

22. GEOCHEMISTRY AND PETROGENESIS OF BASALTS FROM HOLES 767C, 770B, AND 770C, CELEBES SEA¹

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ABSTRACT

Major-, trace-, and rare-earth element analyses are presented from a suite of basaltic rocks from the basement of the Celebes Sea. The major elements and trace-elements were determined by X-ray fluorescence techniques, and the rare-earth elements were analyzed by instrumental neutron activation analysis. Compositionally the Celebes Sea basalts are very similar to typical normal mid-ocean ridge basalts, such as those described from the Indian Ocean triple junction. Petrogenetic modeling shows that all of the basalts analyzed can be formed by 10% to 20% partial melting of a light rare-earth element-depleted spinel lherzolite followed by fractional crystallization of mixtures of olivine, plagioclase, and iron oxide. The Celebes Sea is interpreted as a fragment of the basement of the Jurassic Argo abyssal plain trapped during the Eocene to the north of Australia.

INTRODUCTION

The origin of the Celebes Sea (Fig. 1), a small ocean basin, is in dispute. Lee and McCabe (1986) have suggested that it represents a trapped part of a once larger ocean basin, but it is also possible that the basin formed by back-arc spreading. There are commonly significant differences in the major- and trace-element compositions of volcanic rock suites erupted during the formation of a major ocean as compared to those formed in back-arc environments. Among the objectives of ODP Leg 124 was to use the nature and composition of the basement of the Celebes Sea, together with the data on the stratigraphy and sedimentology of the overlying sediments, to help determine its origin.

The major- and trace-element data published for the volcanic rocks making up the basement of the Celebes Sea (Shipboard Scientific Party, 1990), supplemented by additional trace- and rare-earth element (REE) data, are used in this study. The data, together with a summary of the mineralogy and petrography of basement samples recovered during Leg 124, are compared with the characteristics of well described suites which have erupted in known tectonic environments. The geotectonic significance, in the evolution of the southeast Pacific, of the origin of the Celebes Sea implied by this comparison, is evaluated.

PETROGRAPHY AND GEOCHEMISTRY

Recovery

Three holes, 767C, 770B, and 770C, were drilled to basement in the Celebes Sea, on ODP Leg 124. Only 42 cm of core, consisting of four pieces, were recovered from the basement of Hole 767C. About 53.18 m of igneous rocks were penetrated at the bottom of Hole 770B and core recovery averaged

47.0%; 106.30 m were penetrated at the bottom of Hole 770C with an average recovery of 42.8%.

The original subdivision of the basement rocks recovered from Holes 770B and 770C, was made using their lithological and structural characteristics (Shipboard Scientific Party, 1990, Fig. 14, pp. 359–369). Minor revisions have been made to the grouping of the rocks into units using more detailed mineralogical, petrographic, and geochemical characteristics, and geochemical logs (Shipboard Scientific Party, 1990, pp. 379–381). In the subdivision of the rocks recovered from Hole 770B, the original Units 2 and 3 are amalgamated into a new Unit 2, and the original Units 4, 5, and 6 are combined to make up the new Unit 3. In Hole 770C the only change made to the original subdivision involves the incorporation of original Units 3 and 4 into the new Unit 3. The original Units 5, 6, 7, 8, and 9 are renumbered as new Units 4, 5, 6, 7, and 8. The thicknesses and positions within the cores of the new units are described in Table 1.

Sample Description

The mode of occurrence of the samples from the basement of Hole 767C is indeterminate. The rocks consist of hypocrySTALLINE, cryptocrystalline to fine-grained basalts with variolitic, spinifex, fasciculate, and intersertal textures indicative of the rapid quenching of a superheated basaltic magma (Augustithius, 1979, pp. 65–67, and Walker et al., 1979, Fig. 5). Their groundmass comprises intergrown skeletal, lath, and prismatic crystals of olivine, plagioclase, clinopyroxene, and grains of Fe-Ti oxide in variable proportions, set in dense unresolvable mineral aggregates and devitrified glass. The olivines are commonly pseudomorphed by green and red clays whereas plagioclase and clinopyroxene appear to be unaltered. Vesicles are ubiquitous and generally filled with clays. Fractures filled with clay, carbonate, iron ore and chalcedony also occur.

The basement rocks recovered from Holes 770B and 770C occur as pillow lavas and pillow breccias, as massive, commonly brecciated lavas, as sills, and as very small dikes. All of the samples studied are basalts and their mineralogical and petrographic characteristics are summarized in Table 1. The majority of these rocks comprise plagioclase (An₆₀₋₇₀, estimated optically) and olivine phenocrysts set in a matrices of plagioclase (An₅₀₋₇₀), clinopyroxene, glass and/or devitrified mesostasis.

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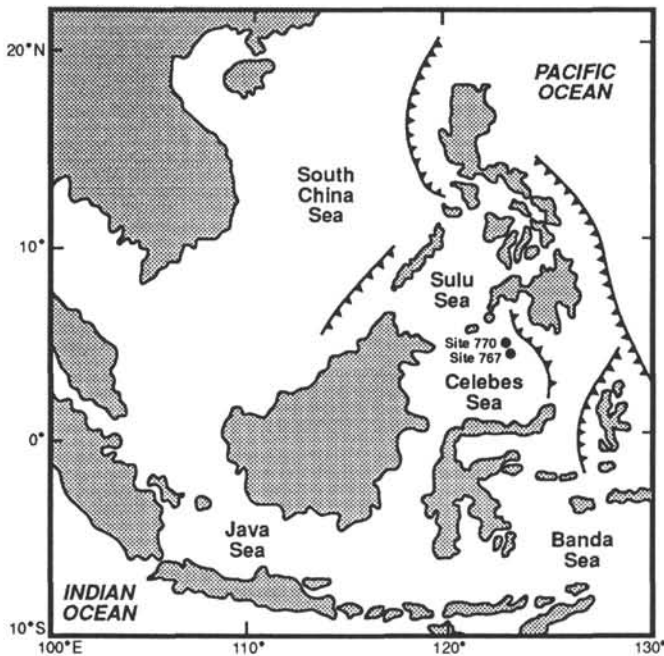


Figure 1. Simplified tectonic map showing the locations of Sites 767 and 770, Celebes Sea.

The phenocryst assemblages and petrographic characteristics of these rocks suggest that in the majority of cases crystallization started with olivine and plagioclase as the liquidus and near-liquidus phases. In Unit 6 the aphyric to plagioclase phyric dolerite (Table 1), plagioclase is on the liquidus. Following the crystallization of olivine and plagioclase phenocrysts, the remainder of the melt was quenched to yield a mixture of skeletal crystals of plagioclase, clinopyroxene, and iron oxide set in a glassy mesostasis, in all samples. The textures, mineralogy, and crystallization history of these olivine-plagioclase phyric basalts are typical of, but not exclusive to, mid-ocean ridge basalts (MORB's) (see Basaltic Volcanism Study Project 1981, pp. 134–138).

METHODS

Details of the shipboard analytic methods are given in Shipboard Scientific Party (1990, pp. 28–29). The additional trace-element analyses were carried out at Laurentian University using a Philips PW1400 X-ray Spectrometer. The rare-earth element contents were determined by instrumental neutron activation analysis (INAA) at X-Ray Assay Laboratories, Toronto. Full details of the methods are given in Abbott and Smith (1978) and Huang and Smith (1983) for XRF, and Peck and Smith (1989) for XRF and INAA.

