32. PETROCHEMISTRY AND GEOCHEMISTRY OF BASALTS IN THE SHIKOKU BASIN AND DAITO BASIN, PHILIPPINE SEA

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ABSTRACT

Tholeiitic basalts cored during Deep Sea Drilling Project Leg 58 in the northern Philippine Sea vary in composition: in Hole 443, they correspond to mid-ocean-ridge basalts; in Hole 446A, they correspond to ferrobasalts. There is also a respective increase in degree of differentiation of the parent magma of each type of basalt, with eventual accumulation of iron, titanium, and alkali. The behavior of major and minor elements agrees with an in-chamber magma differentiation. The low magnesium content of the off-ridge basalts in the Shikoku Basin (Hole 442B) is assumed to represent a special case of off-ridge basalts. Ferrobasalts of the Daito Basin clearly indicate that this type of rock occurs extensively among sea-floor basalts. These are also found among continental plateau basalts and as the final products of differentiation of tholeiitic intrusions (ferrogabbros). Hornblende in the ferrobasalts indicates a relatively high water content (as much as 3%) in the magma. Basalts in Hole 442B do not contain hornblende, which may be attributed to a higher magma temperature.

INTRODUCTION

Drilling into the ocean floor in the northern Philippine Sea has yielded information ample for studying the composition and evolution of a basalt magma within the Shikoku Basin and Daito Basin. A total of 583 meters was drilled in basalts, of which 28.5 meters was drilled in Hole 442A, 163 meters in Hole 442B, 120 meters in Hole 443, 44.5 meters in Hole 444A, 25 meters in Hole 446, and 180 meters in Hole 446A. Holes 442A, 442B, 443, and 444A were drilled in the Shikoku Basin, whereas Holes 446 and 446A were drilled south of the Daito Ridge, which is an ancient remanent arc west of the Kyushu-Palau Ridge.

Approximately 100 samples were studied under the microscope and analyzed by different methods (chemical analysis, X-ray fluorescence, atomic absorption, emission spectroscopy, gamma spectroscopy) for major, minor, and rare elements. A certain degree of rock alteration was recognized, and it was the freshest basalt samples which were selected for further investigation. Petrochemical and geochemical characteristics of the rocks are presented, average basalt compositions are compared, and magma differentiation is considered.

Basalts from Holes 442B, 443, and 446A were regarded as most representative. In addition, information from Holes 444A and 446 was used. Basalts from Hole 442A are not considered because of intensive alteration.

PETROGRAPHY

Site 442

Basalts from Holes 442A and 442B are characterized by high vesicularity (as much as 30%), by intensive oxidation, and by calcite deposition, in veinlets and vesicles. The upper 59 meters of the basalts in Hole 442B is represented by aphanitic to medium-grained, aphyric varieties. Rock texture is intersertal, intergranular to subophitic. Less common (Hole 442B) are sparsely phyric basalts with phenocrysts of plagioclase and extremely rare clinopyroxene. Two basalts have spherulitic texture, with randomly distributed plagioclase spherulites in a cryptocrystalline groundmass with plagioclase and clinopyroxene microlites.

The lower units of Hole 442B (102 m below a sedimentary-rock interlayer) are pillow basalts, which are actually cobbles with a glass rind up to 10 mm thick. The internal parts of the pillow basalts are rocks with intersertal and, less commonly, intergranular texture. A variolitic texture, 1 to 2 mm thick, which is typical of pillow basalts, is formed at the contact with the glass rind.

Plagioclase (An_{60-70}) and clinopyroxene (augite) are the principal rock-forming minerals of the basalts in Hole 442B. There is no olivine, and ore minerals are subordinate.

Site 443

Lava flows from Hole 443 are primarily phyric basalts, with subordinate pillow basalts. The latter are confined to the lowermost part of the section, where they are intercalated with the lava flows (Site 443 report, this volume). Vesicularity of the flows is 0 to 5 per cent; it reaches 30 per cent in the pillow basalts. The vesicles are filled by calcite, smectite, and occasionally by wellformed pyrite octahedrons. The rocks have a fine- to medium-grained texture, with plagioclase phenocrysts (An₆₀; as much as 20%) and, less commonly, olivine (Fo₇₅₋₈₅) phenocrysts.

The groundmass texture varies from cryptocrystalline and intersertal in flow contact zones to intergranular and subophitic in the central parts of flows, which are mostly well crystallized. The groundmass is composed of plagioclase (30-50%), clinopyroxene (20-45%), olivine (0-15%) and ore minerals (2-7%). Depending on basalt texture, glass content varies from 5 or 10 per cent to 90 per cent. Olivine is essentially replaced by an aggregate of serpentine and talc; glass is palagonitized.

The thickest flows exhibit a melt differentiation, that is, olivine content increases toward the flow bottom.

The pillow basalts, compared to those of Hole 442B, have a more-devitrified glass rind. Their internal parts are composed of rocks with intersertal and intergranular textures. In mineral composition, these rocks are similar to the flow basalts.

Site 444

Hole 444A penetrated a sill, 12 meters thick, separated from underlying basalts by a 20-meter sequence of sedimentary rocks. The sill is aphyric and mediumgrained, with a texture ranging from intersertal at the contacts to intergranular and diabasic in the central parts. The rock consists of plagioclase (An₆₀₋₈₀; 30%), augite (20–25%), olivine (1–15%), magnetite (2–3%), and groundmass (30–45%) which contains chlorite, clays, and actinolite. Olivine content increases from top to bottom (from 1 to 15%), which indicates magma differentiation in the process of sill formation.

The basalts below the 20-meter unit of sedimentary rocks are plagioclase phyric varieties with a plagioclase phenocryst content (An₆₀) of 2 to 30 per cent. The basalts have intergranular to diabasic texture and are composed of plagioclase (An₇₀, 30–50%), augite (25–30%), olivine (1–10%), and magnetite (1–5%); the groundmass is composed of a fine-grained aggregate of chlorite, clay, and (apparently) actinolite.

