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# 19. PETROLOGY OF BASIC IGNEOUS ROCKS FROM THE FLOOR OF THE SULU SEA[1]

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## ABSTRACT

Major and trace elements, mineral chemistry, and Sr-Nd isotope ratios are reported for representative igneous rocks drilled from the Sulu Basin basement (Site 768) and Cagayan Ridge (Sites 769, 771) during Ocean Drilling Program Leg 124.

The Sulu Basin basement rocks, cored for about 220 m beneath late early Miocene pelagic sediments, consist, downhole, of pillow basalts (Unit 1), dolerite (Unit 2), and two-pyroxene microgabbro (Unit 3), followed by pillowed and massive basalts (Units 4, 5, 6, 7, and 8). Basalts and dolerites are relatively homogeneous in petrochemical features, except for LOI and elements such as Na, K, Rb, Cs, Li, and Ti, which suffered intense and variable mobilization due to seawater alteration and low-grade greenschist facies oceanic metamorphism. Ca and Mg contents also appear significantly influenced by halmyrolysis in some samples.

Some basalts of Unit 1 have a picritic character (mg = 77), which mainly reflects the composition of the primary magma as evidenced by their quenched texture. The high mg (81–77) of the two-pyroxene microgabbro in Unit 3 reflects not only a primary picritic composition, but also olivine accumulation.

Basalts and dolerites of Units 1, 2, 4, 5, 6, and 7 have mg (74–64), Ni (234–46) and Cr (490–47), variations compatible with moderate fractionation of mantle-derived primary magmas.

Clinopyroxene chemistry, together with the presence of orthopyroxene, indicate a subalkaline nature of Sulu Basement magmas. Their relatively high ratios between LFSE (K, Rb, Ba, Th) and HFSE (Nb, Zr, Hf, Ti, Y) and the REE distribution ($Ce_N/Yb_N$ = 1.6–1.0) coherently indicate normal-MORB/IAT transitional features. Consistent isotope ratios were obtained for picritic basalts and basalts from Unit 1 and microgabbro from Unit 3 ($^{143}Nd/^{144}Nd$ = 0.51297–0.51301 and $^{87}Sr/^{86}Sr$ = 0.70308–0.70340). These petrochemical characteristics imply that oceanic crust creation in the Sulu Basin developed from a basaltic magmatism generated from MORB-like mantle sources, which were modified by subduction-related geochemical components.

Basaltic to andesitic lava flows and clasts in tuffs cored beneath late early to early middle Miocene sediments in the Cagayan Ridge suffered only seafloor alteration, which did not substantially affect their primary composition. Petrographical and geochemical features are completely comparable with tholeiitic ($Ce_N/Yb_N$ = 1.5–2.9) and calc-alkaline ($Ce_N/Yb_N$ = 2.8–2.9) island arc magmas, except for unusually low Nd isotope ratios ($^{143}Nd/^{144}Nd$ = 0.51286–0.51280 with $^{87}Sr/^{86}Sr$ = 0.70292–0.70309).

The data obtained in this paper, while confirming the arc-magma affinity for Cagayan Ridge volcanics, further indicate that Sulu Basin back-arc magmatism with MORB/IAT transitional character was also generated from subduction-modified intraoceanic mantle sources. The older (middle Eocene) Celebes Basin oceanic crust, generated by a pure, normal MORB magmatism thus represents a distinct magmatic system with respect to that of the Sulu Sea.

## INTRODUCTION

Drilling of three sites in the Sulu Sea by Leg 124 (Fig. 1) provided important data bearing on the origin and evolution of this small marginal basin and the adjacent Cagayan volcanic ridge. The seafloor was reached at Site 768, located in the abyssal plain of the southeast Sulu Sea, and was drilled to about 220 meters below seafloor (mbsf). Basaltic lavas and minor shallow mafic intrusives were recovered below pelagic sediments of late early Miocene age. The nature and age of the basement recovered at Site 768 confirmed previous interpretations of the southeast Sulu Sea as a basin floored by oceanic crust. The time of its formation has been determined as late early to early middle Miocene on the basis of radiolarian faunas found in the sedimentary cover. Preliminary petrological investigations performed on board (Rangin, Silver, von Breymann, et al., 1990) showed a tholeiitic nature of Site 768 basement volcanics, with some features suggesting a transitional affinity between mid-ocean ridge basalt (MORB) and island-arc tholeiite (IAT).

Sites 769 and 771, on the flank of the Cagayan Ridge, penetrated a section of submarine volcaniclastics, basaltic to andesitic in composition and early- middle Miocene in age, thus confirming that this ridge was built by arc volcanism nearly concurrently with the formation of the Sulu Basin.

The marginal basins from the west Pacific show a wide spectrum of age, physiographic, and structural characteristics that reflect the complexity of the tectono-magmatic processes occurring in island arc-back arc systems. Igneous processes generating new oceanic crust differ both in time and space with regard to the nature of the sources and mode of fraction-

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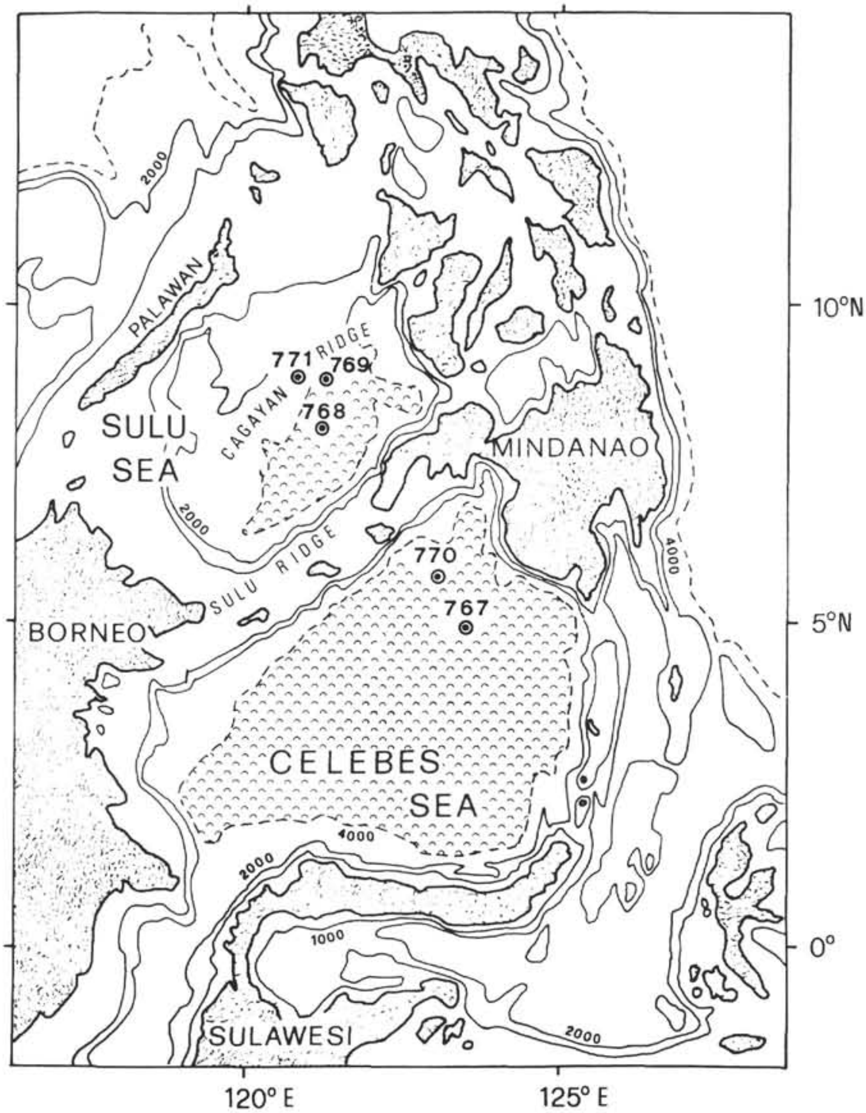



Figure 1. Location of the sites drilled during Leg 124. Bathymetric contours are in thousands of meters. Oceanic basement is denoted with half circles.

ation. The petrology and geochemistry of the erupted products mostly reflect these genetic features, and are therefore of major importance for the understanding of the tectono-magmatic processes in marginal basins.

This study presents petrological, mineralogical, and geochemical data on the igneous rocks from Sites 768, 769, and 771, and explores their petrogenesis mostly by means of high-quality trace-element and isotopic data.

## GEOLOGICAL OUTLINES

The Sulu Sea is a structurally complex basin, elongated in a northeast-southwest direction. It is 650 km long and 400 km wide, located between the South China Sea to the north and the Celebes Sea to the south (Fig. 1). It is subdivided by the submerged Cagayan Ridge into a northwest sub-basin that has water depths between 1000 and 2000 m, and a southeast sub-basin that is much deeper, reaching maximum depths of 4500–5500 m in the southernmost part along the Sulu Trench extending off the Zamboanga Peninsula of Mindanao and Negros Island.

The northwest Sulu Basin has a relatively thick crust (Murauchi et al. 1973) of island-arc type (Rangin, 1989), and belongs to the Sabah-Palawan orogenic belt that developed along the continental margin of the South China Sea from early Paleogene to middle Miocene (Rangin, 1989). It is bounded to the north by the Palawan Ridge, consisting of imbricated thrust slices of Paleozoic and Mesozoic continental rocks (North Palawan block), of Mesozoic oceanic rocks, and Tertiary clastic sediments (south and central Palawan).

Southward, the Cagayan Ridge is a northeast-trending bathymetric high. It has been considered in previous studies to represent an old island-arc (Kudrass et al., 1986; Hinz et al., 1986) related to a northwestward-dipping subduction zone (i.e., to the subduction of the Celebes Sea beneath the Sulu archipelago; Hamilton, 1979; Mitchell et al., 1986), or alternatively to a southward-dipping subduction zone, i.e., to subduction of the proto-South China Sea (Holloway, 1981).

Sites 769 and 771 were drilled, during Leg 124, in the southern flank of the ridge. Submarine volcaniclastics with minor lava flows, basaltic to andesitic in composition, referred to early middle Miocene, were recovered below Quaternary to late middle Miocene sediments. Although drilling did not reach a real basement, the produced sections confirmed that the Cagayan Ridge was built by arc volcanism.

The southeast Sulu Basin, where Site 768 was drilled, extends south from the Cagayan Ridge and is bounded to the east by Negros and Mindanao Islands; these are underlain by Mesozoic and Tertiary accreted terrains belonging to the central Philippine Mobile Belt (Rangin, 1989). To the south, the southeast Sulu Sea is separated from the Celebes Sea by the Sulu Archipelago, which represents the emerged part of the Sulu Ridge extending from southern Sabah to the Zamboanga Peninsula. The Sulu Ridge is composed of a Holocene volcanic chain (Sulu arc) lying on an older and deformed volcanic arc recognized in both Sabah and Zamboanga, which in eastern Zamboanga is sited on a "melange" of metamorphic rocks of continental and oceanic provenance (Letouzey et al., 1988; Rangin, 1989).