The precisions of all of the additional trace-element determinations, calculated using the average standard deviation for each element for several replicate analyses, are 5%. The precisions of the REE determinations, calculated in the same manner, are 5% for La, Nd, Sm, Eu, Tb, Yb, and Lu, and 10% for Ce.

Comparison of the additional trace-element analyses with those determined on board ship shows excellent agreement for samples from the same units that have similar Mg-numbers, with two exceptions (Table 3). There are considerable differences in the Rb concentrations of similar rocks that may be the results of alteration and/or analytical error. Therefore, Rb is not used in the discussion below. The values of Nb in similar rocks agree well at concentration levels above 5 ppm, but at lower concentrations the shipboard values, are about

half of those determined at Laurentian University on similar samples (Table 3). Nb is immobile during the alteration of the rocks and these differences are the result of analytical error. The Laurentian values are more precise than those determined on board ship, which show large errors (Shipboard Scientific Party, 1990, p. 265), and are therefore used in evaluating the petrogenesis of the basalts.

ALTERATION

All of the samples studied have undergone mineralogical alteration (Shipboard Scientific Party, 1990, Hole 767C Table 17, Holes 770B and 770C Tables 10 and 11). The effects of this alteration on the chemical composition of the rocks are evaluated below. See Table 2. Sub-alkaline basalts generally contain <1.0% water and generally do not contain either normative nepheline (Ne) or corundum (C). Thus, basalt samples with >2.0% loss on ignition (LOI) and those containing normative C or Ne should not be used in classification or petrogenetic studies without justification. None of the samples recovered contains normative C and samples 2.5 and 3.1 (for sample numbers see Table 3) contain normative Ne (0.49% and 1.26%, respectively) (Shipboard Scientific Party, 1990, Holes 770B and 770C Table 15). Samples 3.1, 3.2, 3.5, 5.1, and 6.1 contain >2.0% LOI (Shipboard Scientific Party, 1990, Holes 770B and 770C Table 13). They are included in the study because their multielement patterns are essentially identical with samples containing <2% LOI (see below). In addition, these basalts may have formed in a back-arc basin environment and their higher than average volatile contents could be original (Saunders and Tarney, 1984; Rauterschliien et al., 1985).

Plots (Beswick and Sourcie, 1978) of the major-element chemistry, determined on board ship, of the basement rocks of the Celebes Sea suggest that there have been some changes in the composition of the volcanic sequence during alteration. The changes include slight increases in the original K_2O contents, and small decreases in the original Na_2O contents. The diagrams also suggest that the SiO_2 , MgO , CaO , and $Fe_2O_3^t$ (total iron expressed as Fe_2O_3) contents were relatively unaffected by alteration and are close to the original values (Fig. 2 contains two representative plots selected to illustrate the chemical changes that have occurred, See legend for further explanation).

The contents of Rb, Ba, Th, U, and Sr do not show systematic covariation with Zr or regular distribution on multielement plots. This suggests that these elements were mobile during alteration, and they are not used in the discussion below. The systematic covariation of the Nb, Y, P_2O_5 , TiO_2 , Ni, Cr, Sc, and the REE vs. Zr, as demonstrated by the consistent elemental ratios and REE and multielement distribution (Tables 3 and 4, Figs. 3 and 4), suggests that these elements have been relatively immobile during alteration (see also Condie 1977; Gelinis et al., 1982; Ludden et al., 1982; Kokelaar et al., 1984; Pearce et al., 1984; Saunders and Tarney, 1984; Condie et al., 1985). Their original concentrations are little changed, even where major elements have been altered. The immobile element compositions of the rocks showing the most mineralogical alteration lie in the middle of the range of the suite and have very similar trace-element distributions to less altered samples. This indicates that the small amounts of volatiles that may have been added to the compositions of these rocks have diluted, or increased, the concentrations of the immobile minor- and trace-elements by limited amounts.

CHEMISTRY

The contents of SiO_2 , $Fe_2O_3^t$, and MgO are used, together with the immobile minor- and trace-element contents and

Table 1. Summary of the mineralogy, petrography, and thicknesses of the lithological units identified in the basement of Holes 770B, 770C, Celebes sea.

UNIT	PHENOCRYSTS		GROUNDMASS		VESICLES/AMYGDALES			Filling	Percentage
	Size mm	Composition	Percentage	Composition	Percentage	Size mm	Shape		
Unit 1	Estimated thickness 18.42 m in Hole 770B (base at 18R-3, 74 cm), 19.54 m in Hole 770C (base at 4R-1, 14 cm). Moderately Plagioclase-Olivine Phyric Pillow Basalt Lavas and Breccias. Hypocrystalline, fine to medium grained, hyalopilitic, intersertal to intergranular.								
	Olivine	<1.0		An ₅₀₋₇₀	1-10	0.5-2.0	Spherical	Clay, Limonite	<2.0
	Plagioclase	<4.0			2-15		Lobate	Calcite, Silica	
	Clinopyroxene						Irregular		
	Mesostasis								20-80
UNIT 2	Estimated thickness 18.71 m in Hole 770B (base at 20R-3, 35 cm), 9.46 m in Hole 770C (base at 5R-2, top). Highly Plagioclase-Olivine Phyric Pillow Basalt Lavas and Breccias. Hypocrystalline, cryptocrystalline to fine-grained, intersertal, intergranular, and sub-ophitic.								
	Olivine	<3.0		An ₆₀	3-10	<1.0	Spherical	Clay, Calcite	<2.0
	Plagioclase	<5.0			10-20				
	Clinopyroxene								10-40
	Mesostasis								0-30
									0-70
UNIT 3	Estimated thickness 19.92 m in Hole 770C (base at 7R-1, 82 cm), >16.05 m in Hole 770B (base not reached). Moderate to Highly Plagioclase-Olivine Phyric Amygdaloidal, Brecciated Lavas. Hypocrystalline to holocrystalline, fine- to medium-grained, intersertal, intergranular, intrafasciculate and sub-ophitic.								
	Olivine	0.5-1.5		An ₅₀₋₆₅	1-10	0.5-3.0	Spherical	Iron Oxide	5-15
	Plagioclase	1.0-5.0			1-15		Lobate	Calcite, Clay	
	Clinopyroxene						Irregular		25-50
	Mesostasis								10-35
									5-20
UNIT 4	Estimated thickness 18.68 m in Hole 770C (base at 9R-1, top). Moderate to Highly Plagioclase-Olivine Phyric Pillow Basalt Lavas and Breccias. Hypocrystalline, cryptocrystalline, hyalopilitic and intersertal.								
	Olivine	0.5-2.0		An ₇₅	1-5	0.5-3.0	Spherical	Carbonate	1-10
	Plagioclase	1.0-3.0			5-15			Clay	
	Clinopyroxene								75
	Mesostasis								
UNIT 5	Estimated thickness 10.54 m in Hole 770C (base at 10R-1, 84 cm). Moderately Plagioclase-Olivine Phyric Basalt Lavas and Dikes. Hypocrystalline, fine-grained, intersertal and intergranular.								
	Olivine	1.0-2.0			5-10	1.0-3.0	Spherical	Calcite	1-3
	Plagioclase	1.0-2.0			2-5			Clay	
	Clinopyroxene								
	Mesostasis								
UNIT 6	Estimated thickness 11.10 m in Hole 770C (base at 11R-2, 74 cm). Sparcely Plagioclase Phyric to Aphyric Dolerite Sill. Hypocrystalline to holocrystalline, fine-grained, intersertal, intergranular and sub-ophitic								
	Olivine	1.0-2.0		An ₉₀	1-3	30-60			None
	Plagioclase					38-42			
	Clinopyroxene					20			
	Mesostasis								
UNIT 7	Estimated thickness 10.68 m in Hole 770C (base at 12R-3, 22cm). Sparcely to Highly Plagioclase-Olivine Phyric Dolerite Sill. Holocrystalline, fine-grained, intergranular.								
	Olivine	0.5-3.0		An ₇₀	1-15				None
	Plagioclase	1.0-3.0			0-5	36			
	Clinopyroxene					33			
	Mesostasis					10			
UNIT 8	Estimated thickness is greater than 6.38 m in Hole 770C (base not reached). Moderately to Highly Plagioclase-Olivine Phyric Basalt Lavas and Dikes. Hypocrystalline, fine-grained, intersertal and intergranular.								
	Olivine	0.2-10			3-5	0.5-3.0	Spherical	Calcite	6
	Plagioclase	1.0-4.0		An ₈₀	12			Clay	
	Clinopyroxene					26			
	Mesostasis					32			
						20			