Site 446

Basalts in Holes 446 and 446A occur as sills 0.3 to 22 meters thick in the sedimentary-rock sequence; they were encountered at sub-bottom depths of 384 to 628.5 meters. These basalts are massive and are characterized by chilled zones both at the top and bottom, fine- to medium-grained texture, and generally low vesicularity (0-10%, on the average 3%). However, in a number of cases vesicularity increases to 15 to 30 per cent (Site 446 report, this volume).

The basalts are essentially aphyric, with intersertal and intergranular texture. They contain as much as 35 per cent plagioclase (An_{60-80}) , 25 per cent clinopyroxene, and 20 per cent titanomagnetite. Basalts with a high vesicularity (15–30%) contain as much as 15 per cent hornblende, which is confined to well-formed grains in the groundmass (glass), filling spaces between clinopyroxene grains. This may be vividly exemplified by basalts of Section 446–13–1, 17 cm, where the slightly devitrified groundmass (60%) contains only large crystals of titaniferous clinopyroxene and smaller, but well-formed hornblende grains. This, and the magmatic nature of the amphibole, points to crystallization of magma with the removal of pyroxene and, subsequently, hornblende from the melt, evidently without crystallization of plagioclase in the early stages of the process.

Olivine has not been found in Hole 446A basalts. However, a number of sills apparently contain pseudomorphs of secondary minerals after olivine.

ORE MINERALS

The most common ore minerals in the basalts are titanomagnetite, pyrite, chalcopyrite, and native copper.

Titanomagnetite forms irregular, platy, skeletal and dendritic grains. The latter occur primarily in the basalts of Hole 446A. The mineral is generally single-phase, without exsolution structures. However, there are occasional two-phase grains with titanomagnetite in the center and magnetite at the periphery (Section 442B-6-3, 27 cm). In some cases, zoned and polysynthetic aggregates are found (Section 442B-8-1, 80 cm). In addition, the basalts have some magnetite impregnated in silicates.

Sulfides (pyrite, chalcopyrite) are represented by irregular grains and droplets. The grains are confined to interstices and, in certain cases (pyrite), to vesicles, where they may have considerable size (as much as 1.5-2 mm). Chalcopyrite is occasionally crystallized along with titanomagnetite. Almost all the basalts contain drop-like sulfide inclusions, indicating immiscibility of sulfide and silicate melts. These are found both in interstices and within rock-forming minerals (for example, in plagioclase).

Native copper commonly occurs as fine, reddish grains and is apparently a secondary mineral formed by sulfide oxidation and redeposition of copper by solutions forming carbonate veins in the basalts.

METHODOLOGICAL PROBLEMS

To arrive at reliable petrochemical and geochemical conclusions, particular attention was paid to analysis quality. For this purpose, 18 of 30 elements were analyzed by two or even three independent methods. For example, major elements were analyzed by X-ray fluorescence and (60% of the samples) by chemical methods. Copper, nickel, cobalt, vanadium, and strontium were analyzed by atomic absorption and spectrochemical methods. Phosphorus and chromium were analyzed by atomic absorption, X-ray fluorescence, and spectrochemical methods. Comparison of the obtained data has shown good agreement.

For petrochemical analysis, we have primarily utilized chemical data, with subordinate (40%) application of the X-ray-fluorescence results.

Rock alteration and sample representativeness are additional principal problems.

Almost all the oceanic basalts have been subjected to various degrees of reaction with sea water, hydrothermal alteration, and metamorphism. The total effect of these superimposed processes may be considerable, sometimes greatly changing the initial chemical composition of rocks. For instance, even low-temperature interaction of sea water and pillow basalts within a distance of 2 cm from the chilled zone represented by a glass rind results in removal of more than 1 per cent magnesium and in a doubling of the potassium content (Table 1, sample from Hole 442B; see also Nisterenko et al., this volume).

Sometimes even more conspicuous are the intensively altered internal parts of pillow basalts, where addition of potassium is also observed (Table 1, sample from Hole 443). Iron is strongly oxidized in this process. The intensive removal of silica from basalts, previously noted by Hart (1976), is not clearly evident in these rocks, which are slightly bleached near the chilled (glass) zone and considerably altered (gray-yellow color) in the internal parts of the pillow basalts.

Alteration results from interaction of the basalts with sea water, formation of palagonite, and replacement by low-temperature secondary minerals such as smectite and zeolites with high potassium and low magnesium content (Frey et al., 1974). An increased calcium content is accounted for by deposition of calcite in veinlets and vesicles. No interrelation between element distribution and water content, which may be a rock-alteration index, has been ascertained for Shikoku and Daito basalts (Hart, 1976).

There is a close interdependence between calcium and carbon-dioxide concentration (Figure 1). This apparently points not only to calcite deposition in the rocks whose content increases proportional to carbon dioxide concentration, but also, as is shown in Table 1, to an apparent supply of alkali to the rock and magnesium removal.

Norms of these basalts show nepheline., i.e., they shift to the alkali zone. As shown in Figure 1, we have taken 0.3 per cent carbon-dioxide concentration as the upper limit for unaltered (slightly altered) basalts. All the analyses for Hole 442A and some of those for other holes (see appendix) are thus excluded.