In previous studies the southeast Sulu Sea has been interpreted as a back-arc basin whose active arc was either the Cagayan (Holloway, 1981) or the Sulu Ridge (Hamilton, 1979; Mitchell et al., 1986). In the first case, the basin would be related to the southward subduction of the proto-South China Sea; in the second case, to the northward subduction of the Celebes Sea. An alternative interpretation by Lee and McCabe (1986) that the Sulu, as well as the Celebes and Banda seas, originated from the entrapment of an old fragment of oceanic crust is questioned by Rangin (1989) and is not supported by the results of Leg 124 drilling, which demonstrated that the basements of the Sulu and Celebes seas are different in both composition and age, the Celebes being much older (middle Eocene) than the Sulu Basin.

## ANALYTICAL METHODS

Minerals (Tables 2, 3, and 4, backpocket microfiche) were analyzed at the University of Milano using an electron-probe microanalyzer with a SEMQ-ARL unit at an accelerating voltage of 15 kV, a specimen current of 5 nA, beam diameter of 2 to 3 $\mu$m, and counting time of 20 s. Natural silicates and oxides were used as standards, and the raw data were corrected with the ZAF program using Bence and Albee (1968) factors.

Some of the X-ray fluorescence (XRF) analyses (columns C in Table 5, A and B, backpocket microfiche) were made on board using ODP techniques (Rangin, Silver, von Breymann, et al., 1990). New analyses were performed at the University of Udine (columns A in Table 5, A and B, backpocket microfiche) by XRF for major elements, Cr, and Sc on lithium borate glass disks (flux-to-sample ratio 10:1 to overcome matrix effects), and for trace elements V, Ni, Rb, Sr, Ba, Y, Zr, and Nb on powder pellets (Compton scattering technique adopted for matrix absorption corrections) using a wavelength-dispersive automated Philips spectrometer. Loss on ignition (LOI) was determined by the gravimetric method. REE and Y were determined at the Centre de Recherches Pétrographiques et Géochimiques of Nancy, France by inductively coupled plasma (ICP) emission spectrometry (concentrations in ppm with decimals in columns A and C of Table 6, A and B, backpocket microfiche). Sc, V, Li, Be, Cs, Rb, Ba, Sr, Zr, Hf, Th, U, Ti, Pb, Nb, Y, and REE were analyzed at St. John's Memorial University by ICP-mass spectrometry (ICP-MS) using the method of standard addition to correct matrix effects (columns B of Table 6, A and B, backpocket microfiche); the analytical procedure is described in detail in Jenner et al. (1990). Cross checking of trace-element analyses done in duplicate (columns A/C vs. B) show a good agreement for Rb, Sr, Ba, Nb, and REE, with a maximum span of 10%–15% between data. Zr by XRF and Y by ICP are about 10%–15% and 20%, respectively, higher than ICP-MS analyses.

Sr and Nd isotopic compositions were obtained at the University of Naples after cold leaching with 2.5 N or 6.15 N (the latter only for Sr) hydrochloric acid for about 30 s. Measurements were done with a VG 354 mass spectrometer. For the reference sample NBS987, the $^{87}Sr/^{86}Sr$ ratio = 0.71026+2, and for La Jolla STD the $^{143}Nd/^{144}Nd$ ratio = 0.51186+3 were obtained. The reported errors are at the 95% confidence level.

## PETROGRAPHY AND MINERALOGY

### Sulu Basin - Site 768

The igneous basement of the Sulu Basin was reached at this site underlying a sedimentary section 1046.6 m thick, consisting, at the base, of red pelagic clays of late early Miocene. The igneous section was penetrated for 221.8 m and subdivided into eight lithologic units, which include pillowed, brecciated, and massive lavas as well as dolerite and microgabbro sills (Fig. 2).

All the basement rocks from Site 768 have been pervasively altered, to a variable, but generally great extent, so that, for instance, no olivine or glass has been preserved. Furthermore, all basalts and dolerites are characterized by fine amygdaloidal textures, related to the filling of disseminated vesicles by secondary minerals. Amygdules are generally filled with carbonate, zeolites, and clay minerals, suggesting rock/seawater interaction at low temperature. However, the widespread occurrence of chlorite, serpentine, talc, and actinolite, together with the occasional albitization of plagioclase, indicate that the rocks also suffered hydrothermal metamorphism under low greenschist facies conditions (cf. Elthon, 1981; Alt et al., 1986). Representative samples of all lithological units have been studied in detail, and a synthetic description of their petrographic features is reported in Table 1A, backpocket microfiche.

#### *Basalts and Picritic Basalts from Pillow Lavas (Lithologic Units 1, 4, 6, and 8)*

The most deeply altered basement rocks were encountered among pillow basalts. Alteration generally increases downward in the section. The rocks are glass-rich or glassy and highly vesicular in origin (up to 30% in volume). Among the magmatic minerals, plagioclase pro-parte, clinopyroxene (even in skeletal crystals), opaques, and Cr-spinel are preserved. In the diagram of Figure 3A the analyzed clinopyroxenes plot in the endiopside field. Their composition clearly indicates an affinity with subalkaline magmas (Table 2A, backpocket microfiche). In the discrimination diagram of Figure 4A (Beccaluva et al., 1989) they reveal a closer affinity for those of island-arc tholeiites (IAT) rather than for MORB, being characterized by comparatively lower Ti, Al, and Na contents and higher $SiO_2$ saturation.

The effects of overcooling are reflected in anomalously high Ti and Al contents of the smallest clinopyroxene microlites of the groundmass (Table 2A, backpocket microfiche, and Fig. 4A), which extends accordingly to the salite field in Figure 3A.

Olivine is pseudomorphed by clay minerals, serpentine + talc, carbonate, and iddingsite. It reaches 14%–19% modal content in the picritic varieties of Unit 1. Plagioclase is rarely replaced by albite; but it also appears partially replaced by clay minerals. Its composition varies from An 75 to An 50 in oscillatory zoned crystals, to An 30 in the rims and groundmass (Table 3A, backpocket microfiche, Fig. 5A). Cr-spinel has a composition in the range of those of both IAT and MORB (Table 4A, backpocket microfiche, Fig. 6). The glassy mesostasis is devit-

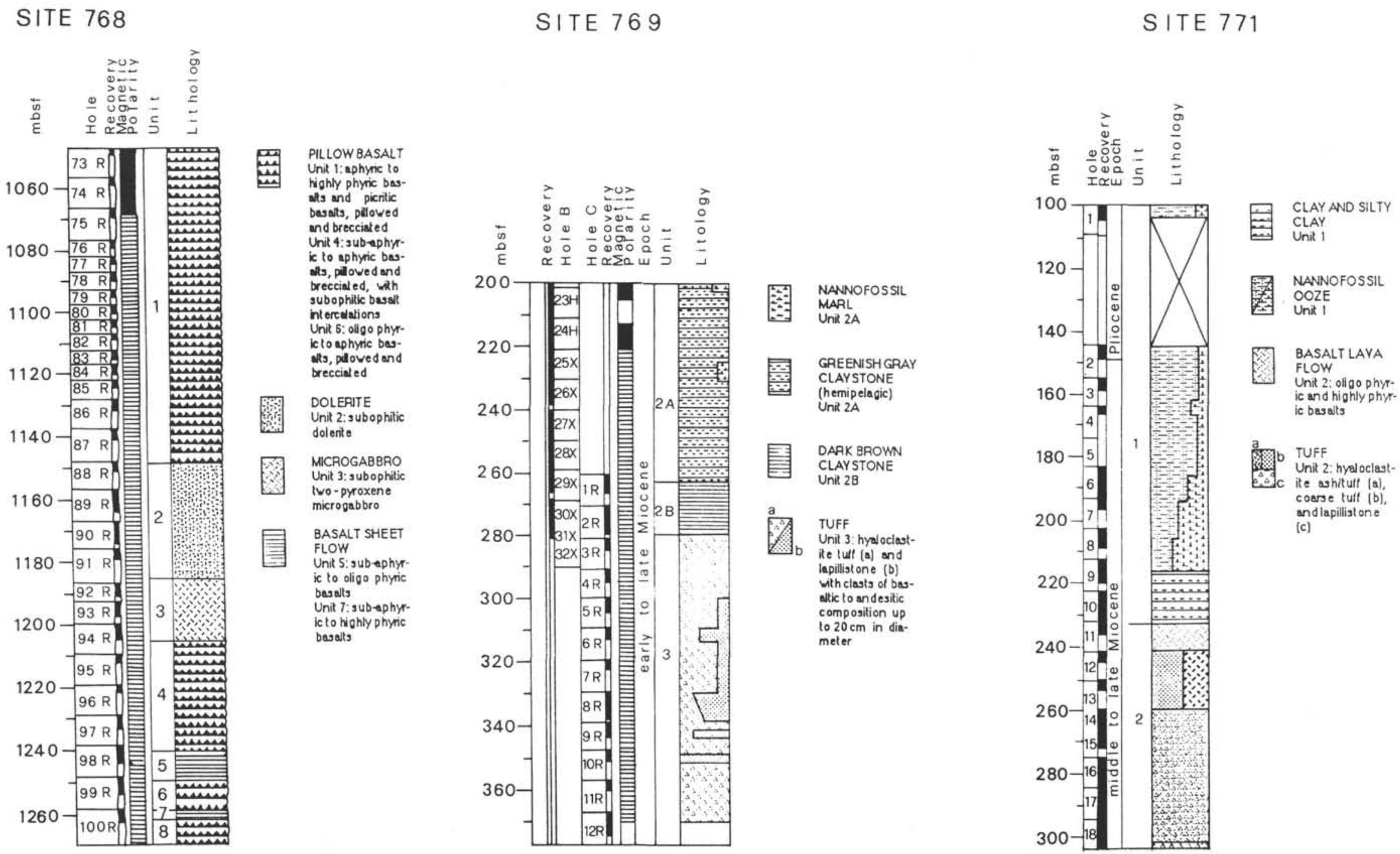



Figure 2. Stratigraphic log of Site 768 Sulu Basin basement and Sites 769 and 771 Cagayan Ridge (Rangin, Silver, von Breymann, et al., 1990).

rified and replaced by variable amounts of smectite and sometimes by zeolites. The ubiquitous vesicles are mostly filled with zeolites, clays, serpentine, Fe-hydroxides, and carbonates adding about 10% to the original rock volume.

*Basalts from Massive Lavas (Lithologic Units 5 and 7)*

The thin lava sheets are similar in primary features and alteration to pillow lavas. The two relatively thick lava sheets from the lower section contain more abundant and coarser magmatic minerals, particularly pyroxene. Pyroxene and Cr-spinel (Tables 2A and 4A, backpocket microfiche, Figs. 3A, 4A, and 6) are unaltered, plagioclase (Table 3A, backpocket microfiche; Fig. 5A) is significantly replaced by clay minerals, and occasionally by albite in Unit 5, and by clay minerals and zeolites in Unit 7. The mesostasis is mostly replaced by smectite and zeolites. Vesicles are filled with clays and zeolites.