ratios to classify the basement rocks. They show a very limited range of major-element composition (Table 2 and Shipboard Scientific Party, 1990; Hole 767C Table 18; Holes 770B, 770C Table 13) and strong similarities to average N-MORB composition (from Condie, 1985, Table 1). The SiO₂ contents range from 47% to 50%, thus all of the samples are basalts (<52% SiO₂; LeMaitre, 1976) chemically as well as petrographically, and their Nb/Y ratios (<0.25, Table 3) show that they are all sub-alkaline (Floyd and Winchester, 1978).

Using the classification of Yoder and Tilley (1962) the majority of the samples in Units 2, 3, 4, 7, and 8 are olivine-normative tholeiites, although a few quartz-tholeiites also occur. In Units 1, 5, and 6 all of the samples are quartz-normative tholeiites (Table 2 and Shipboard Scientific Party, 1990, Hole 767C Table 18, Hole 770B, 770C Table 15).

Two suites, each with its own distinct chemical characteristics, can be recognized geochemically (Tables 2, 3, 4, and Shipboard Scientific Party, 1990, Hole 767C Table 18, Holes

Table 2. The average major-element chemistry and normative mineralogy of the basaltic rock units from Holes 767C, 770B, and 770C, Celebes Sea.

Hole 770 Core, section Interval (cm) Suite	770C			770C	
Unit sample #	2	1	1	7R-5 3-6	7R-6 44-47 Int.
	1.Av	2.Av	3.Av	4.1	5.1
MAJOR ELEMENT COMPOSITION WT %					
SiO ₂	48.49	49.11	48.30	49.06	48.32
TiO ₂	2.26	1.24	1.40	1.29	2.26
Al ₂ O ₃	16.09	18.35	17.33	17.47	16.49
Fe ₂ O ₃	10.63	8.05	8.76	9.22	9.75
MnO	0.23	0.15	0.15	0.15	0.18
MgO	5.32	6.44	6.84	7.41	5.26
CaO	11.64	12.55	12.93	12.41	11.48
Na ₂ O	2.71	2.53	2.25	2.33	2.86
K ₂ O	0.23	0.19	0.33	0.36	0.20
P ₂ O ₅	0.25	0.10	0.11	0.10	0.24
LOI	1.84	2.79	4.59	2.77	0.31
Mg#	60.54	70.61	69.79	69.53	63.49
Al ₂ O ₃ /TiO ₂	7.12	14.80	12.38	13.54	7.30
CaO/TiO ₂	5.15	10.12	9.24	9.62	5.08
NORMATIVE MINERAL COMPOSITION %					
Q	2.75	0.39	0.00	0.00	2.70
Or	1.44	1.11	2.01	2.14	1.24
Ab	25.37	23.11	20.64	21.08	26.88
An	32.38	38.82	37.11	36.46	33.07
Di	20.89	19.05	22.26	19.96	19.93
Hy	9.24	12.62	12.30	13.17	8.24
Ol	0.00	0.00	0.35	2.23	0.00
Mt	4.10	2.92	3.10	2.94	4.12
Il	3.28	1.76	1.99	1.81	3.30
Ap	0.56	0.22	0.24	0.21	0.53

Hole 770 Core, section Interval (cm) Suite	770C		770C	767C	767C
Unit sample #	2	1	1	1	1
	6.Av	7.1	8.1		
MAJOR ELEMENT COMPOSITION WT %					
SiO ₂	49.73	47.74	49.06	48.03	49.08
TiO ₂	2.09	1.33	1.29	1.59	1.59
Al ₂ O ₃	16.09	15.71	17.47	16.87	16.76
Fe ₂ O ₃	8.59	10.61	9.22	11.98	9.90
MnO	0.18	0.22	0.15	0.29	0.31
MgO	6.27	8.74	7.41	4.99	5.35
CaO	11.71	11.87	12.41	12.07	12.84
Na ₂ O	2.71	1.79	2.33	2.51	2.28
K ₂ O	0.21	0.23	0.36	0.29	0.16
P ₂ O ₅	0.21	0.11	0.10	0.12	0.28
LOI	1.24	3.22	2.70	1.55	2.31
Mg#	71.29	68.99	69.53	50.94	57.40
Al ₂ O ₃ /TiO ₂	7.70	11.81	13.54	10.61	10.55
CaO/TiO ₂	5.60	8.92	9.62	7.59	8.08
NORMATIVE MINERAL COMPOSITION %					
Q	3.71	0.00	0.00	0.00	1.75
Or	1.28	1.40	2.14	1.76	0.96
Ab	25.14	16.51	21.08	23.55	21.31
An	32.16	35.12	36.46	35.47	36.49
Di	21.18	19.73	19.96	21.05	22.34
Hy	9.21	20.72	13.17	11.66	12.94
Ol	0.00	1.34	2.23	2.38	0.00
Mt	3.87	3.04	2.94	1.56	1.28
Il	3.00	1.90	1.81	2.32	2.31
Ap	0.45	0.24	0.21	0.27	0.61