Also important is sample representativeness. This problem warrants particular investigation, because

TABLE 1 Chemical Compositions of Fresh Basaltic Glass and Altered Pillow Basalt

	Sample 442B	-10-1, 118	-121 cm	Sample 4 105-10	43-57-2,)8 cm	Sample 443-57-2, 114-118 cm			
	Glass Rind of Pillow Basalt	Pillov (1-2 c glas	v Basalt :m from s rind)	Glass R Pillow	lind of Basalt	Inner part of Pillow Basalt (10 cm from glass rind)			
Major Oxides (%)	X-ray fluor	escence	Chem- ical	X-ray fluo- rescence	Chem- ical	X-ray fluo- rescence	Chem- ical		
SiO ₂	50.20	49.20	48.40	49.60	48.70	49.90	47.10		
TiO2	1.63	1.59	1.62	1.77	1.84	1.82	1.93		
Al2O3	15.64	15.36	15.25	15.36	14.50	14.61	14.60		
Fe ₂ O ₃ FeO	10:05	10.79	7.22 4.12	10.63	1.95 9.32	11.96	6.34 5.55		
MnO	GH	0.18	0.18	0.18	0.19	0.18	0.22		
MgO	7.02	5.78	5.63	7.65	7.60	5.75	5.86		
CaO	11.87	13.10	11.94	10.26	10.25	12.20	11.70		
N20	2.99	3.11	3.20	2.60	2.70	2.86	2.88		
K20	0.20	0.48	0.40	0.32	0.28	0.68	0.56		
CO ₂	-	0.17	0.17	0.60	0.62	1.03	0.70		
H20+	1.000	-	1.75	-	0.91	-	0.79		
Total	99.60	99.90	100.54	98.60	99.32	100.20	99.40		

there is no compositional homogeneity (or else homogeneity is extraordinary); thus, random sampling may not reflect average composition. This is clear from Figure 2. An individual sample may only fortuitously reflect the average composition of a lava flow. In view of this fact, we have taken, wherever possible, average values of several determinations for a flow. Data for the leastaltered samples (carbon-dioxide concentration below 0.3%) and averages for individual flows are given in Table 2. Analyses of unrepresentative samples are given in an appendix; these represent basalts with high carbon-dioxide concentration and extensive oxidation.

PETROCHEMISTRY

Table 2 and Figures 3 and 4 show that almost all basalts in the Shikoku Basin and Daito Basin are tholeiitic (Irvine and Baragar, 1971). Only the upper lava flow of Hole 444A and two samples of Site 446 are in the alkali fields of Figures 3 and 4. According to normative composition (Table 2), basalts of Hole 443 are olivine tholeiites; those of Hole 442B are saturated tholeiites (normative hypersthene); and those of Site 446 are oversaturated tholeiites (normative quartz and hypersthene) (Yoder and Tilley, 1962).

However, basalts of Sites 442 and 446 should actually be more basic. Their high acidity with respect to normative composition may be accounted for by substantial oxidation of iron by low-temperature reactions with sea water. Therefore, ferric oxide equals or exceeds ferrous oxide. Hence, the norm shows exceptionally high, unnatural concentrations of magnetite (6-10%), without olivine. This is exemplified by basalts of Hole 443. The first three samples listed for this hole in Table 2 have a nearly normal Fe₂O₃/FeO ratio, and they show normative olivine. Rocks of the same hole with a higher degree of oxidation of iron show no normative olivine. We should, therefore, believe that the lava flows of Hole 442B are actually olivine tholeiites, as are the typical pillow basalts of the same hole (Table 2). They differ greatly from the basalts of Hole 443 in a lower content of normative olivine for most of the rocks (Figure 5).

This also applies to basalts of Site 446, which apparently correspond not to oversaturated but to rather saturated tholeiites.

Comparison of average chemical compositions of basalts of these three holes with typical oceanic-profile samples (TOPS) and mid-ocean-ridge basalt (MORB) (Table 3) shows that the Hole 443 rocks correspond to MORB although they have somewhat lower iron, chromium, and nickel contents.

The basalts of Holes 442B and 446A have somewhat lower contents of magnesium, chromium, and nickel than does MORB, and they have somewhat higher contents of iron, potassium, strontium, and rubidium. The K/Na and Ti/Cr ratios are also higher for basalts of Holes 442B and 446A than for MORB.

Some comparisons among Leg 58 basalts are shown in Figure 6.

The basalts of Hole 442B are distinct from MORB not only in the lava flows making up the upper units, but also in the fresh glass of the pillow basalt in the



Figure 1. Relationship between calcium and carbon-dioxide contents in basalt. Rocks with carbon-dioxide content exceeding 0.3 per cent (dashed line) are considered strongly altered. Here, and in other figures, the numbers refer to: (1) Hole 442B basalts; (2) glass in Hole 442B pillow basalts; (3) Hole 443 basalts (and two lava flows in Hole 444A; Table 2); (4) glass in Hole 443 pillow basalts; (5) Hole 446A basalts; (6) Hole 444A alkaline basalt sill; (7) Hole 442A basalts.



Figure 2. Vertical variations in chemical composition of basalt flows.

lower part of the hole (Tables 2 and 3). Because the Hole 442B basalts are of off-ridge origin (Klein et al., 1978), their lower magnesium content is natural. The data presented by Hart (1976) on the composition of

TOPS suggest that the chemical features of Hole 442B basalts probably are typical of off-ridge basalts.

