above their solidus. However, compared to melts, experimentally produced by melting of basaltic starting materials at pressures between 5 and 8 kb (Helz, 1976; Rapp *et al.*, 1991), the dacites are low in Al_2O_3 (Fig. 10), though they are high in Al_2O_3 compared to other dacites from arcs (e.g. 15% for Tonga dacites in the 60–63% SiO_2 -range; Ewart, 1979).

Finally it should be noted that the low-K suite may have been generated by a combination of several processes, e.g. by mixing of differentiated magma, derived from basic precursors, with anatectic melts. Because the lower crust of the arc and the subducted South China Sea crust are likely to have similar isotopic compositions, such mixing might not be seen in isotopic systematics.

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