

## 6. VOLCANIC ROCKS AND TERTIARY CARBONATES DREDGED FROM THE CAGAYAN RIDGE AND THE SOUTHWEST SULU SEA, PHILIPPINES<sup>1</sup>

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### INTRODUCTION

The Cagayan Ridge divides the Sulu Sea into two basins. The 1500–2000 m deep northwest basin is underlain by a several kilometer thick layer of partly deformed sediments. In the 4000–5000 m deep southeast basin the assumed oceanic basement is covered by sediments only 1 km thick (Murauchi et al., 1973; Mascle and Biscarrat, 1978; Rangin, 1989; Hinz et al., this volume). The northeastern part of the Cagayan Ridge faces the steep slope of the accretionary wedge of the subduction zone extending along the eastern rim of the southeast basin (Figs. 1 and 2). The northern section of the ridge is capped by numerous reef islands, where 400-m-thick reef deposits were drilled at the Tubbataha Island. The central and southern part of the ridge is not as pronounced because some broad seamounts lie along the eastern side of the ridge.

Several hypotheses have been published explaining the origin of the Cagayan Ridge and the two basins of the Sulu Sea. According to Holloway (1981) the southeast basin of the Sulu Sea originated in back-arc spreading coincident in part with the opening of the South China Sea. In this model, the Cagayan Ridge formed in the Oligocene to mid-Miocene as a volcanic arc southeast of the accretionary wedge of Palawan.

Alternatively, the northward subduction of the Celebes Sea under the Sulu Archipelago is thought to have induced back-arc spreading forming the Sulu Sea (Hamilton, 1979; Mitchell et al., 1986; Rangin, 1989). The Cagayan Ridge originated in the Oligocene/early Miocene as a related volcanic arc along the southern margin of a fragment of the proto-China mainland. Lee and McCabe (1986) and others suggest entrapped Eocene oceanic basement as the origin of the southeast basin.

So far only one sample from the Cagayan Ridge was available, consisting of andesitic basalt with a K/Ar age of  $14.7 \pm 0.6$  Ma (Kudrass et al., 1986). In this paper we describe dredge samples from the Cagayan Ridge and the southeast Sulu Basin obtained during two pre-site cruises with the *Sonne* (1987, 1988) (Table 1).

Dredge hauls were performed and sampling sites were determined as described by Kudrass (1986). Prospective sites were chosen along seismic records (Hinz et al., this volume) where basement outcrops were indicated, or on nearby steep slopes. Recovery ranges between some chips of rocks to 500 kg. In one case, basement could be sampled by piston coring when two pebbles at the base of a slump deposit were recovered.

### VOLCANIC ROCKS

Volcanic rocks were recovered from 12 sites on the Cagayan Ridge and from two seamounts in the southeast basin of the Sulu Sea. The rocks were analyzed by petrographic, geochemical, and K-Ar methods.

According to their chemical composition the volcanic rocks can be classified as basalt, basaltic andesite, andesite, and dacite (Table 2, Fig. 3). Basalt was recovered from two seamounts in the southeast basin (Fig. 1): SO58-65 near ODP Site 769 and SO58-90 near Site 768. At the southern end of the Cagayan Ridge, near Maeander Reef, samples of basaltic andesite were dredged (SO23-15) or cored (SO49-96) as phosphatized pebbles from a slump deposit. Volcanic rocks from the northern end of the Cagayan Ridge (Fig. 2) are richer in silica and range from basaltic andesite to dacite (Fig. 3). Within this small sub-area, the composition varies independently of water depth or the position of the sample along the ridge.

In general, the basalts of the seamounts have a tholeiitic composition, whereas the other volcanic rocks from the Cagayan Ridge are predominantly calc-alkaline (Fig. 4).

Except for some volcanic sandstone and tuff, the volcanic rocks consist of mostly vesicular, porphyritic rock commonly bearing phenocrysts of plagioclase, clinopyroxene, and some orthopyroxene (Table 3). Altered olivine occurs in the basalt of the seamounts and in the basaltic andesite from the southern end of the Cagayan Ridge. Phenocrysts of plagioclase up to 2 cm in length are present in each rock type, quite often including some glass aligned parallel to the zonal texture (Fig. 5). The plagioclase of the basaltic andesite of SO58-55-3 is especially rich in glassy inclusions that contain small bubbles of fluid and gas (Fig. 5).

The groundmass usually contains fine to microcrystalline laths of plagioclase and sometimes clinopyroxene. In some samples, light brown to light-colored glass is present. As a main component, glass occurs in the dacitic pumice (SO58-43-3) and is partly devitrified in smectitic sphaerolites (SO58-47-1).

The massive dacite (SO49-59) contains numerous large amphiboles of ferrian tschermakitic hornblende (after Leake, 1978 and Rock and Leake, 1984; Fig. 6; for chemical composition see Table 2), which are surrounded by a thin layer of opaque grains, except at the contact of the amphiboles with the labradorite phenocrysts (for chemical composition see Table 2). The unusual occurrence of this amphibole, which otherwise occurs in mesozonal metamorphic rocks, may be explained either by a resorption of an amphibolite by a dacitic lava or by a volcanogenic mobilization of amphibole-bearing metamorphic rocks. The divergent K-Ar data of the amphibole (Table 4) also prove its xenolithic character.

### GEOCHEMISTRY

The geochemical composition of the various volcanic rocks was used to characterize their volcano-tectonic origin.

As the samples have been obtained from outcrops, which were exposed for long periods to seawater, diagenetic alteration may have changed their composition. However, the petrographic analysis and the relative low concentration of LOI (mostly 2–4%, Table 2) indicate that a severe alteration is limited to some samples only, which were excluded from the discussion. Another limitation is the X-ray fluorescence detection limit of about 5 to 15 ppm for rare-earth elements and some other trace elements.

<sup>1</sup> Rangin, C., Silver, E., von Breyman, M. T., et al., 1990. *Proc. ODP, Init. Repts.*, 124: College Station, TX (Ocean Drilling Program).