770B, 770C Tables 13 and 14). The majority of samples (Units 2, 3, 4, 7, 8, and Hole 767C) fall into Suite 1, which is characterized by relatively high Al₂O₃ contents (16.49%–19.23%) and Mg-numbers (62.93–72.06) and low concentrations of incompatible minor elements (TiO₂, 1.18%–1.60%; P₂O₅, 0.07%–0.17%), and trace-elements (Nb, 2–5 ppm; Y, 26–36 ppm; Zr, 67–109 ppm; La, 2.8–5.1 ppm; Yb, 2.8–3.65 ppm). Most of the remaining samples (Units 1 and 6) fall into Suite 2, which is characterized by lower Al₂O₃ (15.67%–16.49%) contents and Mg-numbers (53.77–67.31), and higher incompatible element contents (TiO₂, 2.07%–2.32%; P₂O₅, 0.20%–0.27%; Nb, 6–9 ppm; Y, 41–45 ppm; Zr, 141–171 ppm; La, 7.9–8.1 ppm; Yb, 4.3–4.47 ppm) (Tables 2, 3, and 4, and Shipboard Scientific Party, 1990, Hole 767C Table 18, Holes 770B, 770C Tables 13 and 14) than those in Suite 1. The ranges of Al₂O₃ contents and Mg-numbers of the two suites overlap but those of the incompatible minor- and trace-element contents do not. The geochemistry of sample 5.1 is intermediate between that of Suite 1 and Suite 2. Its elemental concentrations may lie in the range of overlap of Suite 1 and Suite 2 (Al₂O₃, 16.49%) or between their ranges of concentration (Zr, 112 ppm; La, 5.3 ppm; Yb, 3.59 ppm), be typical of Suite 1 (Y, 35 ppm) or Suite 2 (TiO₂, 2.26%; P₂O₅, 0.24%; Nb, 8 ppm) contents (Tables 2, 3, and 4). All of the rocks analyzed are characterized by light rare-earth element (LREE)-depleted normalized patterns (Fig. 3). Both suites show limited ranges of Zr/TiO₂, Zr/Y, and primordial mantle normalized (La/Sm)_{PM}, (La/Yb)_{PM} ratios and have multielement patterns that lack any significant elemental anomalies (Tables 3 and 4, Figs. 3 and 4). The geochemical signatures of both suites of samples are compared in Table 5 to the characteristic signatures of the mean compositions of ocean-ridge and -floor tholeiites (OFT) (equivalent to N-MORB), oceanic and continental back-arc tholeiites (BAT), tholeiites from island-arcs and continental margins (LKT), enriched mid-ocean ridge basalts (E-MORB), and ocean island tholeiites (OIT) (all from Holm 1985, Tables 2 and 3), and transitional mid-ocean ridge basalt (T-MORB) (from Wood et al., 1979a).

The average composition of Suite 1 is similar in elemental concentration and degree of fractionation ((La/Yb)_{PM}, 0.66) to average OFT ((La/Yb)_{PM}, 0.67) (Table 5). Suite 2 has higher average concentrations of incompatible elements and a slightly less fractionated REE pattern ((La/Yb)_{PM}, 0.91) than those of average OFT (Table 5). The compositional ranges and REE patterns of both suites lie within that of Group 1 (depleted) MORB's (Bryan et al., et al, 1976, Table 3). Both suites have relatively high average Zr/Nb ratios (Suite 1, 28.00; Suite 2, 20.68), and low average Zr/Y ratios (Suite 1, 3.86; Suite 2, 3.55) and slightly LREE-depleted patterns ((La/Yb)_{PM} ratios above). These ratios for both suites (Table 5) lie within or close to the ranges typically associated with normal "depleted" MORB (Le Roex et al, 1983, p. 300, LREE depleted (La/Yb)_N, 0.35–1.1; Zr/Nb, 17–64; Zr/Y, 1.8–3.6).

The following differences are noted in comparison with the other characteristic suites. The average Nb to P contents of Suite 1 are similar to those of LKT, but the average Zr to Yb contents of Suite 1 are much higher than those of LKT, as are all average elemental contents of Suite 2 (Table 5). The LREE contents, (La/Sm)_{PM} (0.88), and (La/Yb)_{PM} (1.33) ratios of average BAT are much higher than those of Suite 1 (Table 5), and Suite 2 has much higher concentrations of all incompatible elements than average BAT (Table 5). Neither Suite 1 nor Suite 2 shows the negative Nb anomalies on primordial mantle normalized multielement plots (Fig. 4), which are typical of arc-related basalts. T-MORB (Zr/Nb, 9.19), E-MORB (Zr/Nb, 6.88) and OIT (Zr/Nb, 8.70) have much higher concentrations of Nb relative to Zr than both Suite 1 and Suite 2, and

Table 3. The trace-element contents and ratios of the basaltic rocks from Holes 767C, 770B, and 770C, Celebes Sea.

Hole 770 Core-Ssection Interval (cm) Suite Unit Sample #	B 16R-4 84-87 2 1.1	B 17R-3 134-137 2 1.2	C 2R-3 59-62 2 1.4	C 3R-2 125-128 2 1.5	2 1.Av
TRACE ELEMENT CONTENTS (ppm)					
V	331	342	335	348	339
Cr	206	228	222	234	223
Co			75	62	69
Ni	118	115	95	117	111
Cu	63	64	62	60	62
Zn	98	100	104	106	102
Rb	3	2	5	5	4
Sr	195	186	187	193	190
Y	44	45	44	45	45
Zr	165	171	165	168	167
Nb	6	7	9	7	7
Ba	5	3	7	62	19
TRACE ELEMENT RATIOS					
Zr/TiO ₂	0.0074	0.0074	0.0074	0.0074	0.0074
Zr/Y	3.75	3.80	3.75	3.73	3.76
Zr/Nb	27.50	24.43	18.33	24.00	23.07
Y/Nb	7.33	6.43	4.89	6.43	6.43
Mg#	54.97	53.77	57.03	57.38	

B 19R-1 99-102 1 2.2	B 19R-2 42-45 1 2.3	B 20R-2 102-105 1 2.4	B 20R-3 10-15 1 2.5	C 4R-1 27-30 1 2.6	1 2.Av
281	270	278	286	233	270
404	383	338	302	329	351
				54	54
150	144	154	205	132	157
76	78	80	74	68	75
87	76	69	72	75	76
3	3	1	1	3	2
111	107	111	108	124	112
31	29	26	28	31	29
70	67	69	69	84	72
3	2	2	2	4	3
24	5	24	9	6	14
0.0055	0.0057	0.0056	0.0057	0.0068	0.0058
2.26	2.31	2.65	2.46	2.71	2.48
23.33	33.50	34.50	34.50	21.00	27.62
10.33	14.50	13.00	14.00	7.75	11.92
63.86	62.93	71.87	72.06	64.45	

B 20R-4 135-140 1 3.1	B 21R-1 96-99 1 3.2	B 21R-4 7-77 1 3.4	B 21R-6 15-18 1 3.5	C 5R-2 49-51 1 3.6	C 6R-3 45-48 1 3.7
237	263	260	244	227	260
352	244	263	238	316	301
				60	59
104	249	190	152	136	116
93	73	80	76	81	74
84	78	81	78	75	87
2	9	6	6	10	11
114	129	138	141	111	139
29	31	33	31	29	34
72	86	97	95	79	100
3	3	3	3	5	5
1	28	16	13	36	4
0.0059	0.0062	0.0061	0.0064	0.0063	0.0065
2.48	2.77	2.94	3.06	2.72	2.94
24.00	28.67	32.33	31.67	15.80	20.00
9.67	10.33	11.00	10.33	5.80	6.80
67.44	67.92	65.22	66.16	66.52	65.30

Table 3 (continued).