Thus, a lower magnesium content is seemingly characteristic of ocean-floor and marginal-sea basalts which

TABLE 2													
Chemical Composition and Norms of the Freshest	t Basalts, Shikoku Basin and Daito Ridge												

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Sample (interval in cm)	SiO ₂	TiO ₂	A1203	Fe ₂ O ₃	FeO	MnO	MgO (CaO	Na ₂ O	K20	P2O5	H ₂ O+	H ₂ O-	C02	Total
442B-3-3, 140-146	49.61	1.26	15.80	6.15	2.89	0.13	6.90	11.63	2.71	0.33	0.114	0.77	0.75	0.11	99.15
4-2, 35-40	49.20	1.23	16.35	5.72	2.95	0.11	6.41	12.33	3.06	0.34	0.119	0.73	1.29	0.34	100.26
6-3, 27-35	49.60	1.81	15.00	2.43	8.70	0.11	7.38	10.65	2.58	0.20	0.039	1.61	0.30	0.21	100.09
7-1, 35-42	49.00	1.26	16.20	6.01	3.50	0.15	6.20	11.30	3.06	0.19	0.132	1.90	0.30	0.21	99.41
8-1,80-85	49.20	1.12	17.20	4.07	4.98	0.14	8.40	8.60	2.73	0.13	0.140	3.64	1	0.05	99.98
8-4, 60-65	48.00	1.21	16.05	3.48	6.05	0.13	8.80	9.65	2.92	0.18	0.080	1.69	0.47	0.10	98.81
8-6, 50-55	49.00	1.16	15.20	4.73	5.10	0.12	8.25	9.70	3.02	0.16	0.107	2.66		0.23	99.44
(Avg., 7-1 to 8-6) 8-6 135-140	48.72	1.18	16.00	4.30	5.15	0.14	8.16	9.77	2.87	0.16	0.116	2.73	0.35	0.15	99.60
8-7, 47-52	48.60	1.19	15.10	6.76	3.32	0.14	8.50	8.55	3.41	0.35	0.040	2.74	0.60	0.12	99.42
(Avg., 8-6 and 8-7)	49.05	1.22	15.60	6.09	3.54	0.12	8.05	9.27	3.26	0.25	0.046	2.30	0.67	0.07	99.57
9-1,10-15	49.80	1.03	16.45	5.53	2.53	0.15	8.03	10.26	2.71	0.27	0.107	1.93	0.23	0.05	99.08
10-1, 93-96ª	48.10	1.61	13.75	9.	78	0.16	6.19	13.15	3.12	0.34	0.119	0.95	1.02	0.21	98.50
(Avg., upper 59 m. of	49.16	1.35	15.70	5.16	4.35	0.12	7.14	10.90	2.94	0.29	0.103	1.96	0.62	0.15	99.56
10-1, 118-121b	48.40	1.63	15.25	7.22	4.12	0.18	5.63	11.94	3.20	0.40	0.140	1.75	0.52	0.17	100.54
14-1, 35-40a,b	50.77	1.67	16.27	9.	18	-	7.15	11.83	2.87	0.21	-	10100	-	-	100.00
14-1, 85-90a,b	51.07	1.56	16.09	9.3	20	-	7.14	11.67	2.98	0.25	100	7.3	-	-	100.00
16-1, 35-47	49.40	1.33	16.24	5.23	4.74	0.16	5.54	12.00	2.99	0.24	0.150	1.67	0.13	0.11	100.00
17-1, 50-55	49.60	1.74	16.10	5.58	4.83	0.17	5.33	11.86	3.20	0.40	0.203	0.75	0.62	0.08	100.46
17-1, 84-86a,b	51.54	1.63	15.60	9.9	90	-	6.50	11.56	2.98	0.25	-	-	-	-	100.00
17-2, 10-15a,b	51.54	1.64	15.55	10.0	01	-	6.80	11.45	2.95	0.27	_	-	_	3	100.00
19-2, 65-70a,b	51.90	1.65	15.70	9.1	89	2	6.56	11.49	2.52	0.24	-	-	-	2	100.00
20-1, 57-61a,b	51.72	1.64	15.66	9.1	80	-	6.86	11.64	2,38	0.25	-	100	-	1	100.00
(Avg., lower 102 m of the hole)	50,76	1.60	15.90	9.1	70	-	6.49	11.74	2.87	0.29	÷.	~ 1	-	-	
(Avg., Hole 442B)	49,72	1.49	15.81	9.3	39	- 21	6.78	11.36	2.91	0.29	177.) 12000-14	177.1 1797.200	15 2002	- 733 1999 - 1999	ः २०२२ - २२
443-53-1, 15-20	48.60	1.48	16.70	2.92	7.37	0.16	7.65	11.00	2.80	0.11	0.116	0.76	0.47	0.13	100.27
54-7, 63-67	48,40	1.46	15.60	2.81	7.55	0.16	8.15	11.40	2.65	0.07	0.103	1.13	0.11	0.24	99.83
57-2, 105-108a,b	49.88	1.77	16.11	10.0)7	-	7.52	11.84	2.49	0.28	-	-	5	5	100.00
57-3, 0-5	48.80	1.24	16.10	4.10	4.59	0.11	8.03	10.10	3.05	0.23	0.189	0.47	2.43	0.13	99.57
58-2, 125-128	49.20	1.70	16.35	5.29	4.05	0.10	7.08	9.95	3.12	0.36	0.155	1.30	0.50	0.15	99.30
58-3, 121-125	49.20	1.88	15.30	4.16	5.72	0.11	7.82	9.77	3.08	0.30	0.183	1.79	0.52	0.13	99.96
(Avg., 58-2 to 58-3)	49.07	1.79	15.68	5.15	4.90	0.11	7.17	9.64	3.15	0.39	0.172	1.64	0.47	0.16	99.73