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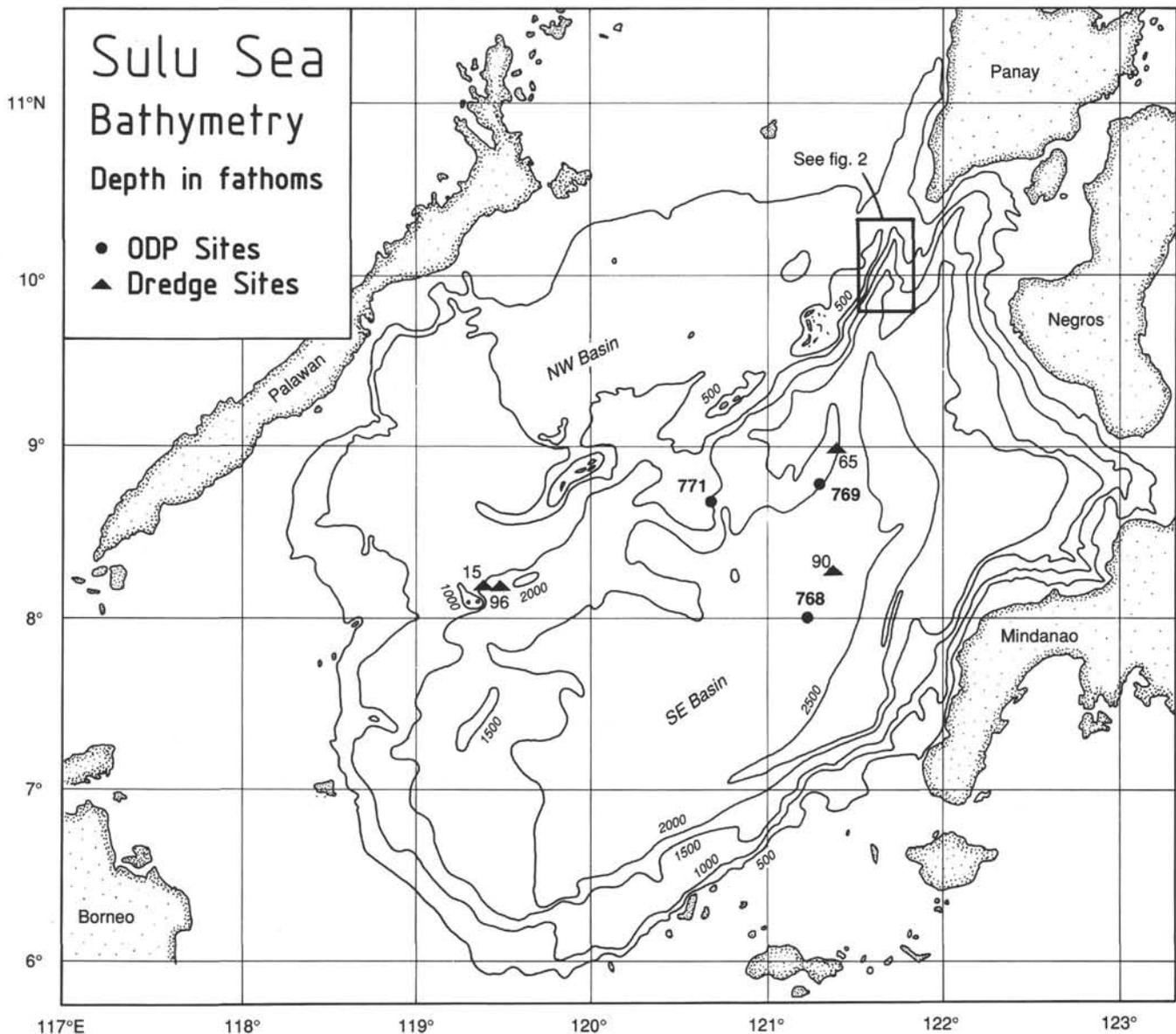


Figure 1. Location map of the Sulu Sea drill sites of ODP Leg 124.

The distribution of trace elements in the basalt samples from the two seamounts (SO58-65, -90, Fig. 7) is typical for transitional mid-ocean ridge basalt (E-MORB) after Pearce (1982). The great deviation of P in the samples of SO58-65 is presumably caused by a diagenetic phosphatization during the long-term exposure to seawater. The high variability of  $P_2O_5$  from 0.7 to 2.6 wt %, which correlates with an increase of CaO from 9.2 to 12.3 wt %, indicates this alteration. Two pebbles from the Maeander Reef (SO49-96) were also phosphatized ( $P_2O_5 = 6.06$  wt %). An 8-cm-thick manganese crust covering the outcrops of basalt of sample SO58-90 may have prevented this alteration ( $P_2O_5$ -concentration 0.31 wt %). The SO58-90 deficit of Cr with respect to E-MORB is presumably caused by early magmatic differentiation.

The intermediate and acid volcanic rocks from the Cagayan Ridge itself are difficult to interpret, as their original composition, indicative of their volcano-tectonic environment, is masked by fractional crystallisation and contamination. The basaltic andesite dredged from the Maeander Reef (SO23-15) fits to calc-alkaline volcanic-arc basalts (Fig. 7); the rest of the higher dif-

ferentiated rocks from the northern end of the Cagayan Ridge cannot be classified. Typically these volcanic rocks are extremely low in Nb and Cr, usually below detection limits, poor in  $TiO_2$  (0.7–0.4 wt %) and Ni (usually below 40 ppm).

#### K-Ar DATA

K-Ar data were obtained from andesite (SO49-55) and dacite (SO49-59) samples dredged from the northern end of the Cagayan Ridge (Table 4, Fig. 2). In SO49-55 three varieties of andesite and in SO49-59 two varieties of dacite were investigated. Plagioclase (pl), amphibole (am), and rough-ground whole-rock (wr) were analyzed in different grain-size fractions, as well as one magnetic fraction (mf) of whole rock.

Usually, the relative standard deviations of the determinations of radiogenic argon and potassium are less than 1%. But in the present case, the large scatter of the K-Ar dates and the differences between the dates for different-size fractions of the same material suggest the presence of inhomogeneous material. Indeed, three duplicate analyses yielded differences in radiogenic argon of two to four times the possible analytical uncer-

**Table 1. Coordinates and water depths of dredge samples.**

Number	Coordinates (North/East)	Water depth (corrected)
SO23-15 KD	8°10.390' 119°21.800'	3312 m
SO49-55 KD	10°00.608' to 10°01.900' 121°35.709' to 121°35.890'	2683 to 2014 m
SO49-56 KD	9°59.860' 121°39.065'	3780 m
SO49-57 KD	9°55.522' 121°36.187'	2677 m
SO49-58 KD	9°56.076' to 9°56.130' 121°35.052' to 121°34.700'	2167 to 2065 m
SO49-59 KD	10°10.791' 121°41.339'	2400 to 2100 m
SO49-96 KL	8°11.10' 119°28.05'	3634 m
SO58-33 KD	10°18.26' to 10°18.62' 121°44.05' to 121°43.87'	1650 to 1620 m
SO58-43 KD	9°59.11' to 9°59.33' 121°35.97' to 121°36.06'	2700 to 2580 m
SO58-44 KD	9°59.90' 121°35.80'	2220 m
SO58-46 KD	10°05.59' to 10°05.37' 121°40.92' to 121°40.97'	3580 to 3700 m
SO58-47 KD	9°48.10' to 9°49.20' 121°34.02' to 121°33.42'	3220 to 2890 m
SO58-65 KD	8°59.74' 121°22.52'	3500 m
SO58-66 KD	9°00.30' 121°23.45'	3400 m
SO58-90 KD	8°16.07' 121°22.26'	3600 m