1 3.Av	C 7R-5 3-6 1 4.1	C 7R-6 44-47 Int. 5.1	C 10R-2 43-47 2 6.1	C 11R-1 91-93 2 6.2	2 6.Av
213	280	290	317	335	326
245	320	298	230	235	233
60	74	73	66	70	68
135	136	95	109	110	110
68	39	54	67	65	66
69	94	93	104	94	99
6	10	13	6	4	5
110	132	141	158	158	158
27	34	35	43	41	42
76	109	112	152	141	147
3	5	8	8	8	8
14	8	1	49	45	47
0.0054	0.0084	0.0070	0.0073	0.0067	0.0074
2.83	3.21	3.20	3.53	3.44	3.49
24.05	21.80	14.00	19.00	17.63	18.31
9.00	6.80	4.38	5.38	5.13	5.25
	66.73	57.38	61.82	67.31	

C 12R-2 34-41 1 7.1	C 12R-3 64-66 1 8.1	767C 12R-CC 26-28 1	767C 12R-CC 36-39 1
270	227	386	344
387	322	344	353
64	68		
173	162	172	171
53	75	71	28
69	76	107	201
7	9	5	3
105	108	124	123
32	29	33	36
90	80	91	92
3	3	2	2
43	55	12	13
0.0068	0.0062	0.0057	0.0057
2.81	2.76	2.76	2.56
30.00	26.67	45.50	46.00
10.67	9.67	16.50	18.00
67.27	66.73	50.94	57.40

Note: Samples with Co values were determined at Laurentian University.

E-MORB ((La/Yb)_{PM}, 2.92) and OIT ((La/Yb)_{PM}, 4.15) have LREE-enriched patterns rather than the depleted patterns of both Suite 1 and Suite 2 (Table 5).

The Celebes Sea may be a trapped fragment of the Indian Ocean floor (Lee and McCabe, 1986). N-type (depleted) MORB, T-type (transitional) MORB, and P-type (plume or enriched) MORB suites have all been reported from the Indian Ocean, commonly in close association. The range of LREE-depleted immobile element compositions reported for Indian Ocean N-MORB's (Bryan et al., 1976, Fig. 5; Frey et al., 1980, Fig. 4; Subbarao and Reddy, 1981, Fig. 2; Le Roex et al., 1983, Figs. 2, 3, and 6; Price et al., 1986) is sufficiently large to include the total range of composition of both Suite 1 and Suite 2. Suite 1 is comparable to the N-MORB described by Price et al., 1986, Tables 4 and 5) from within 70 km of the Indian Ocean triple junction (IORa, Table 5). Suite 2 basalts are more difficult to classify. A detailed comparison shows that Sample 36-7 (IORb, Table 5) which is classified as an N-MORB (Le Roex et al., 1983, Table 2, pp. 271-272), is very similar in composition to the average composition of Suite 2, but has slightly more fractionated REE patterns ((La/Sm)_{PM}

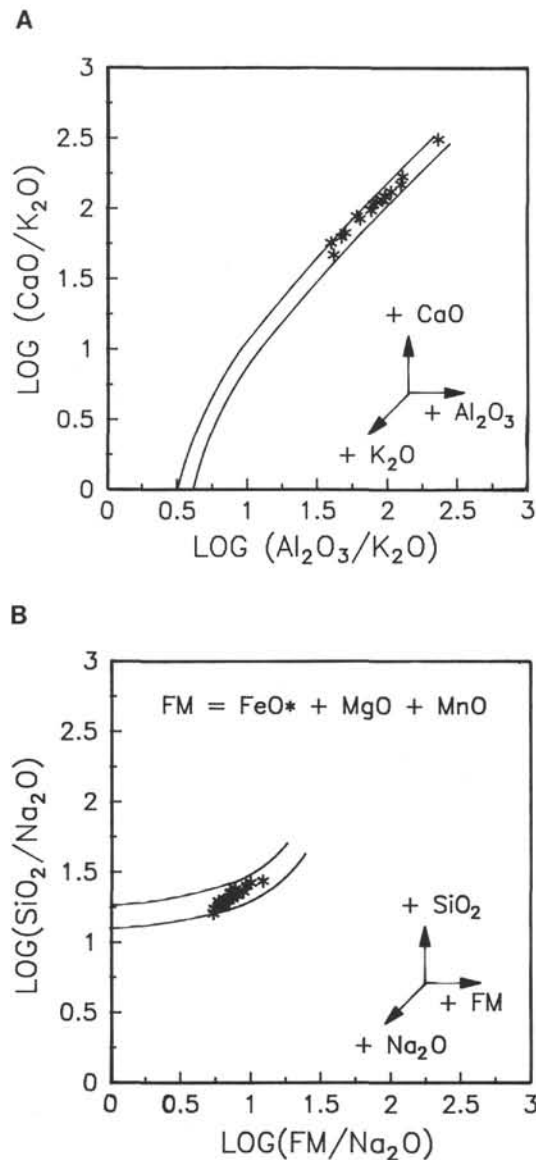


Figure 2. Selected Beswick and Soucie (1978) diagrams illustrating the chemical changes due to alteration of the rocks from Sites 767 and 770, Celebes Sea. The boundary curves enclose the fields of unaltered rocks and the arrows represent vectors of secondary enrichment. A. The log (CaO/K₂O) vs. log (Al₂O₃/K₂O) illustrates the increase in K₂O contents. B. The log (SiO₂/Na₂O) vs. log (FM/Na₂O) illustrates the increase in Na₂O contents.

1.01, (La/Yb)_{PM} 1.28). In addition, they have higher Zr/Nb and Y/Nb ratios (14–23, and 4.4–6, respectively) and lower (La/Yb)_{PM} ratios (0.79–0.98), as compared to typical ranges reported for T-MORB's from the Indian Ocean (Le Roex et al., 1983, Zr/Nb 7.7–11.8, Y/Nb 1.3–3.0, (La/Yb)_N 1.7–4.3). Price et al., (1986) report a suite of T-MORB's (IORc, Table 5) that occurs at distances of greater than 250 km from the Indian Ocean triple junction, which have lower concentrations of Nb, La, Sm, Ti, Y, and Yb, but more fractionated REE patterns ((La/Yb)_{PM} 1.27), than those of Suite 2. On balance, the rocks of Suite 2 are considered to be N-MORB's. Thus all of the rocks recovered from Holes 767C, 770B, and 770C are identified as N-type (depleted) MORB's.

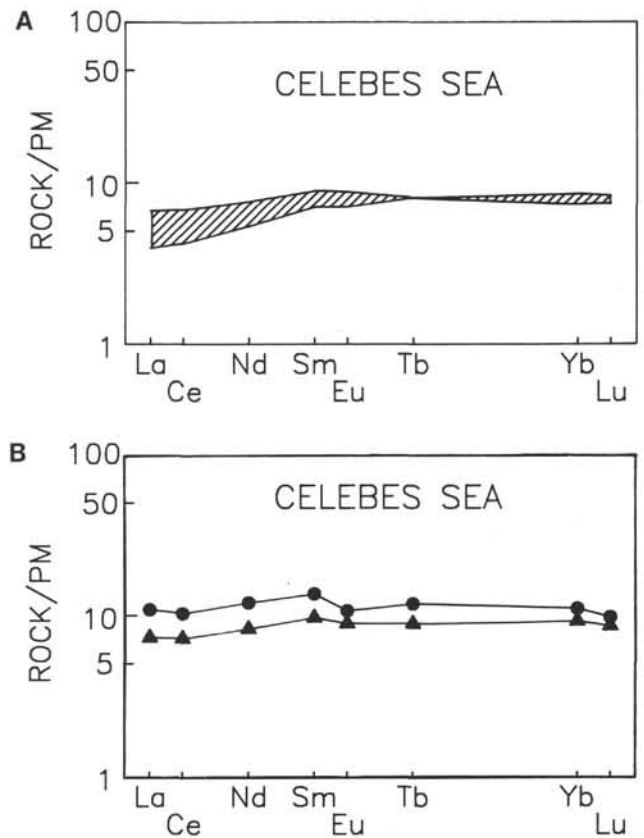


Figure 3. Primordial mantle-normalized (Wood et al., 1979a) rare-earth element plot of basaltic rocks from Sites 767 and 770. A. Shows the range of variation in Suite 1, lower limits defined by sample 2.3, upper limits by sample 3.5. B. Suite 2 sample 1.1 (solid circle), and intermediate sample 5.1 (solid triangle).