62-1, 88-93	49.60	1.32	16.20	3.07	4.86	0.12	7.73	11.97	2.77	0.11	0.110	1.41	0.52	0.25	100.04
63-8, 89-94	49.00	1.32	16.20	5.34	3.69	0.13	7.86	11.21	2.92	0.10	0.103	2.05		0.17	100.09
64-2, 84-86 (Avg. 63-8 and 64-2)	48.00	1.26	16.20	6.48	2.34	0.15	8.28	10.85	2.78	0.09	0.096	1.19	1.74	0.14	99.57
(Avg., Hole 443)	48.72	1.39	16.11	4.31	5.18	0.14	8.03	10.85	2.83	0.15	0.120	1.08	0.79	0.16	99.79
444A-20-1, 39-43 ^c	49.70	2.18	15.32	8.1	8	0.15	5.78	8.66	3.88	2.61	0.140	3.50	-	0.21	100.31
20-1, 77-810	47.30	2.08	15.60	3.83	4.28	0.16	5.42	10.06	3.90	2.39	0.196	4.64	0.10	0.25	99.93
(Avg., 20-1 to 20-4)d	47.83	1.92	15.84	3.56	4.56	0.15	6.74	8.69	3.74	2.30	0.142	3.88	0.54	0.23	100.12
25-3, 111-115	49.20	1.53	17.12	4.13	5.20	0.15	6.79	11.85	2.79	0.20	0.146	0.64	0.73	0.10	100.58
26-1, 76-80	49.20	1.50	16.40	3.80	5.40	0.16	6.90	12.43	2.81	0.24	0.164	0.86	0.48	0.11	99.12
27-1, 131-135ª	48.50	1.39	16.30	9.3	20	0.16	7.49	12.00	2.75	0.32	0.160	1.26	-	0.11	99.67
27-3, 145-150ª	49.30	1.43	15.18	9.4	43	0.16	8.23	11.63	2.52	0.30	0.146	1.19	1.55	0.19	99.78
27-4, 119-1234	49.40	1.46	15.03	3.61	5.88	0.16	7.68	11.70	2.64	0.29	0.162	0.48	0.60	0.10	98.58
(Avg., 26-1 to 27-5)d	49.32	1.42	15.92	3.70	5.64	0.16	7.45	11.68	2.73	0.29	0.153	1.04	0.50	0.14	100.14
446A-5-1, 4-10	49.20	3.80	13.05	4.44	9.60	0.20	5.53	9.62	2.47	0.70	0.320	0	.96	0.06	100.03
9-3, 90-95	47.60	4.20	13.14	6.50	8.65	0.24	5.50	8.85	2.43	0.40	0.390	1	.38	0.08	99.55
10-5, 97-102	44.00	5.40	14.00	5.23	7.23	0.21	6.00	11.50	2.96	1.58	0.755	0	.63	0.08	99.57
14-3, 97-1024	50.30	3.67	13.13	12.5	52	0.16	6.54	10.15	2.44	0.32	0.274	1	42	0.08	99.60
17.CC, 24-32	49.40	4.40	15.20	6.83	6.46	0.15	5.87 4.87	9.45	2.61	1.26	0.520	1	.43	0.08	99.42
19-3, 0-8	48.20	3.90	14.00	5.14	7.99	0.20	6.12	8.93	3.20	0.38	0.389	1	.03	0.10	99.55
19-3, 67-73	48.00	4.20	13.80	5.49	8.60	0.24	5.07	9.50	2.67	0.36	0.366	1	.30	0.10	99.70
21-2, 82-88a	49.30	3.88	12.95	13.3	0.29	0.16	5.98	11.12	2.30	0.12	0.297		-17		99.42
21-5, 140-146a	50.60	4.02	12.06	13.6	53	0.17	5.11	9.91	2.72	0.76	0.389		2.5	-	99.40
21-6, 53-58	51.60	4.10	12.90	6.02	7.82	0.20	4.87	7.00	2.92	0.72	0.458	0	.83	0.07	99.48
21-6, 69-74	47.40	4.10	14,70	5.47	8.57	0.25	5.20	8.87	3.05	0.74	0.366	0	.70	0.08	99.49
22-1, 132-137	46.00	5.04	14.35	8.60	6.76	0.28	5.41	7.00	3.25	1.03	0.458	1	.59	0.25	100.02
22-4, 0-6ª (Avg 22-1 and 22-4)d	46.90	4.61	12.45	15.3	6.76	0.22	5.56	11.08	2.48	0.22	0.412		50	0.25	99.30
23-6, 78-83	48.10	3.62	14.25	6.25	6.29	0.17	6.86	9.59	2.60	0.42	0.343	î	.30	0.13	99.98
24-3, 78-85a	52.20	3.50	12.52	11.6	52	0.22	4.64	11.28	2.72	0.79	0.366			-	99.90
25-2, 46-51a	51.90	3.42	13.28	12.3	7 54	0.15	5.23	9.42	2.56	0.60	0.343		37	0.17	99.30
(Avg., 24-3 to 25-3)d	50.70	3.49	13.18	5.92	7.54	0.19	5.55	9,71	2.74	0.71	0.366	1	.32	0.17	100.40
26-4, 5-10	47.50	5.55	13.80	4.64	8.53	0.27	6.93	10.41	2.38	0.14	0.343	1	.74	0.09	100.46
446.41 CC 129-1452	46.60	2.04	14.56	0.03	0.73	0.25	4.76	12.03	2.31	2.25	0.374	1		0.20	00.40
44-2, 40-45a	50.10	4.28	13.39	12.7	12	0.33	4.84	10.44	2.79	0.91	0.389		5		100.10
46-1, 45-50 ^a	49.10	4.32	13.20	13.7	17	0.17	5.10	10.90	2.49	0.45	0.439		÷):	-	99.90
(Avg., Holes 446A and 446)	48.35	4.14	13.54	6.04	7.83	0.22	5.55	9.81	2.70	0.66	0.390	1	.24	0.12	100.59