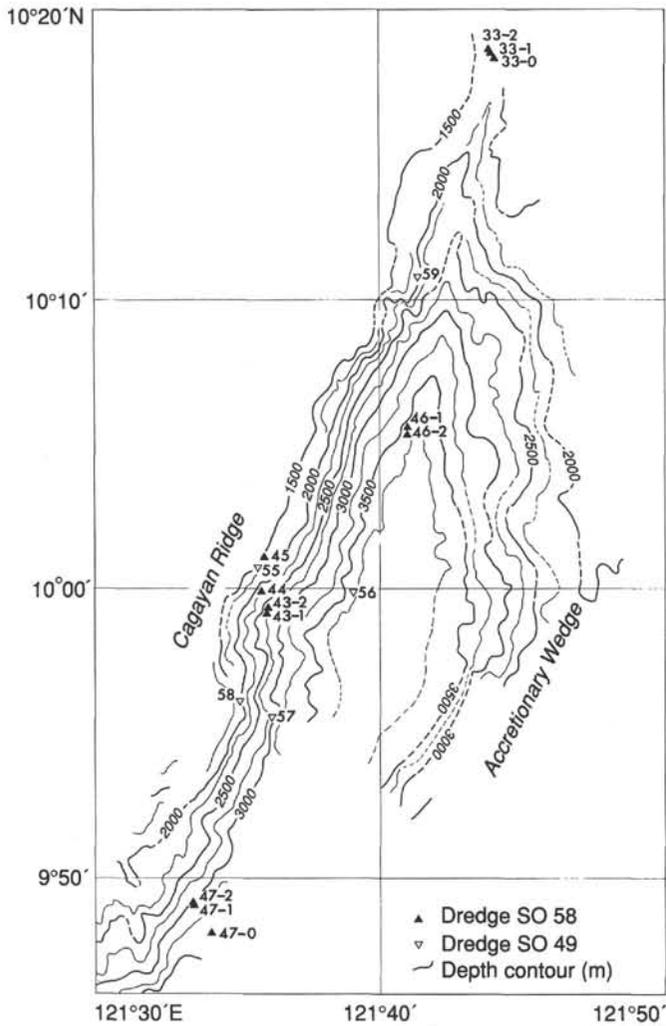


Figure 2. Detail map of the area outlined in Figure 1, Cagayan Ridge.

tainty. We therefore calculate the error of the K-Ar date with an uncertainty of the radiogenic argon arbitrarily enhanced by a factor of four. The only exceptions are the plagioclase dates for Samples SO49-55-3 and SO49-55-9, which have already large analytical uncertainties because of the relatively low concentrations of radiogenic argon.

The amphibole (ferrian tschermakitic hornblende) in SO49-55 exhibits the widest range in K-Ar dates (36–158 Ma). Accord-

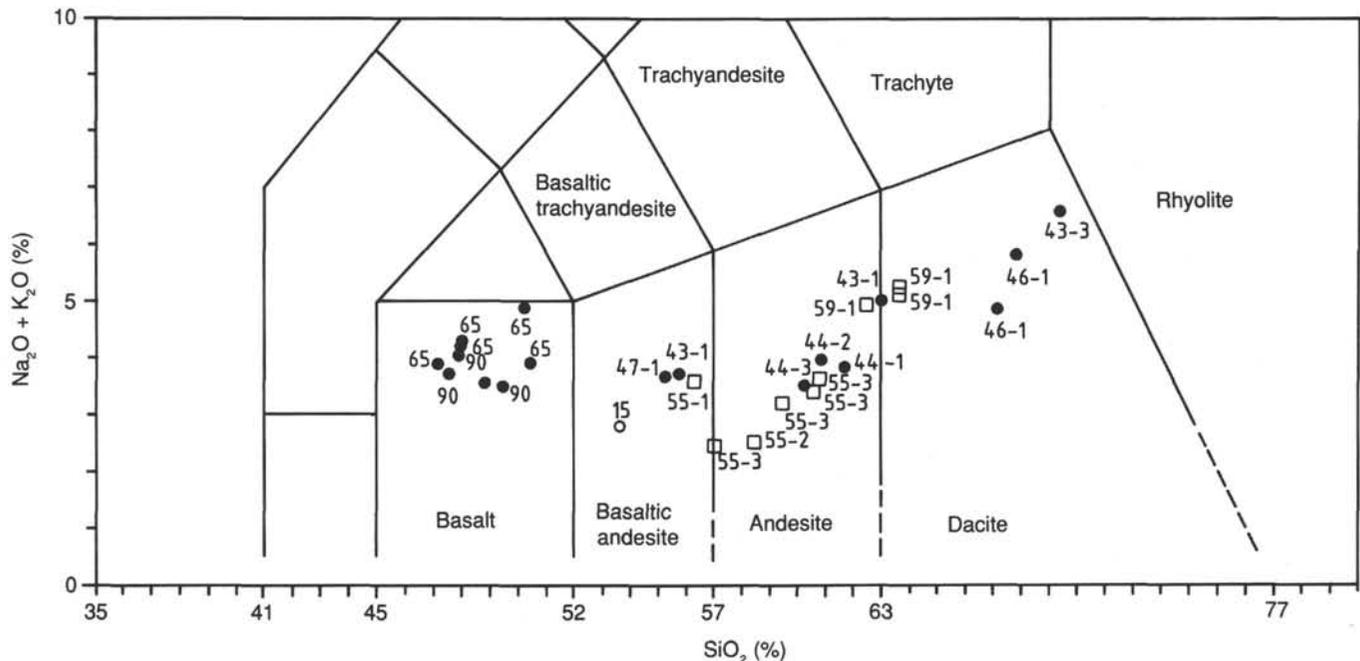


Figure 3. Chemical composition plot of volcanic rocks recovered from two seamounts in the southeast Sulu Basin.

Table 2. Chemical composition of volcanites.