DISCUSSION

The purpose of this section is to show that all of the Celebes Sea basement rocks can be formed from one LREE-depleted source by processes similar to those generally considered to yield MORB's. Multielement plots of rock suites reflect the mineralogical and chemical composition of their source materials, as well as their partial melting, fractional crystallization, and mixing histories (Thompson et al., 1983). There are differences in the concentrations of the incompatible elements between Suite 1 and Suite 2 but their multielement distribution patterns are very similar (Fig. 4). This similarity suggests that they are genetically related (Thompson et al., 1986), and the differences in incompatible element concentrations may result from different partial melting histories and/or fractional crystallization histories. The effects of both of these processes can be identified in the basalts recovered from the Celebes Sea.

Suite 1 has systematically lower TiO₂ contents and higher Al₂O₃/TiO₂ and CaO/TiO₂ ratios and Mg-numbers than Suite 2 (Table 2). This inverse relationship, taken together with the similarities in their trace-element ratios, suggests that both rock suites were formed by different degrees of partial melting of the same, or similar, source materials (Sun et al., 1979 and Subbarao and Veddy, 1981). Higher degrees of partial melting progressively eliminate the major aluminium- and calcium-bearing phases from the mantle source, thus increasing the contents of Al₂O₃ and CaO and their ratios to TiO₂ in the melts. The concentrations of TiO₂ and other

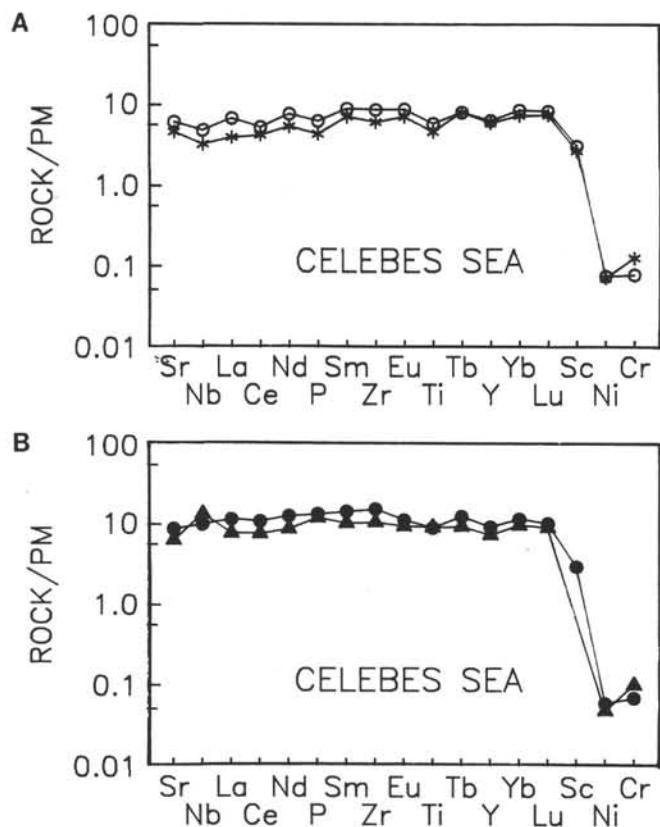


Figure 4. Primordial mantle-normalized (Wood et al., 1979a) multi-element plot of the basaltic rocks from Holes 767C, 770B, and 770C, Celebes Sea. A. Suite 1 unevolved sample 2.3 (asterisk), evolved sample 767C (open circle), B. Suite 2 sample 1.1 (solid circle), intermediate sample 5.1 (solid triangle).

incompatible elements are reduced in proportion to the degree of melting, thereby preserving the incompatible trace-element ratios in the resultant rocks (Suites 1 and 2). The presence of phenocrysts of olivine and plagioclase, in the basalts of both suites (Table 1), is evidence that fractional crystallization has affected the melts from which the rocks were formed. The rocks of Suite 1 are characterized by relatively high Mg-number (60 to 70) and low contents of TiO_2 (1.25%), P_2O_5 (0.10%), and incompatible trace elements. Suite 2 is characterized by lower Mg numbers (53 to 60) and high concentrations of TiO_2 (2.25%), P_2O_5 (0.25%), and incompatible elements (Tables 2, 3, and 4, and Shipboard Scientific Party, 1990; Holes 770B, 770C Tables 13 and 14). Such large differences in incompatible element contents, with such small differences in Mg numbers, cannot be produced by fractional crystallization. Within each suite there are small decreases in Mg-numbers coupled with small increases in incompatible trace-element contents and small decreases in compatible element contents (Tables 2, 3, and 4), which suggest that each suite has undergone a limited amount of evolution through fractional crystallization.

The complex stratigraphic relationships of Suites 1 and 2 are helpful in choosing the type of melting model. The two suites are interdigitated at various levels in the stratigraphic sequence (Table 1), and each suite occurs as pillow lavas, massive flows, and sills. Each suite is also characterized by different Mg numbers and different concentrations of trace elements. The multi-element patterns of the two suites do not cross. These relationships indicate that the rock suite cannot

Table 4. The rare-earth element contents and ratios of selected basaltic rocks from Sites 767 and 770, Celebes Sea. $(\text{La}/\text{Sm})_{\text{PM}}$ and $(\text{La}/\text{Yb})_{\text{PM}}$ are primordial mantle normalized ratios.

Hole 770	B	B	B	B
Core-Section	16R-4	19R-2	20R-2	20R-4
Interval (cm)	84-87	42-45	102-105	105-135
Suite	2	1	1	1
Unit Sample #	1.1	2.3	2.4	3.1
TRACE ELEMENTS (ppm)				
Sc	38	35		38
La	7.9	2.8	2.9	3.3
Ce	20	8	8	9
Nd	16	7	7	7
Sm	5.38	2.73	2.73	2.81
Eu	1.62	1.05	1.13	1.03
Tb	1.2	0.8	0.7	0.7
Yb	4.3	2.8	2.89	2.88
Lu	0.59	0.44	0.41	0.42
Th	0.3	0.6	0.2	0.3
U	0.7	0.1	0.1	0.5
ELEMENTAL RATIOS				
$(\text{La}/\text{Sm})_{\text{PM}}$	0.80	0.56	0.58	0.64
$(\text{La}/\text{Yb})_{\text{PM}}$	0.98	0.54	0.54	0.61
B	B	C	C	767C
21R-1	21R-6	7R-6	10R-2	12R-CC
96-99	15-18	44-47	43-47	26-28
1	1	Int	2	1
3.2	3.5	5.1	6.1	
39	40			48
4.1	4.8	5.3	8.1	5.1
11	10	14	18	11
9	10	11	15	10
3.13	3.44	3.82	5.01	3.8
1.18	1.3	1.35	1.85	1.39
0.8	0.8	0.9	1.2	1
3.05	3.26	3.59	4.47	3.65
0.44	0.49	0.52	0.66	0.54
0.2	0.2	0.2	0.4	0.2
0.3	0.2	0.2	0.1	0.2
0.71	0.76	0.75	0.88	0.73
0.72	0.79	0.79	0.97	0.75

be explained in terms of frequent replenishment and tapping of a magma chamber, as suggested by O'Hara (1977) to explain certain MORB suites, or by the selective dynamic melting model.