TABLE 2 – Continued

Li	Rb	Cs	Sr	В	F	v	Cr	Cu	Ni (ppm)	Co	Zn	Th	U	TR	La	Ce	Y
31	9.4	0.8	180	10	330	290	260	72	52	40	82			-	-	-	~
26	8.2	0.6	170	~10	390	270	230	70	44	43	72	1	7	-	-	177	5
5	3.1	< 0.5	150	<10	250	300	190	78	84	40	94		_	-	-	_	-
10	7.9	< 0.5	150	<10	240	290	190	78	56	38	105	-	-	30	2.28	7.53	10.71
10	5.0	<0.5	110	<10	120	250	200	100	130	44	80	≤0.3	0.7	20	1.58	4.78	5.90
10	6.1	-	130	18	130	290	230	120	100	50	100	-	-	-	-	-	22
10	1.8	<0.5	150	<10	260	320	230	76	110	40	72	= 1	0.7	25	1.82	6.15	9 20
33	5.8	-	140	<10	250	240	190	77	84	38	75	-	-	-	-		-
13	4.2	< 0.5	150	<10	260	240	220	70	100	48	92		3	40	2.80	9.32	12.80
32	9.1	0.8	150	<10	130	330	203	57	92	56	75	-	-	40	2.80	9.32	12.80
13	14.0	0.8	170	22	330	270	260	64	50	81	100	171			-	1	
÷.			150	<10	270	210	150	97	60	150	-	_	-	-	-	~	
		-		- 5-		100	1	- 63	5	6 <u>6</u> 21	- 53			2			
10	13.0	< 0.5	160	<10	270	240	150	52	45	160	100	-	-	-	-	-	-
	-	-	-	_		400	-	-		-				3			
1.9	12	-0.5	100	~10	270	200		74		-			-0.2	æ	-	-	-
10	16	1.6	180	12	270	250	65	75	34	54	105	-50.3	40.2	70	7.98	14.56	26.74
5		-	-	-	-	-	-	-	-	-	-	-	-	=	-	-	-
-			_	12						1			12			-	-
2	-	-			-		-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-		-	-	-	-	-	-	-	-	-		-
-	-	50	132	5		-	5	20	-	17	51	-	27.			\overline{a}	
16	9.2	0.6	183	11	255	277	207	74	73	67	90	0.3	0.7	40	3.66	9.05	14.04
7.3	6.0	< 0.5	140	<10	160	340	270	75	87	46	125	-	-	-	2		120
7.5	3.4	<0.5	120	<10	150	340 440	280	72	97	48	120	<0.3	<0.1	50	3.90	9.50	11.10
-	-	-	-	-	-	-	-	- 67	-	-	-	\rightarrow	-	-	-	-	-
8.8	7.9	< 0.5	120	-10	230	400	210	58	88	81	130	-0.2	-01	1	-		
12	9.8	0.7	130	<10	460	600	200	56	43	74	150	<0.3	<0.1	-	-		-
18	5.1	< 0.5	150	<10	520	370	210	56	80	44	100	-	-	100	7.2	17.3	29.20
15	10.8	<0.5	140	<10	443	480	200	49	62	49	115	<0.3	<0.1	100	7.2	17.3	29.20
9.2	2.0	< 0.5	140	<10	290	270	290	72	92	42	86	< 0.3	0.2	60	9.5	13.1	13.56
10	7.8	<0.5	140	<10	140	265	300	68	100	45	90	-	-	20	1.0		0.0
11	6.4	<0.5	130	<10	120	265	280	40	98	45	87	2		30	1.9	7.3	8.8
10.5	6.8	0.6	171	<10	244	364	271	61	92	50	112	< 0.3	0.1	60	5.6	11.8	15.7
-	-	-	420	<10	250	195	190	58	120	30	<u></u>	-	-	12	-	2	22
7.1	23	1.2	370	<10	310	320	130	56	32	30	76	2.7	0.8	-	-	100	
8.5	19	<0.5	340	<10	227	240	177	42	170	42	70	1.4	0.8	22		-	<u></u>
6.0	3.0		120	<10	200	225	300	68	61	44	71	-	-	25	11		20
5.1	10	< 0.5	150	<10	220	250	240	67	58	43	100	-	-	-	-	-	-
-	-	-	200	<10	220	175	235	65	90	35		-	-	1	-	-	-
-	-	-	170	<10	230	200	245	70	100	45	-	-	-	-	-	-	-
6.6	7.6	0.8	145	<10	1 80	290	310	63	110	46	89			-	-		-
5.8	9.0	0.6	183	<10	195	228	275	64	91	44	95	-	-	22	<u>14</u>		-
6.2	16	0.6	310	<10	370	220	150	140	78	44	170		-	1	<u></u>	120	20
6.5	9.3	1.0	370	<10	330	150	80	150	51	47	170	340	100	1.00			-
6.0	8.4	<0.5	330	<10	420	240	130	160	53	48	180	3		57	3	2	
010			400	<10	400	270	95	215	80	40	-	-	-	-			-
8.8	5.6		310	<10	490	230	140	130	67	46	140	-		-	-	-	-
6.4	14	2.5	340	<10	500	290	160	170	95	53	1 20	1.9	0.3	-	_	-	-
8.6	8.6	< 0.5	360	<10	540	350	30	88	38	45	170		-			-	-
7.5	11.3	1.5	350	<10	520	320	95 50	129	64	49	145	3	-	1	3	- 23	
	. <u>R</u>	<u>.</u>	470	<10	420	260	30	150	40	38	1			4		2	-
11	20	0.8	380	<10	600	370	30	87	35	45	180	1		-	1		
7.4	20	<0.5	380	<10	470	410	40	100	38	48	180	1.7	0.7		-		
7.0	13	< 0.5	410	<10	660	380	20	110	26	54	180	2	-	-	-	20	-
7.0	13	<0.5	500	<10	430	240	37	190	30	38	180		-	-	-	9	8
9.8	15	2.4	380	<10	490	220	180	97	98	40	130	4	2	3	2	2	
-	-	-	460	<10	490	270	54	225	55	45	-	-	+	-	-	-	-
7.5	17	1.3	430	<10	500	270	64 55	140	49	45	145	1.9	0.5			2	2
7.5	17	1.3	410	<10	467	300	58	163	55	41	145	1.9	0.5	-		-	
8.0	8.9	1.9	400	<10	420	285	130	150	63	44	130			-	2	-	
5.9	11	1.0	440	<10	540	240	40	120	40	40	100						
		-	380	<10	440	370	87	270	75	40	-		-	-	-		-
-		-	430	<10	-	210	35	240	30	50	-	- 2	-	_	-	-	-
		1	1.000	1			22			12	1.01						
7.52	14.9	1.3	490	<10	488	272	66	119	56	46	151	1.9	37	-	-	-	-