	SO23-15 wr	SO49-55-1 wr	SO49-55-2 lap	SO49-55-3a wr	SO49-55-3b wr	SO49-55-3c wr	SO49-55-3d wr	SO49-57-2a wr	SO49-57-2b wr	SO49-59-1a wr	SO49-59-1a am	SO49-59-1a pl	SO49-59-1a gm	SO49-59-1b wr	SO49-59-1b am	SO49-59-1b pl	SO49-59-1b gm	SO49-59-1b wr	SO49-59-1b wr	SO49-96 wr
SiO (wt.%)	52.13	53.70	56.98	59.16	57.55	54.95	59.39	48.01	47.34	60.48	44.37	52.03	53.28	61.52	44.01	49.94	52.35	61.31	61.31	38.79
TiO <sub>2</sub>	0.85	0.80	0.53	0.57	0.70	0.44	0.54	0.48	0.46	0.38	1.22	0.02	0.10	0.40	1.22	0.04	0.06	0.40	0.40	0.77
Al <sub>2</sub> O <sub>3</sub>	16.62	15.49	14.53	14.22	15.78	15.87	13.98	12.69	12.35	17.34	11.64	28.01	24.40	17.23	11.52	27.61	26.42	17.54	17.54	17.58
Fe <sub>2</sub> O <sub>3</sub>	9.62	10.60	8.72	7.53	7.98	8.05	7.49	9.94	9.50	5.54	15.29	0.49	1.65	5.59	15.34	0.71	1.10	4.85	4.85	5.59
MnO	0.17	0.16	0.14	0.14	0.14	0.13	0.14	0.04	0.04	0.19	0.60	0.04	0.10	0.14	0.58	0.06	0.05	0.17	0.17	0.12
MgO	5.09	3.60	5.47	4.37	4.33	5.81	5.11	8.74	8.18	2.15	12.11	0.10	1.21	2.20	12.49	0.98	1.17	2.36	2.36	2.23
CaO	10.42	8.25	9.20	8.09	7.64	9.20	8.45	2.94	2.64	6.06	10.67	12.32	10.72	4.80	10.88	9.38	7.78	4.63	4.63	18.56
Na <sub>2</sub> O	1.67	2.53	1.94	2.24	2.37	1.80	2.19	2.45	2.34	3.35	1.87	3.97	3.77	4.03	2.01	3.32	3.56	3.68	2.49	2.49
K <sub>2</sub> O	1.04	0.89	0.51	1.29	0.73	0.56	1.13	1.54	1.72	1.41	0.39	0.55	0.89	0.90	0.39	1.17	1.24	1.35	0.86	0.86
P <sub>2</sub> O <sub>5</sub>	0.21	0.08	0.07	0.16	0.09	0.03	0.07	0.09	0.09	0.20	0.16	0.32	0.30	0.19	0.13	0.60	0.10	0.22	6.06	6.06
SO <sub>3</sub>	0.30	0.12	0.00	0.10	0.00	0.00	0.00	0.00	0.24	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.32	0.32
LOI	1.38	3.13	1.56	1.50	2.44	2.55	1.18	12.80	14.75	2.44	1.19	1.89	3.04	2.58	1.01	5.58	5.75	3.04	6.10	6.10
Traces	0.18	0.13	0.13	0.12	0.10	0.10	0.13	0.10	0.10	0.12	0.11	0.12	0.12	0.10	0.11	0.14	0.09	0.11	0.23	0.23
Total	99.68	99.49	99.79	99.49	99.85	99.50	99.80	99.83	99.75	99.73	99.61	99.85	99.56	99.67	99.68	99.53	99.67	99.73	99.69	99.69
Traces (ppm)																				
As	1	1	1	21	1	1	7	1	14	24	1	10	1	17	1	19	1	1	9	9
Ba	174	79	55	108	61	40	82	1	44	234	1	93	137	136	1	78	103	201	135	135
Bi	1	1	1	1	1	1	1	1	1	9	12	1	10	1	17	1	1	1	1	1
Ce	47	1	1	1	1	1	1	1	1	21	1	1	1	20	1	1	1	1	130	130
Co	12	1	1	1	1	21	24	31	1	1	21	1	1	23	1	1	1	1	1	1
Cr	45	1	180	87	30	59	131	152	142	1	28	1	1	1	1	1	1	1	15	15
Cu	83	97	40	63	25	49	71	41	48	13	19	11	15	14	21	120	7	13	77	77
La	37	22	1	1	1	1	1	1	1	1	22	1	1	1	21	1	1	26	68	68
Mo	1	5	5	5	4	1	1	1	1	5	1	1	1	4	1	1	1	5	1	1
Nb	5	1	1	1	3	3	1	1	1	9	3	4	1	7	5	37	4	4	1	1
Ni	30	10	74	26	19	26	30	54	46	8	14	1	1	5	12	1	1	1	33	33
Pb	8	16	9	19	1	1	15	1	16	15	1	19	11	7	10	43	1	27	23	23
Rb	46	26	12	27	13	15	23	22	33	36	7	11	21	15	8	17	19	15	14	14
Sc	46	37	40	33	29	37	35	38	32	10	57	3	5	10	55	1	4	9	30	30
Sn	1	1	1	1	1	27	1	30	1	1	1	29	1	1	114	1	1	1	1	1
Sr	388	149	138	173	160	143	155	89	89	366	87	820	642	307	78	599	561	306	711	711
Ta	8	1	1	6	1	1	1	1	1	1	1	1	1	6	1	12	1	1	1	1
Th	6	1	1	1	1	1	1	6	7	7	1	1	1	9	1	1	1	10	12	12
U	1	1	1	1	1	1	1	6	1	1	1	1	1	5	1	1	1	1	42	42
V	297	355	247	226	216	222	271	144	147	95	232	1	28	104	223	1	1	92	284	284
W	1	22	1	6	1	1	1	1	11	1	1	1	1	1	1	1	1	1	24	24
Y	19	26	26	20	24	19	21	12	16	16	62	6	11	15	68	9	9	15	103	103
Zn	83	86	88	55	83	66	58	58	70	63	142	9	25	49	143	74	21	47	95	95
Zr	45	46	56	70	66	51	74	20	26	95	53	23	42	93	58	22	33	88	40	40

Notes: X-ray fluorescence analyses by J. Lodziak and D. Requard. Subsamples of one rock type are indicated by a, b, c, ...; LOI = loss on ignition; wr = whole rock; lap = lapilli; gm = groundmass; am = amphibole; pl = plagioclase. Values of 1 indicate concentrations below detection limits.

ing to the petrographic analysis, this mineral is atypical for volcanites and may be derived as xenocrysts from a metamorphic rock. Apparently the transfer of the amphibole did not reset the K-Ar clock of the mineral, or the excess Ar from the metamorphic rock was not released. In any case, the old dates of the amphibole suggest the inheritance of argon from an older metamorphic rock.