*Dolerite from Upper Sill (Lithologic Unit 2)*

Primary minerals include olivine, plagioclase, clinopyroxene, minor Fe-Ti oxides, and Cr-spinel. With the exception of olivine, these are fresh. Hypocrystalline altered mesostasis is abundant, and amygdales filled with smectite and zeolites are also present. Clinopyroxene chemistry is closely similar to that of picritic basalts, except for the extension from the endiopside to the augite field (Fig. 3A) and a tendency to higher Ti and Na (Fig. 4A), reflecting the comparatively more fractionated nature of the host basaltic magma. No anomalously high Ti and Al contents due to overcooling have been detected, as suggested by the hypoabyssal texture of the rocks. Plagioclase shows a gradual variation from An 88 in the cores to An 30 in crystal rims (Table 3A, backpocket microfiche; Fig. 5A). Magnetite is Ti-rich (Table 4A, backpocket microfiche).

*Two-pyroxene Microgabbro from Lower Sill (Lithologic Unit 3)*

The texture is holocrystalline, and vesicles are absent. Olivine is completely altered, and Cr-spinel, clinopyroxene, plagioclase, Ti-magnetite, ilmenite, and orthopyroxene are substantially fresh, whereas the minor biotite is largely altered to chlorite. The secondary minerals consist mostly of actinolite, chlorite, epidote, serpentine, and smectite.

As in the case of dolerites, clinopyroxenes straddle the endiopside-augite field boundary (Fig. 3A) and reveal a common affinity with those of IAT magmas (Fig. 4A). Fractional crystallization processes are reflected in some zoned crystals with an increase in Ti, Na, and Fe from cores to rims (Table 3A, backpocket microfiche).

The presence of bronzitic orthopyroxenes (En 74-77, Table 3A, backpocket microfiche; Fig. 3A) in equilibrium with augitic clinopyroxene confirms the subalkaline nature of the magma. As in dolerite of Unit 2, plagioclase varies continuously from highly anorthitic composition (An 88) in the cores to An 23 in the crystal rims (Table 3A, backpocket microfiche; Fig. 5A). A similar increase of $K_2O$ and decrease of MgO also occur as observed in plagioclase from MORB (Perfit and Fornari, 1983; Ayuso et al., 1976).

Cr-spinel included in olivine has characteristically lower $Mg/(Mg+Fe^{2+})$ ratios with respect to basalts (Table 4A, backpocket microfiche; Fig. 6).

## Cagayan Ridge - Sites 769 and 771

In Site 769, igneous rocks occur as clasts in coarse volcaniclastics consisting of hyaloclastite tuff and lapillistone from 278.45 to 376.9 mbsf (Fig. 2). Samples of coarse lithic fragments up to 20 cm in diameter scattered in the tuff section have been selected for petrographic and chemical study. Although representing a minor component, they can be considered comagmatic with vitric clasts. In fact, the hydroclastic and pyroclastic origin of the volcanic debris and the poor reworking indicate that the materials originated from single eruptive events from a proximal volcanic vent.

The hole drilled at Site 771 penetrated 303 m of sedimentary and volcanic rocks (Fig. 2). The lower volcanic section (Unit 2) consists of hyaloclastite tuff and lapillistone, and minor basalt flows between 233.9 and 303 mbsf. Approximately 1.5 m (Core 124-771-11R) and 58 cm (Core 124-771-18R) of basaltic lavas were recovered respectively at the top and base of the tuff. Both lithic clasts scattered in the tuff and basaltic lava flows from the top and base of the sequence were selected for detailed investigation.

It is to be noted that, unlike the Sulu basement rocks, those from the Cagayan Ridge do not reveal evidence of greenschist facies hydrothermal metamorphism, their alteration being accounted for by common rock/seawater interaction with formation of secondary phases such as carbonates, zeolites, Fe-hydroxides, and clay minerals. Therefore, the absence of albite, chlorite, and sphene suggests that the alteration process took place at temperatures probably below 150°–200°C (cf. Alt et al., 1986). Petrography of the studied samples is summarized in Table 1B, backpocket microfiche.

*Basalt, Basaltic Andesite and Andesite Clasts in Tuff (Site 769 - Lithologic Unit 3)*

Basic lava samples of Unit 3 are predominantly highly phyric with hyalopilitic to intersertal groundmass. Vesicularity is moderate to scarce, generally less than 5% in volume in most samples. Phenocrysts, sometimes in glomerophyric aggregates, consist of plagioclase, clinopyroxene, olivine, and magnetite. Orthopyroxene phenocrysts increase from basaltic andesites to andesites whereas olivine decreases up to ca. 1% in volume. All these mineralogical features are typical of basic lavas from a calc-alkaline island arc series. Microprobe analyses of plagioclase, pyroxenes, and opaques are reported in Tables 2B, 3B, and 4B, backpocket microfiche; and in Figures 3B, 4B, and 5B. Plagioclase is often oscillatory zoned, ranging on the whole between An 93 and An 46 from early to late crystals. $K_2O$ is negatively correlated with anorthite, but it is systematically higher than that of plagioclase from Sulu basement rocks, suggesting comparatively higher potassium contents in the Cagayan Ridge magmas.

Clinopyroxene varies from endiopside in basalts to augite in basaltic andesites and andesites (Fig. 3B). In andesites it is in equilibrium with hypersthene (En 67-64), as commonly found in calc-alkaline suites from island arcs.

Clinopyroxene composition shown in the $TiO_2$-$SiO_2$-$Na_2O$ discriminant diagram of Figure 4B confirms a volcanic arc affinity for all the analyzed lavas that plot where clinopyroxenes from island arc tholeiites, andesites, and boninites overlap.

Olivine is completely replaced by iddingsite. Groundmass consists of intersertal aggregates of plagioclase, clinopyroxene, and Fe-Ti oxides, minor apatite with a variable amount of glassy mesostasis mostly altered to smectite. Vesicles are filled with clays and chalcedony.

*Basalt Clasts in Tuff and Lava Flows (Site 771 - Lithologic Unit 2)*

These lavas vary from oligophyric to highly phyric with a hyalopilitic groundmass. They are scarcely vesicular, generally with less than 5% in volume of vesicles. Phenocrysts consist of clinopyroxene and iddingsitized olivine in the least-differentiated lavas, whereas plagioclase is predominant and magnetite appears on the liquidus in the more evolved members of the crystallization sequence. These features conform well with those of arc basalts and suggest a tholeiitic rather than calc-alkaline affinity. The groundmass is made up

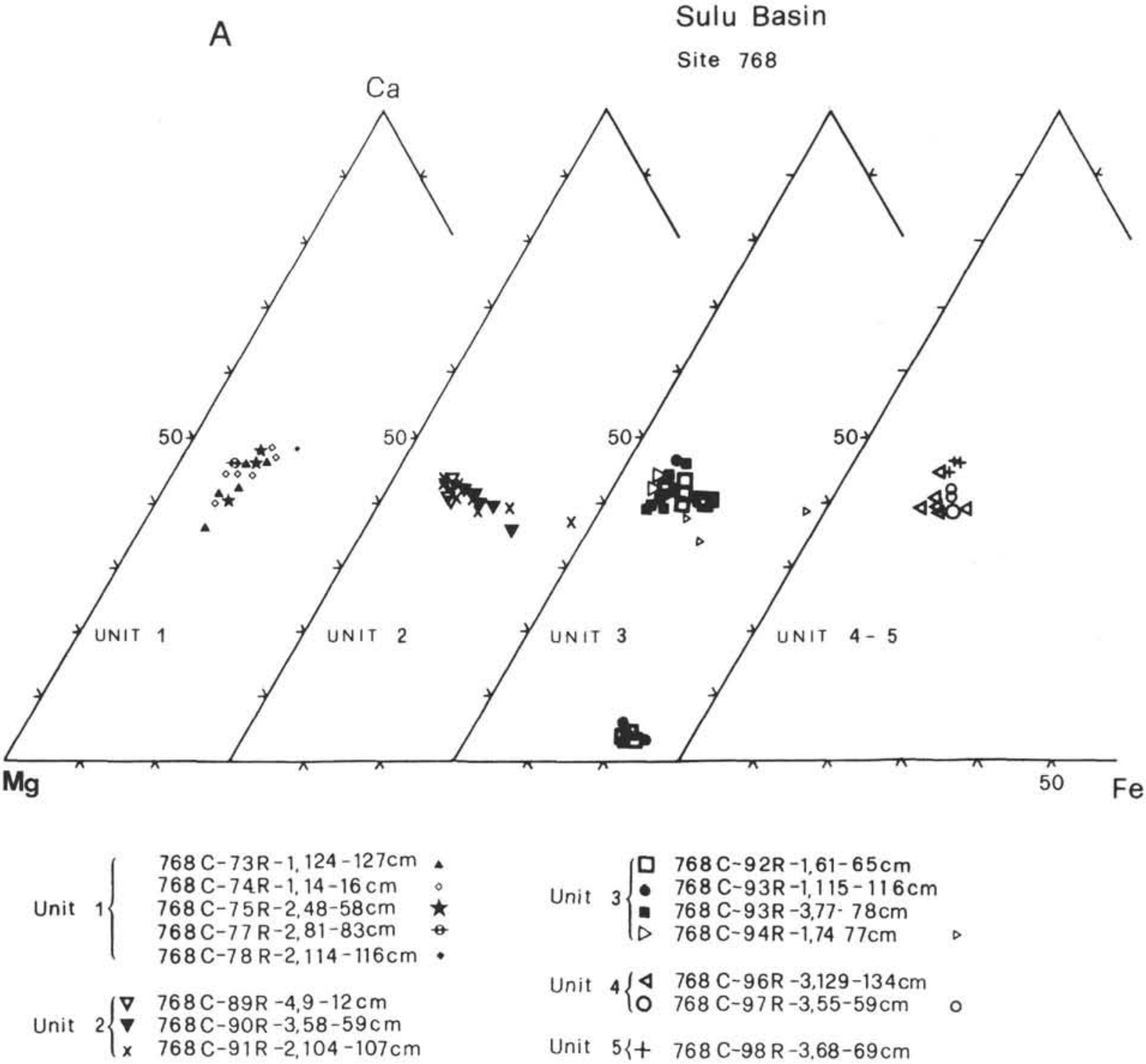



Figure 3. Pyroxene compositions of A. Sulu basement rocks and B. Cagayan Ridge volcanics in the Ca-Mg-Fe diagram (atom%). Large and small symbols denote early and late crystals, respectively.

of plagioclase, clinopyroxene, opaques, and interstitial glass, which appears to have suffered various degrees of alteration. Vesicles are filled with clays, chalcedony, and zeolites.