Tholeiitic magmas are generally considered to form by 15% to 30% partial melting of the mantle, although a few workers consider that all mantle-derived magmas form by very small degrees of partial melting (Thompson et al., 1984). Primordial mantle and chondrite compositions were tested as possible trace-element source compositions. Within the generally accepted limits of partial melting, the major, compatible (Ni, Cr, Sc), and incompatible trace-element contents (Zr, Nb, Y, Ti, and REE) can best be obtained by partial melting of a source with a primordial mantle trace-element composition (Wood et al., 1979a). Partial melting of sources having chondritic trace-element contents can only yield reasonable matches of the trace-element chemistry of the suites at less than 10% partial melting.

The modal mineralogy and the melting proportions of the source were based on the generalized models for the formation of MORB's (Condie, 1985, and Pearce, 1985) modified according to the Ni, Cr, and Sc contents of the resultant melts (Leeman, 1976). The major element contents and the distribution of Ni and Cr in the Celebes rocks (Hanson and Langmuir, 1978) suggest that Suite 1 and Suite 2 were formed

Table 5. A comparison of the average elemental contents and ratios of selected basaltic rocks from Suite 1 and Suite 2 Sites 767 and 770, Celebes Sea, with those of rock suites erupted in various tectonic environments. OFT, mean ocean floor tholeiites; BAT, mean back-arc tholeiites; LKT, mean low-potassium tholeiites; E-MORB, mean enriched mid-ocean ridge basalts; OIT, mean ocean island tholeiites, from Holm, 1985, Tables 2 and 3; T-MORB, transitional mid-ocean ridge basalt from Wood et al., 1979b; IORa, average N-MORB Indian Ocean triple junction, Price et al., 1986, Tables 4 and 5; IORb, N-MORB from Bouvet Fracture Zone, Le Roex et al., 1983, Table 2 (sample 36-7); IORc, average T-MORB 250 km from Indian Ocean triple junction, Price et al., Tables 4 and 5; IORd, T-MORB Islas Orcadas, Southwest Indian Ridge, Le Roex et al., 1983, Table 7 (average of samples 62-30 and 62-49). $(La/Sm)_{PM}$ and $(La/Yb)_{PM}$ are primordial mantle-normalized ratios.

	SUITE 1	SUITE 2	OFT	BAT	LKT	T-MORB
TRACE ELEMENTS (ppm)						
Nb	2	7.4	4.35	3.22	1.26	12.3
La	2.8	7.1	3.6	5.68	2.9	6.1
Ce	8	17.3	10.5	15	8.22	19
P	437	1037	615	669	470	960
Zr	112	153	96	105	37	113
Sm	2.73	4.7	3.19	3.5	1.65	4.71
Ti	7434	13286	8704	7635	4581	10431
Y	29	43	35	26.8	15.6	38.4
Yb	2.8	4.12	3.28	2.58	1.58	3.94
ELEMENTAL RATIOS						
$(La/Sm)_{PM}$	0.66	0.81	0.61	0.88	0.95	0.70
$(La/Yb)_{PM}$	0.66	0.91	0.67	1.33	1.11	0.83

	E-MORB	OIT	IORa	IORb	IORc	IORd
TRACE ELEMENTS (ppm)						
Nb	20.5	20	2.2	9.2	4.3	16.9
La	13.5	15.8	3.08	9.9	5.6	14
Ce	34	38	10.9	20.7	17.3	29.8
P	1175	1284	666	1048	1149	1069
Zr	141	174	93	154	139	145
Sm	5.4	6.24	3.04	4.98	3.52	4.67
Ti	12063	15728	7764	12230	6475	12050
Y	28.7	30.7	30.1	42	29	33
Yb	2.8	2.27	3.02	4.34	2.67	3.22
ELEMENTAL RATIOS						
$(La/Sm)_{PM}$	1.36	1.36	0.55	1.01	0.87	1.64
$(La/Yb)_{PM}$	2.92	4.15	0.55	1.28	1.27	2.63

respectively by approximately 20% and 10% batch partial melting of a peridotitic mantle followed by olivine fractionation. The flat HREE patterns point to partial melting of a spinel lherzolite source, and relatively low Ni and Cr contents are most readily produced when a small amount of spinel remains after the melt has been generated. Both rock suites contain phenocrysts of olivine and plagioclase.

The normalized ratios of the LREE's are lower than those of the heavy rare-earth elements (HREE) in all of the samples analyzed (Suite 1, $(La/Sm)_{PM}$ 0.66, $(La/Yb)_{PM}$ 0.66, Suite 2, $(La/Sm)_{PM}$ 0.81, $(La/Yb)_{PM}$ 0.91) and point toward the derivation of the melts from a LREE-depleted source. The HFSE, HREE, and incompatible element contents of the rocks were used to determine the percentages of partial melting and fractionation involved in their formation. The LREE contents of the primordial mantle source were then modified to produce the best overall fit for both suites. This approach produced a more realistic petrogenetic model than would be the case if source compositions were tailored to each suite individually (Thompson et al., 1986, p. 5989). Three samples, 2.3, 2.4, and Hole 767C, were chosen as representative of Suite 1 for modeling. The composition of the least-evolved rock in Suite 1 (2.3) can be produced by approximately 20% partial melting

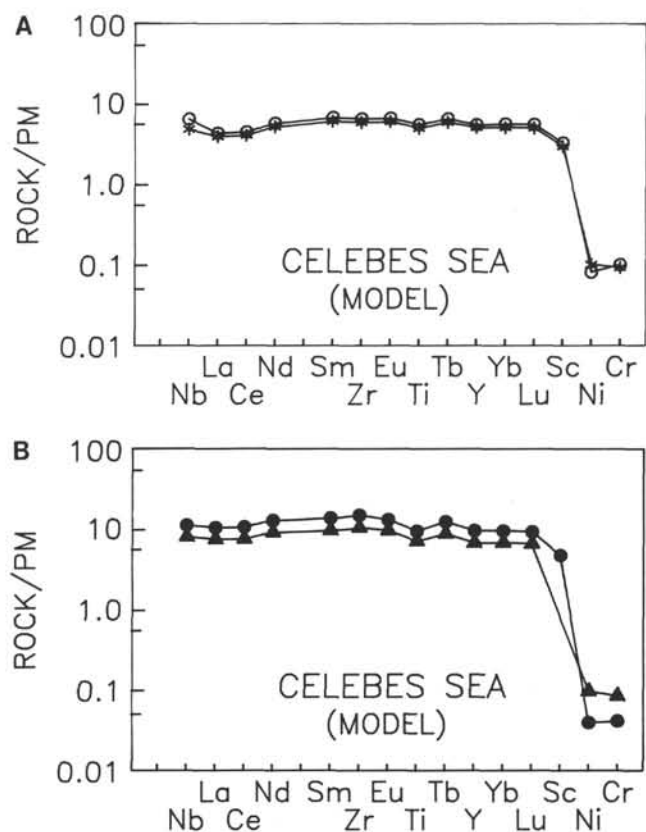


Figure 5. Primordial mantle-normalized plots (Wood et al., 1979) of the modeled compositions of selected samples compared with the measured values plotted in Figure 4. A, Suite 1 sample 2.3 (asterisk), and 767C (open circle), B, Suite 2 sample 1.1 (solid circle), and intermediate sample 5.1 (solid triangle) between the two suites.

of primordial mantle (Wood et al., 1979a) in which the LREE have been depleted, followed by 20% olivine fractionation. Sample 2.4, from Suite 1, may be produced by an additional 10% fractional crystallization of a 60:40 mixture of olivine and plagioclase. The most-evolved sample from Suite 1 was collected from Hole 767C and may be produced from sample 2.4 by an additional 30% of fractional crystallization of the 60:40 olivine:plagioclase mixture (Fig. 5A).