The dates of the phenocrysts of plagioclase in SO49-59 have a smaller range (22 to 26 Ma), with the better-preserved plagioclase of SO49-59-7 yielding the younger dates. The dates for whole-rock fractions lie between the dates of the amphibole and the plagioclase in Sample SO49-59-1, but are comparable or even younger than those of the plagioclase in Sample SO49-59-7.

In the dilemma of proved excess argon and possible losses of argon from the plagioclase and even more from the whole-rock fractions, the youngest dates of SO49-59 (i.e., 22–26 Ma) provide only doubtful limits for the time of volcanic activity at the northernmost position of the Cagayan Ridge.

The K-Ar dates of SO49-55 are generally younger than those of SO49-59, but they also show a wide range (11 to 20 Ma) and a significant scatter for different fractions of the same sample. We have no certain criteria for the reliability of the different results. If the single date of the magnetic fraction is not considered, we have a cluster of two whole-rock samples, one plagioclase date around 15 Ma, and a single one at about 11 Ma that might indicate the time of volcanic activity at the northern end of the Cagayan Ridge. The K-Ar date of  $14.7 \pm 0.6$  Ma for a basaltic andesite (Kudrass et al., 1986: SO23-15) suggests a similar time of volcanic activity at the southern end of the Cagayan Ridge. The deposition of the early to early middle Miocene

shallow-water carbonates (see below) could be associated with this volcanic activity.

### SHALLOW-WATER CARBONATES

At the northern end of the Cagayan Ridge, shallow-water carbonates were dredged at four localities with water depth ranging from 3800 to 1600 m (Fig. 2). The carbonates that consist of algal packstone, biomicrite or foraminifer sandstone contain shallow-water faunal assemblages of larger foraminifers (*Lepidocyclina*, *Cycloclypeus*, Table 5). The larger foraminifers that are frequently reworked indicate, at least for the *Lepidocyclina* species, an early Miocene to early middle Miocene age. The planktonic foraminifers from the younger sediments are of late Miocene (SO58-43) or of probable early Pliocene age (SO49-57).

The occurrence of early Miocene to early middle Miocene shallow-water carbonates, even when they are reworked into younger sediments, indicates that the Cagayan Ridge existed as a shallow area of presumably volcanic islands at that time. Early to middle Miocene carbonates were also dredged near the reef islands of the central Cagayan Ridge (Kudrass, 1987).

### SUMMARY

The tholeiitic basalt samples dredged from two seamounts near ODP Sites 768 and 769 have a trace-element distribution comparable to transitional mid-ocean ridge basalts (after Pearce, 1982). The volcanic rocks obtained from the Cagayan Ridge on which Site 769 was drilled are richer in silica and range from basaltic andesite to dacite. Most of the rocks belong to the calc-alkaline series, possibly indicating that the Cagayan Ridge

Table 2 (continued).

SO58-43-1a lap	SO58-43-1b lap	SO58-43-3 wr	SO58-43-6 wr	SO58-44-1a wr	SO58-44-1b wr	SO58-44-1c wr	SO58-46-1a wr	SO58-46-1b wr	SO58-46-5 wr	SO58-47-1 lap	SO58-47-3 wr	SO58-65-1a wr	SO58-65-1b wr	SO58-65-1c wr	SO58-65-1d wr	SO58-65-2 wr	SO58-90-1a wr	SO58-90-1b wr	SO58-90-2 wr	SO58-90-3 wr
52.53	56.53	63.67	22.71	60.37	59.23	59.39	65.31	66.41	50.54	47.76	43.83	43.95	45.85	43.96	46.23	43.17	46.13	47.16	45.14	44.81
0.67	0.73	0.53	0.27	0.47	0.46	0.46	0.65	0.62	0.72	0.78	1.98	1.18	1.12	1.15	1.08	1.08	1.22	1.26	1.41	1.38
16.02	14.21	13.07	3.46	14.30	14.25	14.30	15.32	15.48	13.49	15.83	16.72	18.37	17.85	18.53	17.06	16.74	19.06	20.23	19.76	19.44
9.59	7.37	3.78	6.24	6.83	7.29	6.96	4.93	4.15	7.95	9.03	14.40	9.30	9.12	9.35	9.99	9.37	10.01	9.19	10.40	10.38
0.11	0.16	0.15	1.28	0.14	0.14	0.15	0.11	0.07	0.20	0.12	0.21	0.09	0.08	0.12	0.62	0.51	0.22	0.14	0.14	0.18
5.73	2.45	1.19	9.67	4.42	5.22	4.64	1.26	0.86	4.17	4.94	7.75	2.78	3.48	2.74	3.01	2.77	5.06	4.30	3.87	4.16
6.62	4.00	3.34	27.45	7.91	8.61	8.15	4.97	4.62	8.18	5.30	6.03	11.29	9.20	11.01	9.70	12.34	9.79	10.01	9.96	10.69
3.12	3.15	4.46	0.98	2.46	2.43	2.65	3.92	4.54	3.14	2.23	4.36	2.85	2.99	3.05	2.60	2.72	2.84	2.88	3.16	2.98
0.39	1.34	1.57	0.32	1.29	1.02	1.21	0.80	1.15	3.73	0.94	0.07	1.00	1.47	0.88	0.99	0.85	0.54	0.46	0.64	0.53
0.10	0.20	0.12	0.26	0.06	0.07	0.07	0.17	0.14	0.38	0.08	0.15	1.34	0.70	1.34	1.07	2.58	0.29	0.31	0.34	0.32
0.00	0.00	0.05	0.36	0.00	0.00	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
4.38	9.50	7.76	26.40	1.21	0.99	1.75	2.25	1.59	6.63	12.63	3.91	7.30	7.68	7.21	6.64	7.34	4.51	3.20	4.68	4.79
0.12	0.09	0.07	0.27	0.12	0.13	0.12	0.08	0.08	0.29	0.09	0.13	0.18	0.18	0.20	0.20	0.19	0.16	0.15	0.15	0.16
99.37	99.72	99.75	99.68	99.58	99.84	99.84	99.77	99.71	99.87	99.73	99.53	99.65	99.71	99.54	99.18	99.70	99.82	99.28	99.66	99.82
1	1	1	1	1	1	1	14	15	1	1	1	1	1	22	1	22	1	1	1	1
48	94	96	32	104	101	111	84	91	295	1	1	66	84	70	169	147	82	70	74	54
1	1	1	17	1	1	1	1	1	1	1	11	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23	1	1	1	1	1
42	1	1	61	34	24	31	1	1	54	25	74	1	1	39	23	25	1	1	1	1
1	1	1	794	125	157	98	1	1	491	1	47	300	339	383	213	226	63	15	1	21
58	35	27	58	55	59	70	14	25	77	60	10	96	70	89	110	103	61	52	59	135
1	1	1	1	1	1	1	1	1	1	1	1	29	1	1	23	1	1	1	1	1
1	4	5	1	6	6	3	1	1	1	1	5	1	5	1	4	1	1	1	4	4
1	4	4	1	6	1	1	1	1	1	5	4	17	11	12	13	13	13	12	13	14
10	1	1	587	25	26	28	1	1	139	1	37	60	69	65	94	85	54	19	26	36
1	1	1	7	1	11	17	7	13	1	1	1	1	1	1	14	1	1	9	11	1
13	21	26	9	30	19	26	14	25	39	15	4	15	24	15	22	14	7	11	9	8
45	24	14	13	29	38	29	19	19	29	29	52	37	39	35	35	33	30	32	32	35
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23	1	1	1
167	194	153	195	170	153	179	193	185	724	180	114	272	248	280	269	302	338	354	349	359
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	10	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	9	1	1	1	1	6
1	1	1	1	6	1	1	1	1	1	1	1	7	1	1	1	7	6	1	1	1
365	101	27	117	189	210	200	70	80	237	187	397	248	207	260	225	225	300	311	325	317
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
23	36	30	10	25	20	24	32	33	14	14	39	34	37	26	57	33	19	24	24	22
69	89	64	41	50	57	48	70	53	75	80	63	120	108	116	113	116	103	100	108	115
32	77	86	19	75	57	66	86	89	53	46	85	80	75	77	74	70	95	74	86	90