TABLE 2 - Continued

Sample (interval in cm)	Q	Or	Ab	An	Ne	Di (%)	Ну	01	Mt	п	Ap	ΣFeO/ (ΣFeO + MgO)
442B-3-3, 140-146	3.62	2.00	23.51	30.75	_	21.53	7.64		6.23	2 45	0.28	54.97
4-2, 35-40	1.07	2.05	26.47	30.55	-	24.28	5.06	-	6.43	2.39	0.29	55.81
5-2,65-70	0.30	1.21	26.96	30.68		18.12	14.08	-	6.02	2.38	0.24	50.80
7-1, 35-42	-	-	-	-	-		-	-	-	-	-	-
8-1, 80-85	27			5	-	55		5		-	21	-
8-3, 120-125 8-4, 60-65	_	-	-		_	_	-	-	-	-	-	_
8-6, 50-55	-	-	-	-	-	-	-	-	-	-	-	-
(Avg., 7-1 to 8-6)	-	0.99	25.16	31.40	-	14.30	16.34	1.76	6.34	2.33	0.26	52.50
8-7, 47-52	Ξ	2	5	. <u>S</u> .	2	_	-	3	_	1	1	2
(Avg., 8-6 and 8-7)	1.27	1.56	28.63	28.13	-	14.97	14.09	2	8.06	2.41	0.11	52.84
9-1, 10-15	3.40	1.65	23.67	32.97		14.68	13.84	1	5.83	2.02	0.26	48.31
10-1, 93-96ª	5.90	2.09	21.01	23.38	3.46	36.04	3.69	10.55	10.51	3.17	0.40	61.23
(Avg., upper 59 m. of	14	242	1475	=	141	47	-	-	-	-	1	642
10-1 118-171b	1.67	2 41	27 59	76.58		25.58	2 43		9 30	3 16	0.34	65 35
14-1, 35-40a,b	-	1.30	24.56	31.19		23.05	5.09	11.51	5.50	3.21	-	56.13
14-1, 85-90a,b	-	1.54	25.49	30.06	200	23.34	4.55	11.97	-	2.99	\rightarrow	56.29
16-1, 35-47	2.31	2.40	25.47	30.40		23.06	4.56	12.12	7.69	2.89	0.36	55.75
17-1, 50-55	2.24	2.39	27.34	28.68	-	23.10	4.25	-	8.17	3.34	0.53	64.89
17-1, 84-86a,b	-	1.50	25.48	28.74	-	24.11	8.44	8.53	-	3.13	-	60.34
17-2, 10-15a,b	_	1.50	22.37	29.72	_	23.54	13.56	5.44		3.15	_	59.53
19-2, 65-70a,b		1.48	21.65	31.19	-	21.93	18.20	2.30	-	3.18	<u> </u>	60.10
20-1, 57-61a,b	0.47	1.54	20.36	31.56	-	21.98	20.88		-	3.16		57.52
(Avg., lower 110 m of the hole)	-	-	-	-	-	-	-	-	-	-	<u> </u>	-
(Avg., Hole 442B)	-	-		1		न ।		1.55			-	1.000 1.000
443-53-1, 15-20	-	0.66	23.95	33.05		17.27	11.67	6.01	4.28	2.85	0.28	56.64
54-4, 115-120		0.84	23.74	31.78	-	18.17	10.91	6.29	4.23	2.66	0.26	55.29
57-2, 105-108a,b	10	1.66	21.06	31.98	-	22.02	10.06	9.78	-	3.37	-	57.24
57-3, 0-5	-	1.41	26.73	30.64	-	15.84	15.87	0.48	6.16	2.45	0.45	50.76
58-2, 125-128	-	-	-	-	-	-	-		-	-	-	-
58-3, 121-125	- TRON	-	-	-	-	-	-	-	+	-	. .	-
(Avg., 58-2 to 58-3)	1.30	2.41	27.31	28.22	-	16.29	12.81	1.05	7.67	3.48	0.42	57.07
62-1, 88-93	0.70	0.66	23.95	32.15	2	22.11	13.69	1.95	4.55	2.56	0.23	49.65
63-8, 89-94	-	-	-	-	-	-	-	1	-	-	-	-
64-2, 84-86 (Avg. 63-8 and 64-2)	1.06	0.67	24.90	32.04		19.27	12.26	-	6.12	2.52	0.25	50.79
(Avg., Hole 443)	1.00	- 0.07	24.00	52.04	-	- 10.57	12.30		0.22		-	- 50.78
4444 20 1 20 422												
20-1, 77-81°	1	-	_	-	-	_	-	-	-	-	-	-
20-4, 41-45°	i An	14.22	22.09	20.59	5.99	18.88	ALC: NO.	10.43	5.43	3.82	0.35	53.53
(Avg., 20-1 to 20-4) ^d	0.57	1.19	23.81	33.91	-	19.43	11.76	-	6.04	2.94	0.35	56.77
26-1, 76-80	-	-	-	-	2	2	2	2	-	3	-	-
26-3, 75-79a	15		1.1	100	÷.			-	-	-		
27-1, 131-1354	-	-		-			-	-				_
27-4, 119-123ª	-		-	-	-	-	-	-	-	-	-	-
27-5, 61-65	-				-						-	
(Avg., 26-1 to 27-5) ^u	1.00	1.74	23.39	30.89	-	22.05	7.12	9.18	5.45	2.75	0.37	54.48
446A-5-1, 4-10 8-2 144-150	5.61	4.18	21.12	22.71	-	19.05	12.78	~	6.51	7.30	0.77	71.08
9-3, 90-95	7.12	2.41	22.52	23.42	<u>-</u>	14.98	10.87	12	9.61	8.13	0.94	72.50
10-5, 97-102		9.44	18.92	20.49	3.47	25.16	-	2.70	7.67	10.37	1.81	66.54
14-3, 97-102 ^a	9.51	1.90	20.75	24.06	-	20.51	23.48	-	9.70	7.00	0.65	65.68
17,CC, 24-32	3.74	7.58	23.16	26.15	-	13.59	6.04	-	9.08	8.51	1.49	72.13
19-3, 0-8	im-	-		-		-	-	-	-	-	-	
19-3, 67-73 (Ave 19-3)	4 83	2 22	25.24	74.06	-	15.94	11.14		7.84	7.82	0.91	70.04
21-2, 82-88a	4.00				- 29	-		1	7.04		-	10.04
21-5, 140-146 ^a				100	100		100	85		100	-	<u> </u>
(Ave 21-2 to 21-6)d	512	3.1.8	22.59	71 77	-	19.07	17.30	~	2.92	7.66	0.92	71.56
21-6, 69-74	2.66	4.43	26.14	24.56		14.14	11.28	-	8.04	7.89	0.88	72.18
22-1, 132-137	-	-	-	12	_	2	-	-	-	-	-	
(Avg 22-4, 0-6ª	2.75	3.76	74.57	22.15	-	12.01	14.06		4.11	0.78	1.04	73.12
23-6, 78-83	5.50	2.53	22.33	26.38	1	15.37	10.87	2	9.20	7.02	0.82	63.46
24-3, 78-85ª	-		=	-	-	160314	-	-	1	-	5	
25-2, 46-51a			1			1					5	-
(Avg., 24-3 to 25-3)d	3.75	4.22	23,40	21.78		20.14	16.19		2.92	6.70	0.88	68.85
26-4, 5-10	3.50	0.84	20.53	26.98	-	18.62	15.12	-	6.83	6.87	0.82	64.70
27-2, 6-12	5.34	1.02	19.83	28.00		19.39	6.35	-	11.05	7.77	1.05	69.69
446-41,CC, 138-145a	-	13.36	5.48	18.55	12.04	37.81	. 2 41 1	4.61	-	7.51	0.65	68.50
44-2, 40-45a	0.37	5.37	23.59	21.32	7	23.33	16.94			8.12	0.92	72.43
46-1, 45-50 ^a	0.75	2.66	21.07	23.53	7	23.20	19.50	-		8.20	1.04	12.97
(Avg., Holes 446A and 446)	1	-	-	12	-	2	2	-		4		