## GEOCHEMISTRY

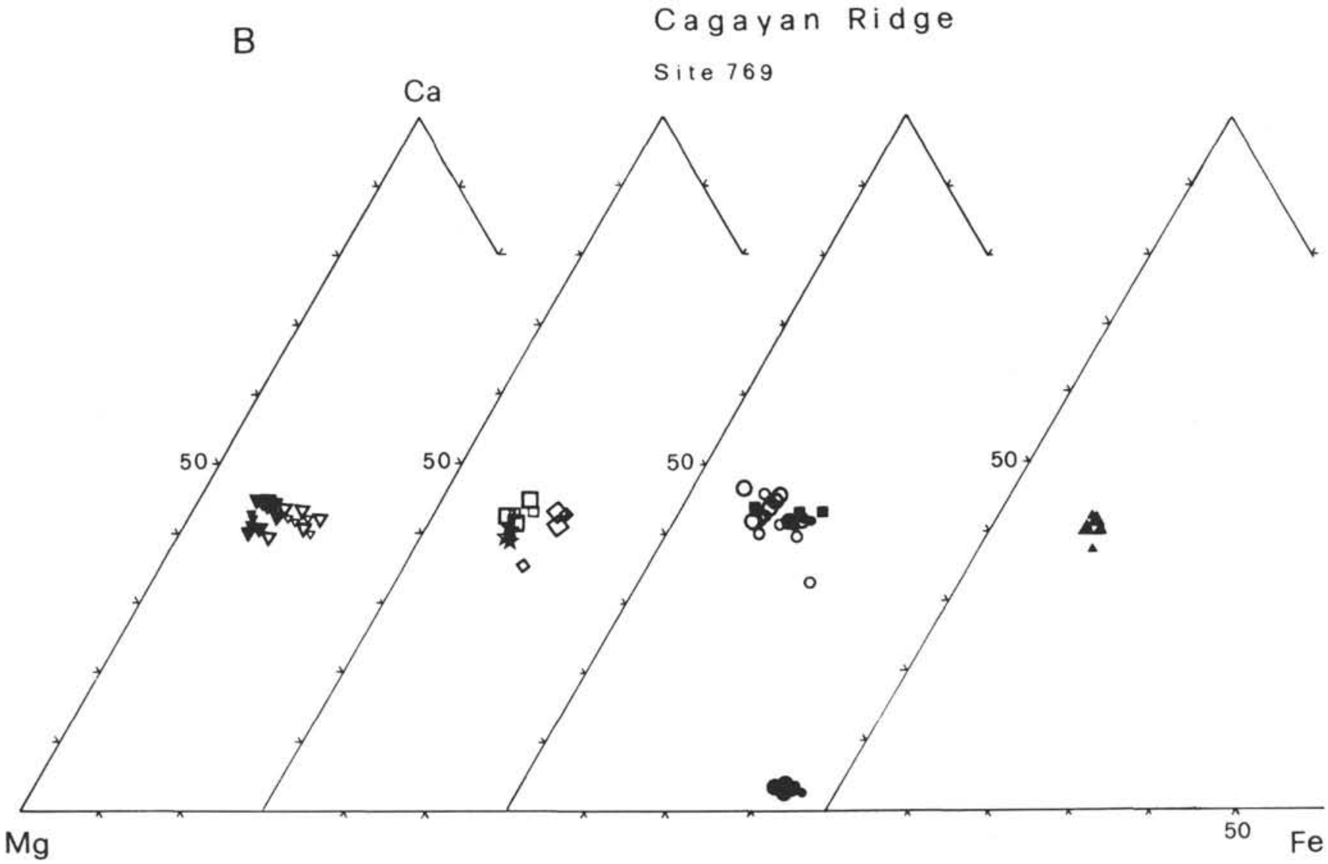
Major-element analyses of representative igneous samples from Sites 768C, 769B, and 769C, and 771A are presented in Tables 5A and 5B (backpocket microfiche). Trace-element analyses on the same samples are reported in Tables 6A and 6B (backpocket microfiche). As all samples have suffered a variable degree of alteration due to rock-seawater interaction and low-grade metamorphism, the interpretation of their chemistry must be performed with care. This is particularly evidenced by the constantly high loss on ignition (LOI) as well as by the erratic content of alkaline elements.

LOI is usually very high (5.5–8.1 wt%) for Sulu basement rocks of Hole 768C, which suffered both seafloor weathering and greenschist facies metamorphism. Most crystalline samples, namely dolerites (Sections 124-768C-89R-4 and 124-768C-90R-3), microgabbros (Section 124-768C-92R-1) and basalts (Section 124-768C-100R-2), appear to be the least altered and show the lowest LOI contents.

Comparatively lower LOI (1.4–5.5 wt%) is found in lavas from the Cagayan Ridge (Holes 769B and 769C and 771A), which were only affected by seafloor weathering. Some samples from this locality could be considered fresh, having 1.1%–1.2% of LOI.

Based on major-elements all basaltic rocks from the Sulu basement (Site 768C) should be classified as tholeiitic basalts with a remarkable picritic tendency in some samples of Unit 1, where MgO ranges from 14.1% to 9.9%. Microgabbros of Unit 3 also show high MgO (18.9%–15.1%) coupled with high Ni, Cr, and minimal incompatible element contents (Table 6A, backpocket microfiche). This feature clearly indicates that these rocks underwent cumulus enrichment of mafic phases during crystallization. The presence of modal orthopyroxene in addition to clinopyroxene confirms the subalkaline nature of these magmas.

Lava clasts and flows from the Cagayan Ridge (Holes 769B, 769C, and 771A) can be classified in terms of major-




Unit 3{▽769 B-31X-CC,26-29cm ▿
▼769 B-32X-CC,9-12cm ▾

Unit 3{★769 C-3R-2,41-43cm ☆
□769 C-4R-5,9-15cm ▫
◇769 C-5R-5,22-25cm ◇

Unit 3{■769C-7R-1,108-112cm
●769C-9R-3,121-122cm •
○769C-9R-4,46-49cm ○
▲769C-12R5,114-117cm ▴

Figure 3 (continued).

element chemistry as basalts ($SiO_2 < 52\%$), basaltic andesites ($SiO_2 < 56$) and andesites ($SiO_2 > 56$). The high- silica and high-alumina character of these rocks, together with their consistently low $TiO_2$ contents (0.6%–1.1%) indicates a clear orogenic magma affinity.

More specifically, basalt to andesite rocks of Holes 769B and 769C show no Fe enrichment and lower iron content with respect to basalts of Hole 771A, thereby confirming a calc-alkaline affinity in agreement with the presence of modal orthopyroxene and early magnetite crystallization. In contrast, all basalts from Hole 771A, plus a single sample (124-769C-3R-2, 41–43 cm) from Hole 769C, reveal a closer affinity with the island arc tholeiite series and a significant Fe enrichment in the most differentiated samples (e.g., 124-769C-18R-8, 21–23 cm).

Comparison between the most- and least-altered samples from all the studied sites suggests that alteration-related chemical changes significantly involved LOI and alkalies, mainly in relation to the amount of zeolites and smectites. In general, Ti, Cs, Li, and Rb appear to be the most sensitive-trace element indicators of seafloor weathering. The comparatively high Cs/U, Rb/U and Cs/Rb ratios in some Sulu basement rocks (Samples 124-768C-97R-3, 55–59 cm, 124-768C-100R-2, 17–19 cm, and 124-768C-90R-3, 58–59 cm) suggest that chemical mobilization was more effective for Cs than for Rb, with U probably not dramatically affected by secondary processes (cf. Hertogen et al., 1980). Ti, in contrast, is commonly five-to-twenty-fold enriched relative to fresh oceanic basalts (Hertogen et al., 1980) even in the slightly altered volcanics from the Cagayan Ridge. Mg removal during halmyrolysis under oxidizing conditions (Seyfried and Bischoff, 1979) may also be suspected, as suggested by the high Ni/MgO ratios in some samples (e.g., Samples 124-768C-97R-3, 55–59 cm and 124-768C-100R-2, 17–19 cm). Some Ca variations appear to be dependent on carbonates, but Sr and Ba do not appear significantly affected by secondary mobilization. As will be shown later, geochemical regularities and interelement correlations of Ti, P, Sc, V, Cr, Zr, Hf, Th, Nb, Y, and REE suggest that these elements might have been virtually immobile, or very slightly mobile, during low-temperature alteration, and could be used as indicators of magmatic processes (Hart et al., 1974; Bienvenu et al., 1990).

In terms of the Ti-Zr discrimination diagram (Fig. 7), the Cagayan Ridge rocks confirm their affinity with tholeiitic (Hole 771A) and calc-alkaline (Holes 769B and 769C) arc magmas, whereas those from the Sulu basement (Hole 768C) appear more ambiguous, plotting between the Cagayan tholeiites and the MORB of the Celebes Sea (Holes 770B and 770C),

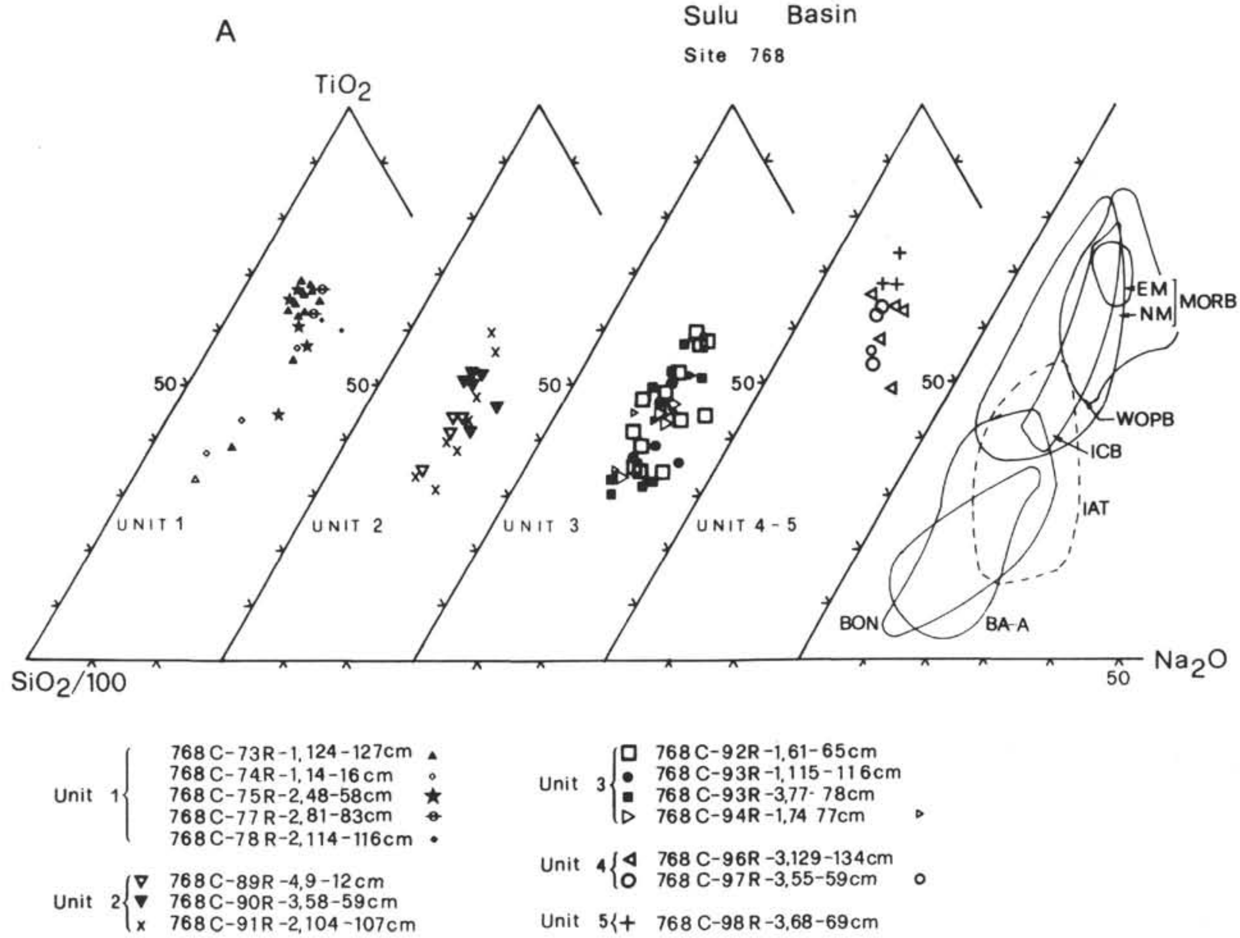



Figure 4. Clinopyroxene compositions of **A.** Sulu basement rocks and **B.** Cagayan Ridge volcanics in the $TiO_2$-$Na_2O$-$SiO_2$/100 diagram (wt%). The discrimination fields for clinopyroxene from basalts of different oceanic settings are reported (after Beccaluva et al., 1989): Abbreviations: normal (NM) and enriched (EM) mid-ocean ridge basalts (MORB); within oceanic plate basalts (WOPB); Iceland basalts (ICB); island-arc tholeiites (IAT); boninites (BON); quartz tholeiites, basaltic andesites, and andesites (BA-A) from intraoceanic fore-arc regions. Large and small symbols denote early and late crystals, respectively.