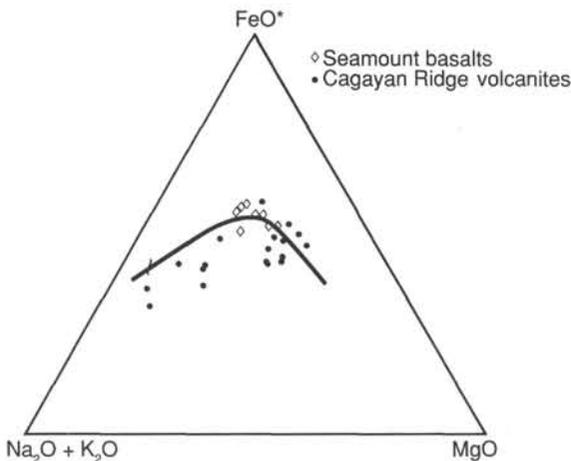


Figure 4. Classification of volcanic rocks from the two southeast Sulu Basin seamounts and the Cagayan Ridge. Separating line between tholeiitic (upper part) and calc-alkaline basalts is after Irvine and Baragar (1971).

originated as a volcanic arc. The K-Ar dates of basaltic rocks and sites from the northern end of the Cagayan Ridge are inconsistent but suggest that the volcanic activity occurred in a period between 10 to 20 Ma. At approximately the same time, shallow-water carbonates of early to early middle Miocene age were deposited on the slopes of presumably volcanic seamounts or islands in the central and northern Cagayan Ridge. Dacites from the northernmost Cagayan Ridge (SO48-59) bear xeno-

crysts of possible metamorphic origin, which obviously contain excess argon.

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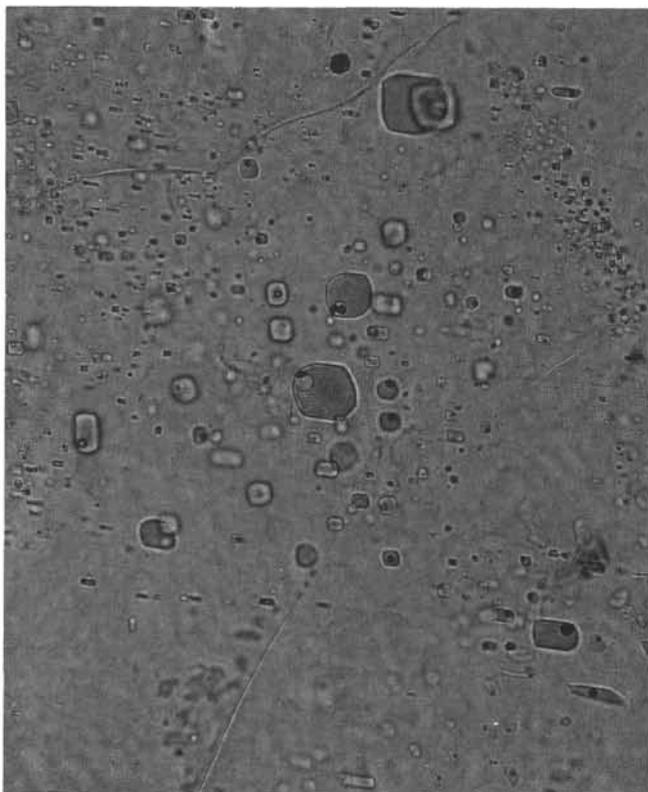


Figure 5. Photograph of phenocrysts of plagioclase with glass inclusions in basalts and basaltic andesite from southeast Sulu Basin seamounts and the Cagayan Ridge. Sample SO49-55-3.

Table 3. Description of the mineralogical composition of volcanites.