There is a limited range of variation in the trace-element composition in Suite 2 and sample 1.1 is chosen as representative for modeling. This sample has a relatively low Mg number and may be modeled in terms of 10% partial melting of the LREE-depleted primordial mantle source, followed by two stages of fractional crystallization, 20% removal of olivine, and 30% removal of a mixture of olivine (58%), plagioclase (40%), and magnetite (2%) (Fig. 5B).

Details of the model used are as follows.

All modeled melts are formed from the same spinel lherzolite source by different degrees of partial melting and fractional crystallization. Source mode ol 60%, opx 26%, cpx 12%, sp 2%. Source elemental composition is LREE-depleted primordial mantle (Wood et al., 1979b). Depletions are La 63%, Ce 66%, and Nd 85% of Wood's values. Suite 1 is formed by 20% partial melting (residue ol 73%, opx 25%, cpx 0%, sp 3%) followed by 20% fractional crystallization of ol to yield 2.3. The composition of 2.4, which is not illustrated, can be formed from 2.3 by 10% more fractional crystallization of the olivine plagioclase mixture. A further 30% fractional crystallization of ol 60% plus pl 40% yields 767C. Suite 2 is

Table 6. Distribution coefficients used in the modeling calculations after Arth (1976), Irving (1978), Pearce and Norry (1979), and Condie (pers. comm.).

Mafic	Ol	Opx	Cpx	Pl
La	0.00001	0.007	0.070	0.150
Ce	0.00001	0.008	0.100	0.120
Nd	0.00007	0.010	0.220	0.081
Sm	0.00060	0.020	0.400	0.067
Eu	0.00100	0.020	0.400	0.350
Tb	0.00200	0.050	0.500	0.060
Yb	0.02000	0.150	0.600	0.070
Lu	0.01600	0.180	0.600	0.060
Y	0.01000	0.010	0.200	0.030
Zr	0.01000	0.030	0.030	0.010
Nb	0.01000	0.010	0.020	0.010
Ti	0.02000	0.100	0.180	0.040
Ni	5.00000	3.100	2.500	0.000
Cr	0.10000	5.000	15.000	0.000
Sc	0.16000	0.160	0.510	0.040

Gnt	Spl	Hbd	Mgt
0.030	0.000	0.200	0.000
0.030	0.000	0.260	0.000
0.087	0.000	0.400	0.000
0.220	0.000	0.700	0.000
1.000	0.001	0.800	0.000
3.000	0.002	0.800	0.000
5.000	0.020	0.600	0.000
5.500	0.016	0.500	0.000
2.000	0.010	1.000	0.200
0.300	0.010	1.500	0.100
0.100	0.010	0.800	0.400
0.300	0.800	1.500	7.500
5.100	16.000	7.000	30.000
17.500	600.000	15.000	150.000
2.270	2.000	1.500	2.000

formed by 10% partial melting (residue ol 66%, opx 26%, cpx 7%, sp 2%) followed by 20% fractional crystallization of ol, and 30% fractional crystallization of 58% ol, 40% pl, and 2% mt yields 1.1. Intermediate rock 5.1 is formed by 14% partial melting, followed by 20% fractional crystallization of ol and a further 40% fractional crystallization of a mixture 59% ol, 40% pl and 1% mt. Distribution coefficients used in the modeling are given in Table 6; Abbreviations: ol olivine, opx orthopyroxene, cpx clinopyroxene, sp spinel, pl plagioclase, mt magnetite (magnetite is used in the calculations in the absence of partition coefficients for Fe-Ti oxide).

Sample 5.1 is intermediate in its trace-element characteristics between Suite 1 and Suite 2. Its composition may be matched by 14% partial melting of the same LREE-depleted primordial mantle, followed by 20% removal of olivine and a further 40% removal of a 60:40 mixture of olivine and plagioclase (Fig. 5B).

Thus the basalts making up the basement of the Celebes Sea are similar to N-MORB's in composition. The variations in their chemistry can be accounted for in terms of different degrees of partial melting of a spinel lherzolite source having a LREE-depleted primordial mantle trace-element composition and different percentages of fractional crystallization of olivine/plagioclase mixtures. These processes are typical of those generally believed to be involved in the evolution of MORB's.

MORB-CELEBES COMPARISON

The MORB-like characteristics of these samples support the contention that the Celebes Sea was once continuous with the late Jurassic Argo abyssal plain, as suggested by Lee and McCabe (1986) on the basis of magnetic anomalies, heat-flow

rates, and bathymetry. In the same study Lee and McCabe (1986) suggested that the Banda Basin to the south, and the Sulu Sea to the north, of the Celebes Sea were also relics of a Cretaceous-Eocene oceanic crust. They suggested that it was possible to identify magnetic anomalies 30 to 33 in the Celebes Sea, indicating that the basin was formed in the Paleocene (65-72 m.y. BP). However, the basaltic basement of the Celebes Sea is directly overlain by radiolarian-bearing red pelagic clay containing fish teeth and manganese micronodules of middle Eocene to Upper Oligocene age. This confirms that the magnetic anomalies present are numbers 18-20 (42-47 m.y. BP Weissel, 1980) and that the basin was formed during Eocene times. Rangin (1989) has suggested that the Sulu and Celebes basins have different origins. He used onshore and offshore data to show that the Celebes plate subducted northward beneath a continental margin, along which an Oligocene-to-early Miocene arc developed. This arc rifted to form the Sulu Sea basin by back-arc spreading, leaving the Cagayan Ridge as a remnant (inactive) arc. Drilling in the Sulu Sea basin has produced data that confirm that it is a back-arc basin formed in late early Miocene times, and that continental arc volcanism ceased on the Cagayan Ridge more or less simultaneously with the formation of the basin, and it became a remnant arc (Smith et al., this volume). The identification of middle Eocene N-MORB basalts in the Celebes Sea, and of middle Miocene back-arc tholeiites in the Sulu Sea strongly support Rangin's (1989) interpretation.

CONCLUSIONS

The basement of the Celebes Sea comprises a series of middle Eocene basaltic rocks having N-MORB-like compositions, very similar to rocks formed at the Indian Ocean triple junction. This fact suggests that the basement represents a trapped fragment of a once larger ocean basin. Regional considerations suggest that the Celebes Plate subducted to the north beneath the edge of the Eurasian continental plate, and that this motion led to the formation of the Sulu Sea by back-arc rifting during the middle Miocene.

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