reported here for comparison. In the Th/Zr vs. Nb/Zr diagram (i.e., elements virtually unaffected by alteration) of Figure 8, the Sulu basement rocks plot just above the normal MORB field, overlapping that of basic lavas from oceanic arcs, owing to a significant Th enrichment. This MORB transitional IAT affinity is also evidenced in the binary diagrams of Figure 9, where Sulu rocks all plot between those from the Celebes Sea basement and the Cagayan Ridge. Their Ba/Zr, Sr/Zr, and $P_2O_5/TiO_2$ ratios, in particular, are significantly and systematically higher than normal MORB and chondrites, being transitional to those of basalts from active and remnant intraoceanic arcs (cf. Saunders et al, 1980; Saunders and Tarney, 1984). The chondrite-normalized REE distribution of the least-differentiated basalts reveals a progressive light-REE depletion from Cagayan tholeiites to Sulu basaltic rocks (Fig. 10). These latter are, in turn, slightly less LREE-depleted than Celebes basement MORB.

The MORB-normalized patterns of Figure 11 permit a comprehensive view of incompatible element distribution in the rocks from the Sulu basement and the Cagayan Ridge. In this diagram we note that all low field-strength elements (LFSE), from Sr to Th, are coherently enriched with respect to MORB in Cagayan rocks, despite their possibly different mobilization by seafloor weathering (cf. Hart et al., 1974). In Sulu basement rocks, comparatively lower, but undoubtedly significant, enrichments are observed for K, Rb, Ba, and Th. This style of element enrichment is typical of arc magmatism (Pearce, 1982), and is commonly considered to result from variable degrees of metasomatism of magma mantle sources by fluid components driven off the subducted oceanic crust. High-field strength elements (HFSE) and heavy REE (HREE), from Zr to Yb, show constantly depleted patterns in relation to MORB, together with a negative Nb anomaly in tholeiitic basalts for both the Sulu basement and Cagayan Ridge. This feature is once again typical of IAT and is usually related to a higher degree of partial melting than MORB and/or remelting of already depleted mantle sources, producing suprasubduction basic magmas.

In conclusion, while the Cagayan Ridge and Celebes basalts conform well to island-arc tholeiite/calc-alkaline lavas and normal MORB, respectively, the Sulu basement rocks have intermediate geochemical features that suggest that metasomatizing fluids derived from a subduction zone might have entered the source regions of Sulu Basin back-arc magmas, producing their MORB/IAT transitional character.

The strontium isotopes of six samples from the Sulu basement and eight on the Cagayan Ridge have compositional ranges 0.70308–0.70441 and 0.70292–0.70346, respectively

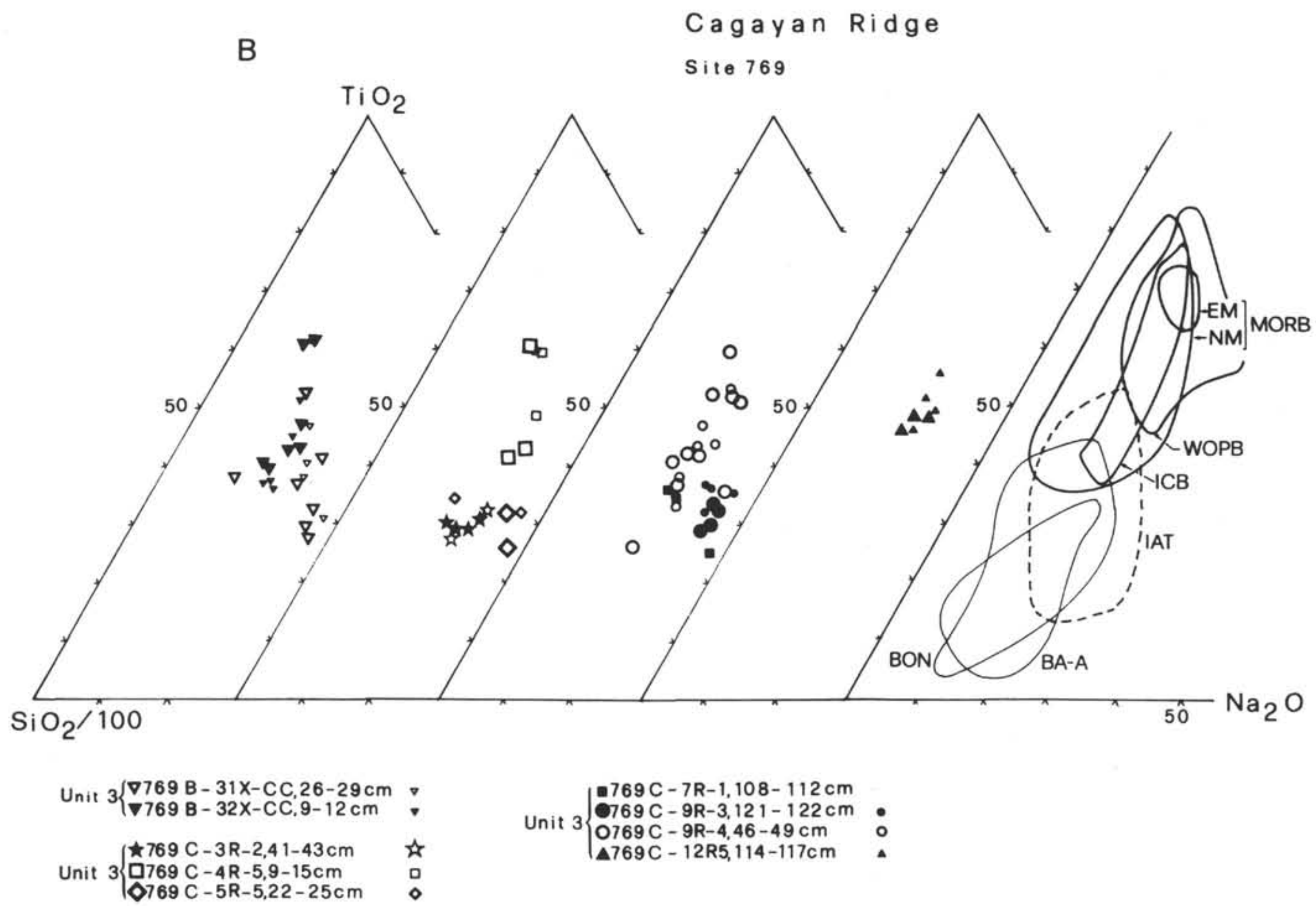



Figure 4 (continued).

(Table 6, A and B, backpocket microfiche). Significantly, the highest value (0.70441) refers to Sample 124-768C-97R-3, 55–59 cm from the Sulu basement, which suffered strong chemical mobilization, and must therefore be interpreted as due to seawater alteration. Sample 124-768C-97R-3, 55–59 cm analyzed in duplicate by HCl 6.15 N cold leaching, to eliminate carbonates, gave a reduced $^{87}Sr/^{86}Sr$ ratio of 0.70375. The same treatment resulted in a reduction in the isotopic ratios of samples analyzed in duplicate by 0.00028–0.00003. Unexpectedly, the ratio of Sample 124-769C-3R-2, 41–43 cm (Cagayan Ridge) treated in the same way increased from 0.70309 to 0.70341.

The $^{143}Nd/^{144}Nd$ measurements gave 0.51301–0.51297 for the Sulu basement picritic basalt and basalt (Unit 1) and microgabbros (Unit 3), and 0.51280–0.51286 for tholeiitic basalts and a calc-alkaline andesite from the Cagayan Ridge (Table 6, A and B, backpocket microfiche).

As the Nd-isotopic ratio is not significantly affected by seawater alteration, the measured ratios reflect the primary composition of magma and, by implication, that of their mantle sources. In the Nd-Sr isotope diagram of Fig. 12 both Sulu basement rocks and Celebes basalts cluster around the mantle array, whereas the tholeiitic basalts and calc-alkaline andesite from the Cagayan Ridge plot well below it, due to their unusually low $^{143}Nd/^{144}Nd$ ratios. This latter isotopic signature, characterized by low $^{87/86}Sr$, intermediate $^{143}Nd/^{144}Nd$, and high $^{206}Pb/^{204}Pb$ ratios (HIMU), has been considered due to intramantle metasomatism (Menzies and Wass, 1983; Zindler and Hart, 1986; Hart, 1988).

## CONCLUSIONS

The data obtained on basic igneous rocks drilled from the Sulu Basin basement and Cagayan Ridge during ODP Leg 124 allow us to draw the following conclusions:

1. Basement rocks of the Sulu Basin (Site 768) drilled for about 220 m beneath early Miocene pelagic sediments consist, downhole, of pillow basalts, dolerite, and two pyroxene microgabbro, followed by pillowed and massive basalts; all of these underwent seafloor weathering and low-grade greenschist metamorphism compatible with their formation at an oceanic spreading axis.

Incompatible element distribution, particular LFSE/HFSE ratios and clinopyroxene chemistry, together with the presence of orthopyroxene, indicate the subalkaline nature of these magmas, which are transitional between normal MORB and IAT. This fact suggests that metasomatizing fluids from a subduction zone might have entered the source regions of Sulu Basin back-arc magmas, producing their peculiar transitional characteristics.

2. Basaltic to andesitic lava flows and fragments in tuffs cored for about 100 m (Site 769) and 70 m (Site 771) beneath late-early to early-middle Miocene sediments in the Cagayan Ridge suffered only seafloor weathering and are by comparison much less altered than Sulu basement rocks. These lavas show typical affinities with tholeiitic and calc-alkaline island-arc magmas with regard to petrographic and most geochemical features. However, their $^{143}Nd/^{144}Nd$ ratios are unusually low,

possibly related to complex metasomatic components in their suprasubduction mantle source.