Sample Number	Description
SO23-15	Porphyritic basaltic andesite, some vesicles. Pc: pl, cpx, some altered ol. Gm: microcrystalline, pl, pyroxene in light-brown glass.
SO49-55-1	Vesicular porphyritic andesite, fine and large vesicles. Pc: pl with inclusions of glass and small cpx. Gm: brown glass with laths of pl and cpx, fluidal texture.
SO49-55-2	Lapilli tuff, lapilli consisting of fine-vesicular porphyritic andesite. Pc: pl with inclusions of glass; some cpx; cpx with inclusions of glass and op. Gm: fine crystalline with pl, cpx, op.
SO49-55-3	Vesicular porphyritic andesite. Pc: zonal pl with inclusions of glass, fluid, and gas; cpx; some opx (hypersthene) with inclusions of glass. Gm: glass with some pl and cpx, devitrification sphaerulites. Glass in pc darker than in gm.
SO49-55-9	Fine-vesicular porphyritic andesite. Pc: zonal pl with inclusions of glass, cpx, and op; opx; cpx; agglomerates of pl, cpx, and opx. Gm: fine crystalline with needles of pl, op; smectite in vesicles.
SO49-57-2	Tuff with lapilli of basaltic andesite, lapilli with fluidal texture.
SO49-59-1	Massive porphyritic dacite. Pc: green am (ferrian-tschermakitic hornblende) and pl (labradorite), both pc contain glassy inclusions, rim of op surrounds am, however not when am contacts pl, large pl have often smectitic or carbonate cores, other pc are apatite, op. Gm: microcrystalline with ?quartz, pl, op, and am.
SO49-59-7	Massive porphyritic dacite similar to SO49-59-1, but somewhat better preserved (no carbonate in pl pc). Gm with chlorite aggregates partly around phlogopite, am pc are not always surrounded by op, some cm-sized microdiortite-like restites.
SO49-96	Two pebbles of highly vesicular porphyritic andesite. Pc: pl, some cpx, altered (?) ol. Gm: microcrystalline laths of pl, grains of cpx, op, brown glass. The rim of the pebbles is phosphatized.
SO58-33-4	Reddish or grey tuffite.
SO58-43-1	Basaltic or andesite grey ash with lapilli consisting of highly fine-vesicular andesite or basaltic andesite. Pc: some pl and cpx. Gm: small laths of pl exhibit fluidal texture.
SO58-43-3	White to light gray ash with dacitic pumice, pumice with faint fluidal texture. Pc: pl, cpx, op. Gm: light colored glass.
SO58-43-6	Greenish carbonaceous, smectitic, sandy tuffite (pl, cpx, green am, brown am, quartz). Rare grains of calcareous algae.
SO58-44	Fine-vesicular andesite. Pc: pl (up to 2 cm in diameter), opx, cpx, op, large pl are corroded and contain many inclusions of glass; medium-sized pl contain some glass inclusions. Gm: brown glass, pl needles, op grains.
SO58-46-1	Fine-vesicular porphyritic dacite. Pc: pl, opx, some cpx, op; pc often in aggregates. Pm: brown glass, very fine crystalline with small needles of pl, some cpx, fluidal texture.
SO58-46-5	Zeolithic, smectitic volcanic sandstone consisting of pl, light-green cpx, green and brown am, biotite, and rare planktonic foraminifers, calcareous algae.
SO58-47-1	Ash with various lapilli, light-brown lapilli consist of andesite to dacitic devitrified glass, vesicles filled with smectite; dark-brown lapilli consist of basaltic andesite with small laths of pl in cryptocrystalline gm.
SO58-47-3	Greenish slightly porphyritic metamorphite (prasinite-like) with chemical composition of basaltic andesite, intersertal texture. Pc: laths of pl, altered cpx. Gm: fine crystalline, pl, chlorite, epidote, leucocene, op, am, vesicles filled with epidote, chlorite, one pebble only, probably an artifact.
SO58-65	Slightly porphyritic basalt with large and small round vesicles (segregation vesicles corresponding to those described by Bideau and Hekinian (1984)). Pc: altered ol, some pl. Gm: cryptocrystalline, intersertal texture, many laths of pl, some cpx, op. Vesicles partly lined by zeolites. Outcrop covered by a 8-cm-thick manganese crust.
SO58-90-1	Slightly porphyritic basalt with large vesicles and microporosity. Pc: pl, cpx, altered ol, some opx. Gm: fine crystalline intersertal texture, smectitic glass with laths of pl, cpx, op, some skeletal opx.
SO58-90-2	Large vesicles lined by zeolite, small vesicles partly filled by smectite. As SO58-90-1, but in gm am (kaersutite) in radial aggregates.

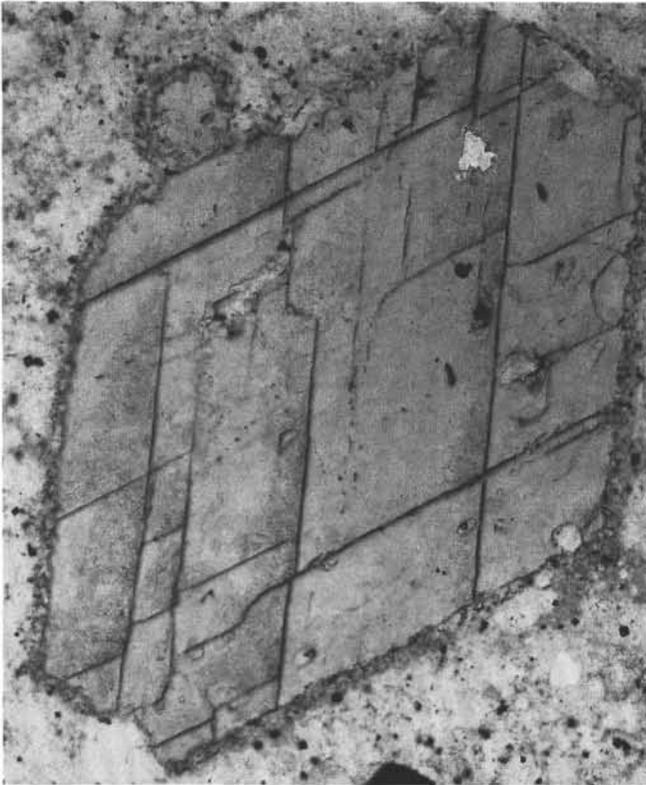


Figure 6. Photograph of dacitic Sample SO49 showing large amphiboles of ferrian tschermakitic hornblende. Sample SO49-59-1.

**Table 4. K-Ar data. Argon determined by standard total fusion mass-spectrometric isotope-dilution analysis and potassium by flame photometry.e.g., (Seidel et al., 1982).**

Sample no. Rock type	Material size ( $\mu\text{m}$ )	K-Ar date (Ma)	K (wt%)	$\text{Ar}_{\text{rad}}$ (nl/g)	$\text{Ar}_{\text{atm}}$ (STP)
SO49-55-1 Porphyritic andesite	wr (200-100)	$14.9 \pm 0.5$	0.476	0.28	1.28
	wr (100-63)	$16.6 \pm 0.9$	0.442	0.29	1.09
SO49-55-3 Basaltic andesite	mf (200-100)	$19.8 \pm 0.7$	1.181	0.914	0.24
	pl (100-63)	$14.7 \pm 1.1$	0.115	0.066	0.38
SO49-55-9 Porphyritic andesite	pl (100-63)	$10.7 \pm 1.5$	0.147	0.061	0.32
SO49-59-1 Porphyritic dacite	wr (600-400)	$36.5 \pm 0.7$	0.930	1.33	0.74
	wr (400-250)	$50.5 \pm 1.6$	0.913	1.82	0.77
	am (250-160)	$158 \pm 5$	0.347	2.23	0.23
	am (160-80)	$36.5 \pm 1.3$	0.335	0.48	0.30
	pl (250-160)	$25.2 \pm 1.3$	0.979	0.98	2.93
	pl (160-80)	$25.8 \pm 1.1$	0.978	0.98	2.88
SO49-59-7 Porphyritic dacite	wr (630-315)	$21.8 \pm 0.7$	1.50	1.28	0.47
	wr (315-200)	$22.0 \pm 0.7$	1.46	1.26	0.41
	am (200-125)	$66.1 \pm 2.3$	0.331	0.87	0.34
	am (125-63)	$60.5 \pm 2.1$	0.323	0.77	0.34
	pl (200-125)	$22.3 \pm 0.9$	0.464	0.40	0.55
	pl (125-63)	$23.9 \pm 1.0$	0.446	0.42	0.52
SO23-15 Porphyritic basaltic andesite	wr (Kudrass et al., 1986)	$14.7 \pm 0.6$	0.863	0.49	0.18

Notes: IUGS recommended constants used (Steiger and Jäger, 1977). Argon in nanoliters per gram at standard pressure and temperature. Error estimates at a level of 95% confidence in the analytical value (see text). Abbreviations: wr = sieve fraction of crushed whole-rock, mf = magnetic fraction of wr, am = amphibole, pl = plagioclase.

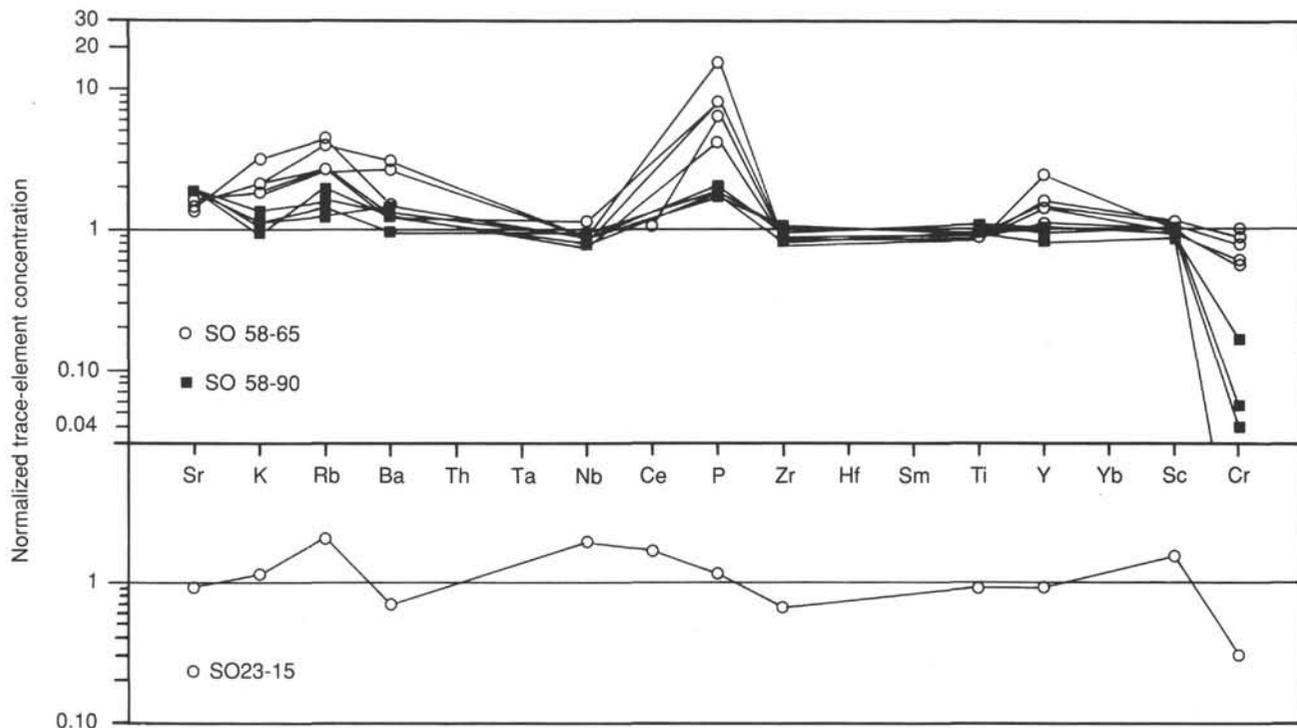


Figure 7. Trace elements in basalts. Upper part: The two seamounts of the southeast Sulu Basin, normalized to E-MORB basalt after Pearce (1982). Lower part: Andesitic basalt from the southwestern Cagayan Ridge, normalized to volcanic arc calc-alkaline basalt after Pearce (1982).

**Table 5. Microfacies, foraminifer fauna, and age of shallow-water carbonates from the northern edge of the Cagayan Ridge.**

Sample no.	Microfacies and foraminifer fauna	Age and remarks
SO 49-56	Algal packstone with larger foraminifers reworked, such as <i>Lepidocyclina (Nephrolepidina) aff. ferreri</i> Provale, <i>Cycloclypeus</i> sp., <i>Operculina</i> sp., <i>Amphistegina</i> sp.	early Miocene to early middle Miocene
SO 49-57	Algal-foraminifer wacke-/packstone with reworked <i>Lepidocyclina</i> specimens, and with <i>Amphistegina</i> sp., <i>Heterostegina</i> sp., <i>Gypsina</i> sp., <i>Calcarina</i> sp., <i>Globorotalia tumida</i> (Brady), <i>Sphaeroidinella</i> specimens	Probably early Pliocene with reworked early to middle Miocene
SO 49-58	Biomicrite with algal fragments and larger forams, such as <i>L. aff. verbeeki</i> (Newton and Holland), <i>Cycloclypeus</i> sp. and <i>Amphistegina</i> sp. and with planktonic foraminifers, such as <i>Globigerinoides</i> sp.sp. and <i>Orbulina universa</i> D'orbigny	early middle Miocene
SO 58-43	Slightly cemented planktonic foraminifer sand with rare benthic and larger foraminifers; with <i>Globoquadrina altispira</i> (Cushman and Jarviz), <i>Globoquadrina dehiscens</i> (Campman, Parr and Collins), <i>Globorotalia aff. merotumida</i> Blow and Banner, <i>Globorotalia aff. plesiotumida</i> Blow and Banner, <i>Orbulina suturalis</i> Brönnimann and others, and with reworked specimens of <i>Cycloclypeus</i> sp., <i>Lepidocyclina</i> sp., and <i>Planorbulina</i> sp.	Probably late Miocene with reworked early to middle Miocene