3. Reconstruction of the geological evolution of the area should take into account that: (a) the Cagayan Ridge was built by arc magmas generated above a subduction zone; (b) the Sulu Basin oceanic crust was formed almost contemporaneously by back-arc magmas, whose transitional MORB/IAT geochemical features also imply their generation in a suprasubduction intraoceanic setting; (c) the much older (middle Eocene) Celebes Basin oceanic crust was generated by pure normal MORB magmatism, therefore representing a distinct magmatic system.

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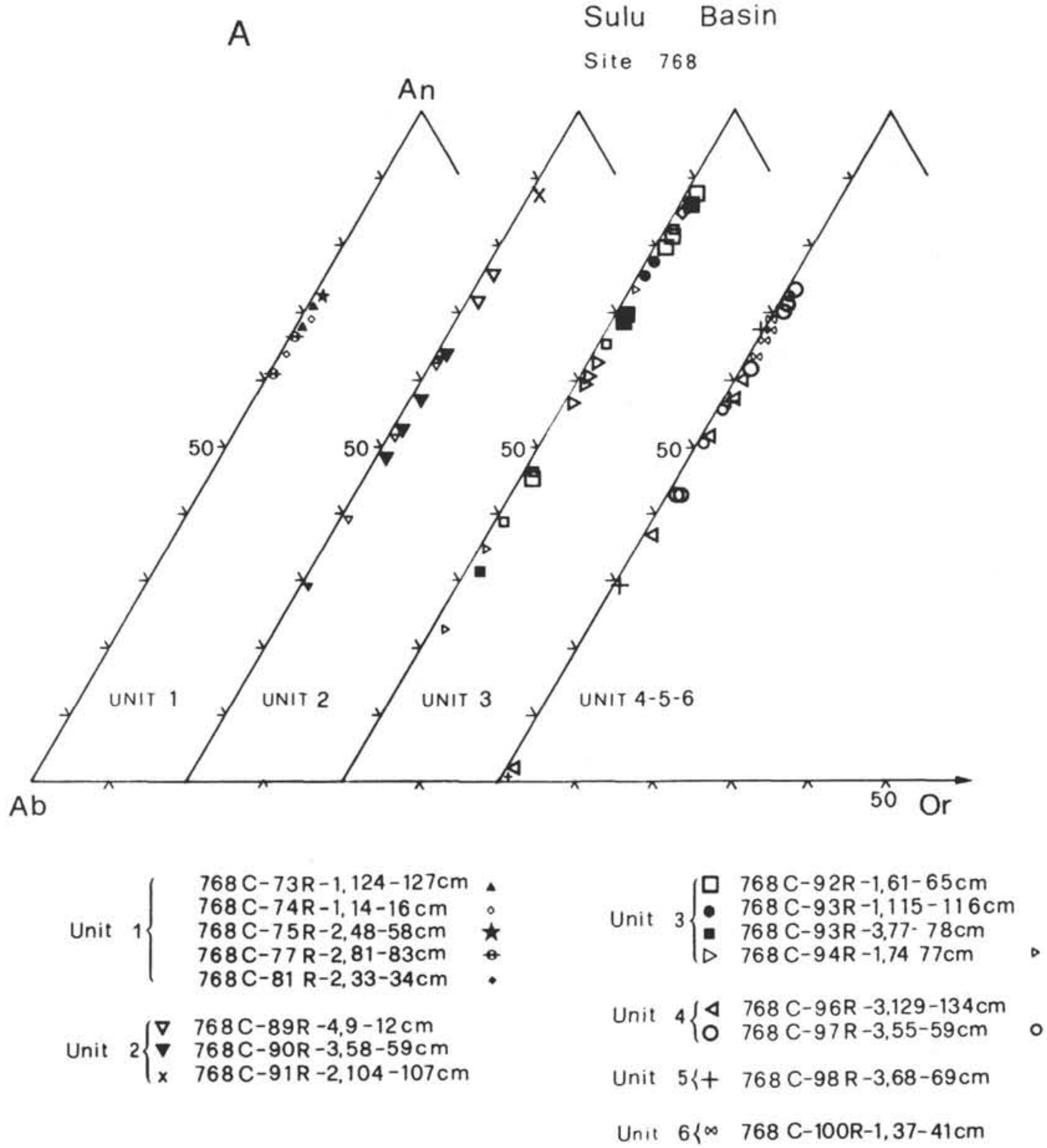
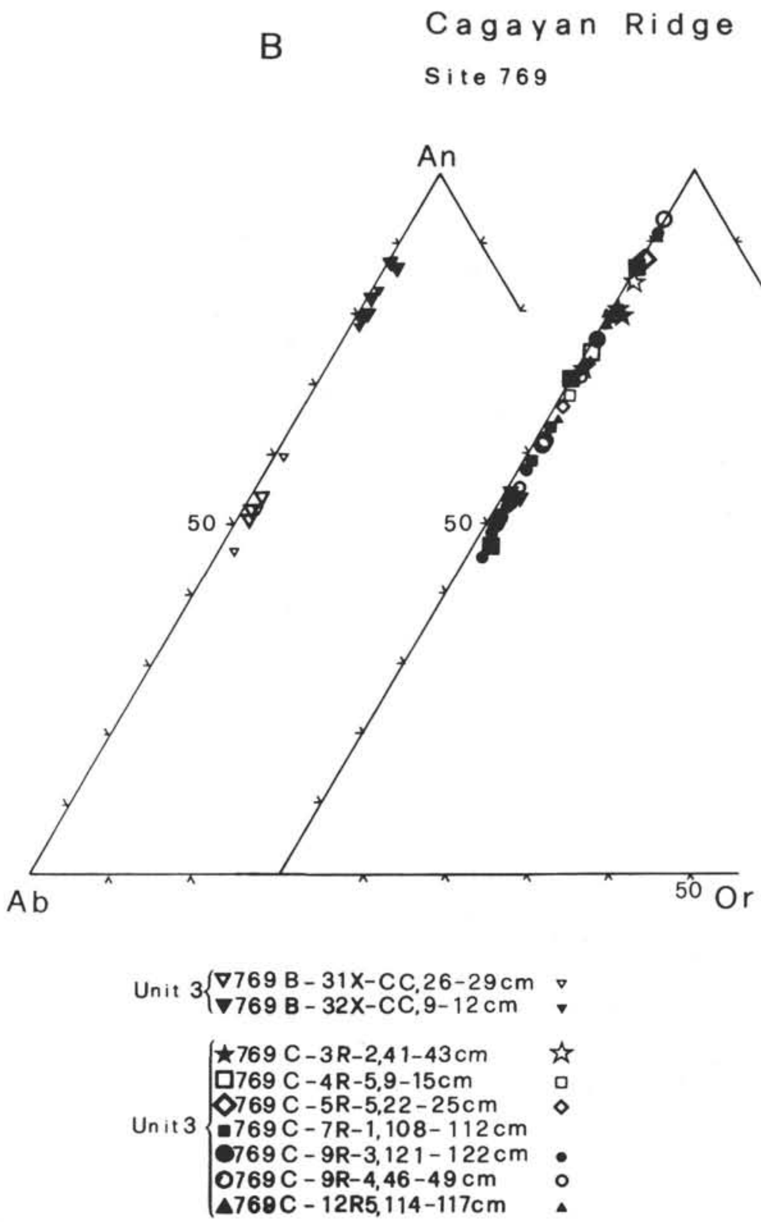



Figure 5. Plagioclase compositions of **A.** Sulu basement rocks and **B.** Cagayan Ridge volcanics in the Ab-An-Or diagram (mole%). Large and small symbols denote early and late crystals, respectively.

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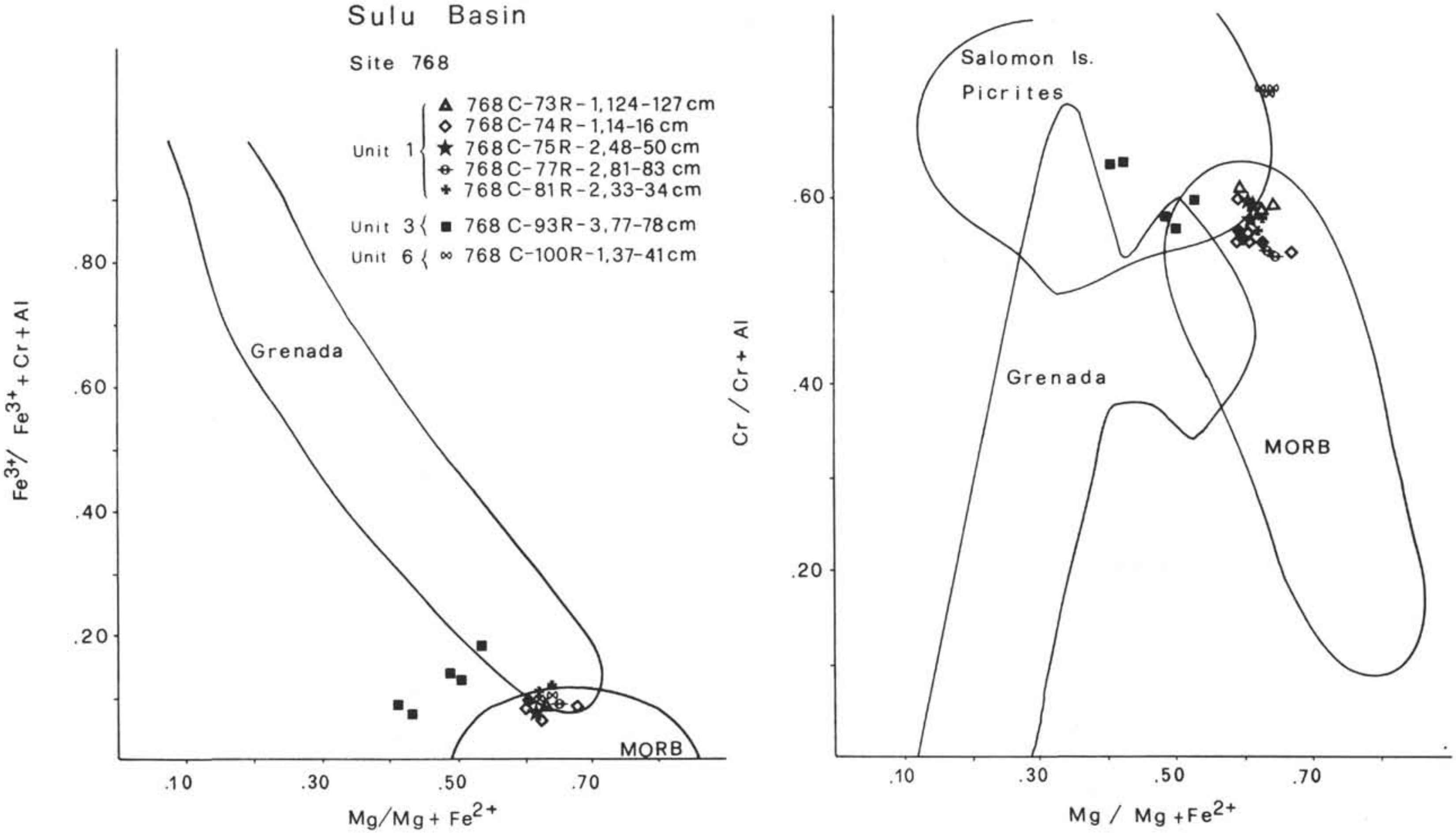


Figure 6. Cr-spinel composition of Sulu basement rocks in the Cr/(Cr+Al) vs. Mg/(Mg+$Fe^{2+}$) and $Fe^{3+}$/($Fe^{3+}$/Al+Cr) vs. Mg/(Mg+$Fe^{2+}$) diagrams (atom%). For comparison, fields for Cr-spinels from Salomon Island picrites, Grenada basanites, and MORB are also reported (after Crawford et al., 1986).

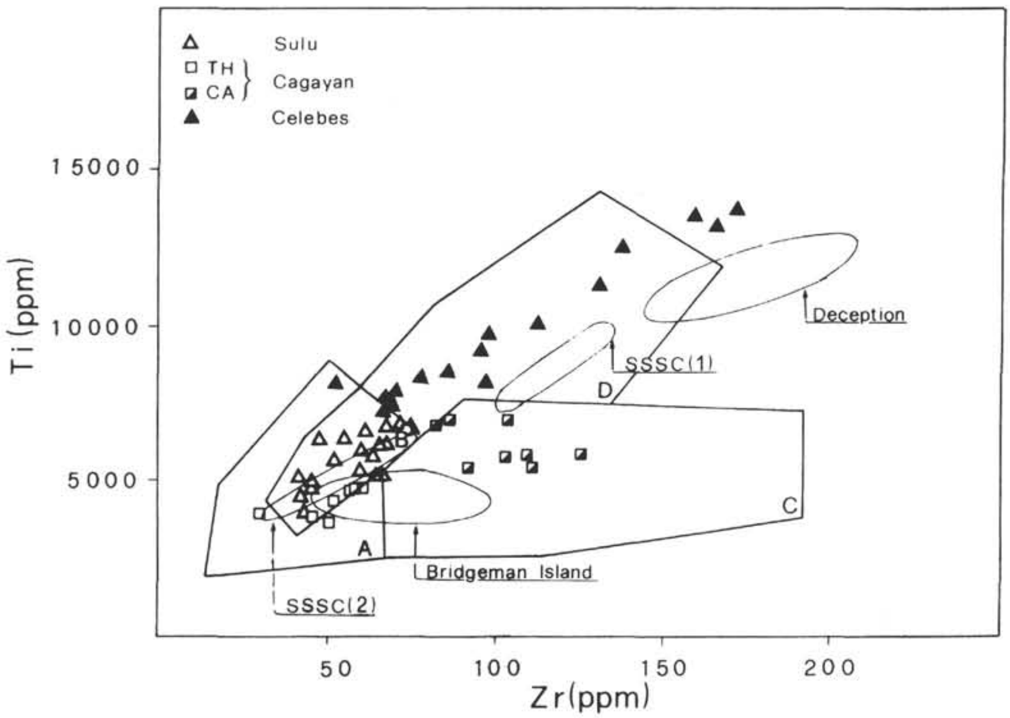


Figure 7. Ti-Zr discrimination diagram for basaltic rocks from Sulu basement (open triangles), Celebes basement (filled triangles), and Cagayan Ridge (open squares, tholeiitic; half-filled squares, calc-alkaline). Field A, B: island-arc tholeiites; B, D: ocean ridge basalts; B, C: calc-alkaline basalts (after Pearce and Cann, 1973). Back-arc basalts are reported for comparison: SSC1 and SSC1, south Sandwich spreading center dredges 20–23 and 22–24, respectively (East Scotia Sea); Deception and Bridgeman Islands, Branfield Strait (Antarctica), (after Saunders et al., 1980).

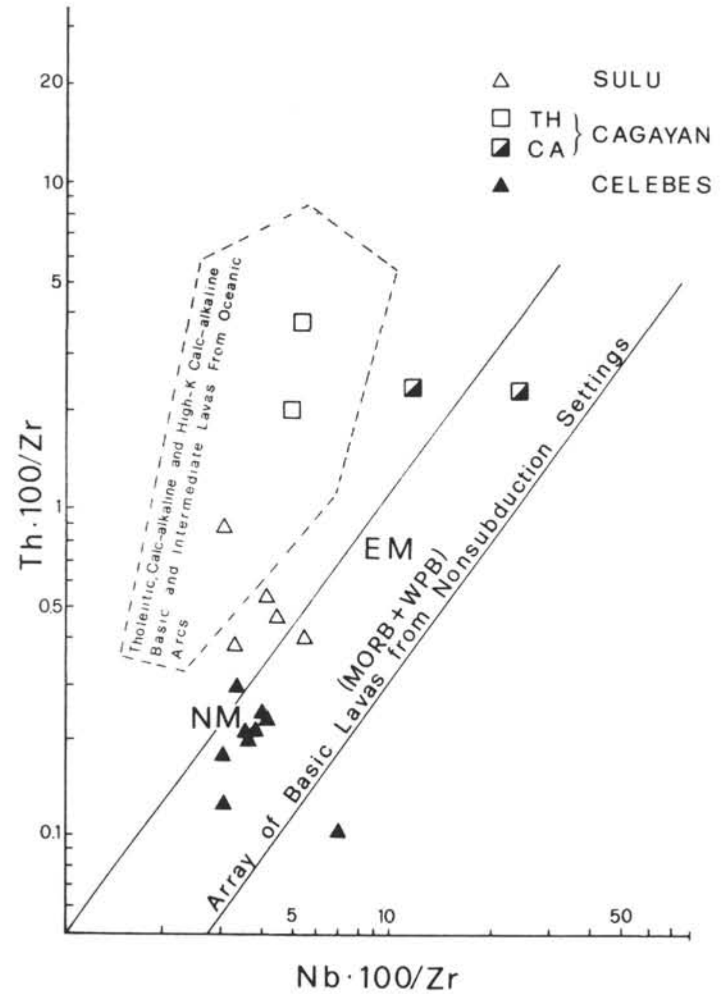


Figure 8. Th/Zr vs. Nb/Zr diagram for basaltic rocks from Sulu basement, Celebes basement, and Cagayan Ridge. Within-plate (WPB)/mid-ocean ridge (MORB) and convergent plate margin basic lavas are clearly discriminated (after Beccaluva et al., 1984). NM and EM, normal and enriched MORB, respectively. Symbols as in Figure 7.

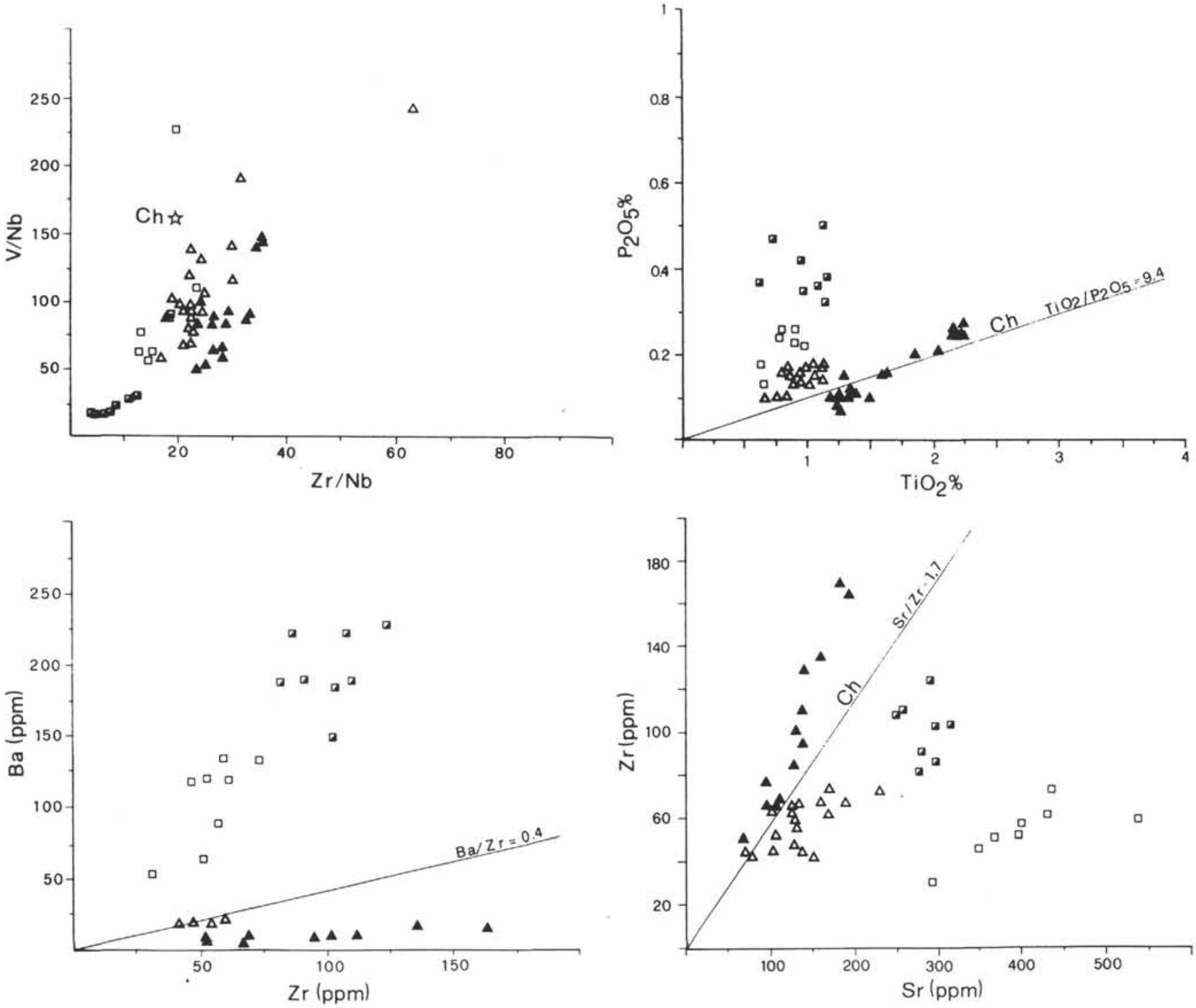


Figure 9. Binary diagrams for basaltic rocks from Sulu basement, Celebes basement, and Cagayan Ridge. Symbols as in Figure 7. Ch, chondritic values after Thompson et al. (1983) and Wood et al. (1979) for Ba.

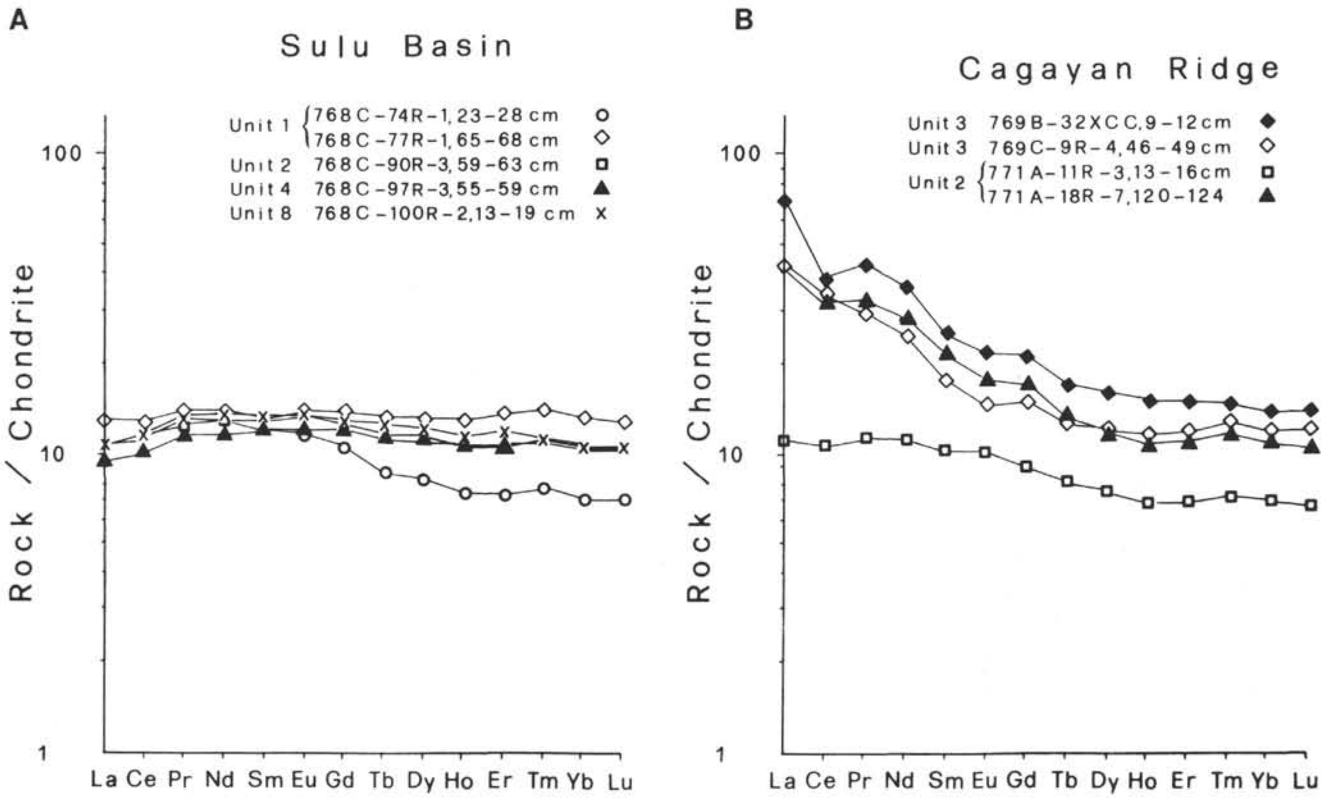


Figure 10. Chondrite-normalized REE patterns for **A.** Sulu basement rocks and **B.** Cagayan Ridge volcanics. Normalizing values according to Taylor and Gorton (1977).

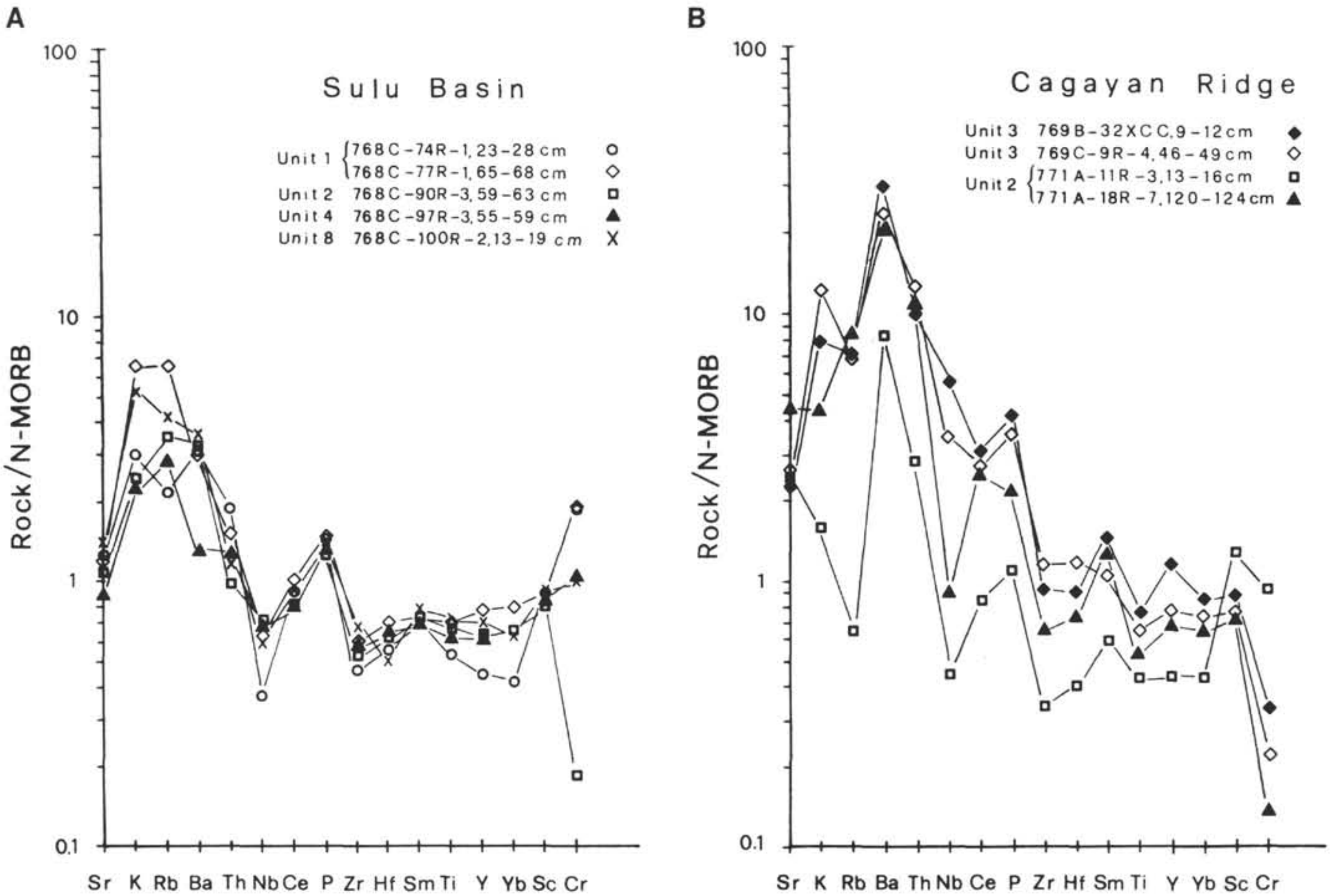


Figure 11. Normal MORB-normalized trace elements patterns for **A.** Sulu basement rocks and **B.** Cagayan Ridge volcanics. Normalizing values after Pearce (1982) and Sun and McDonough (1989) for Ba.

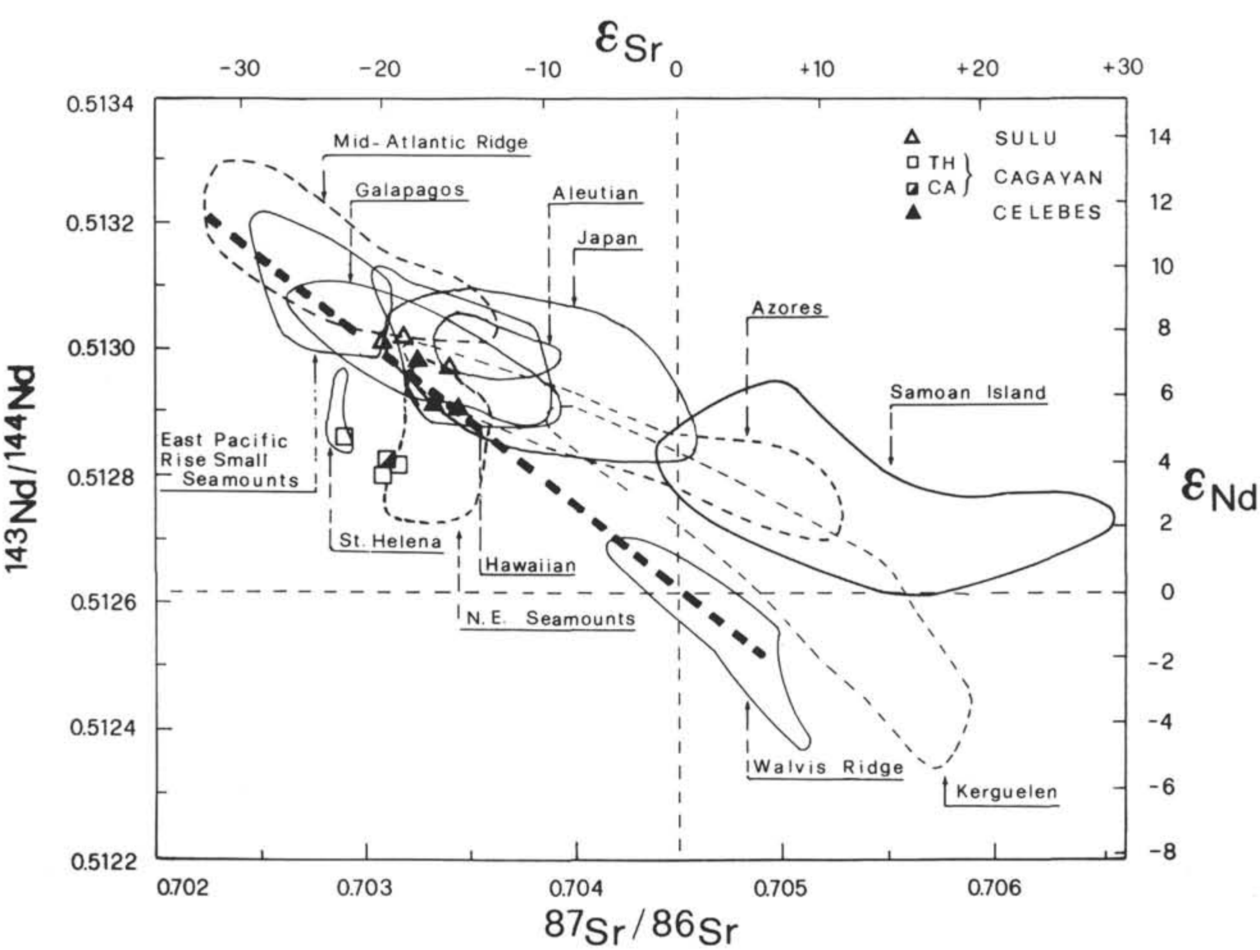


Figure 12. $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ diagram for basaltic rocks from Sulu Sea basement, Cagayan Ridge, and Celebes Sea basement. The mantle array and some compositional fields of MORB within oceanic plate and arc volcanism are reported (after De Paolo, 1988; Faure, 1986; Hart, 1988).