^a X.Ray-fluorescence method.
^bGlass.
^c Alkaline-basalt sill.
^d Chemical data for iron.
Analysts: N. S. Klassova, L. V. Krigman, A. V. Lebedkova, E. I. Tikhomirova, O. M. Kalinkina, N. V. Budarina, I. A. Roschina, T. P. Andreeva, S. M. Chernogorova, V. I. Pavlutzkaja, Institute of Geochemistry, Academy of Sciences of the U.S.S.R., Moscow.



Figure 3. Alkali-silica diagram. Dashed line is the statistical boundary of tholeiitic basalts described by Irvine and Baragar (1971). Symbols are explained in Figure 1.



Figure 4. Positions of basalts in an FMA diagram. Dashed line is the statistical boundary of tholeiitic basalts described by Irvine and Baragar (1971). Symbols are explained in Figure 1.

originated beyond rift zones, and this is characteristic not only of sills (Hart, 1976), but also of lava flows and pillow basalts (Table 2).

The differences in composition of basalts in the northern Philippine Sea are caused both by differences in composition of parent magma and by differentiation. This is shown by the olivine-plagioclase-diopside diagram (Figure 5) and by variation diagrams (Figure 7).

To compare the results of analyses (partly using X-ray fluorescence) presented on the three-component

diagram of olivine-plagioclase-diopside, recalculations for normative composition were performed for ferrous oxide, which is probably reliable, because Mössbauer spectroscopy of glass detected not more than 15 per cent ferric iron. Also, hypersthene is recalculated for olivine and quartz (3 Ol + 1 Q = 4 OPx), as is albite for nepheline and quartz (3 Ne + 2 Q = 5 Ab).

Figure 5 shows that practically all the basalts were formed with plagioclase and olivine removal from the melt. This phenomenon is noticed in thin sections, where phenocrysts of these minerals, particularly plagioclase, occur in glass. A tendency toward removal of clinopyroxene from the melt is seen for Holes 442B and 446A. However, clinopyroxene phenocrysts in a slightly devitrified groundmass occur only in thin sections of Hole 446A alkaline basalts (Sample 446A-13-1, 17 cm). In general, Figure 5 indicates little differentiation of Hole 443 basalts and substantial differentiation of basalts of Holes 442B and 446A.

This feature is most conspicuous in the variation diagrams: in Figure 7, Hole 442B and Hole 446A basalts reach their maximum and have the highest range of differentiation indexes (Hole 442B), with strong enrichment of the final melts in iron, titanium, and alkalis (particularly Hole 446A), and simultaneous decrease in magnesium content. The limited evolution of the Hole 443 basalts suggests inconsiderable differentiation. This also applies to glass of Hole 442B basalts. Figure 7 shows that basalts of each hole have independent trends. For Holes 442B and 443, these are either close to each other or subparallel, but quite distinctive with respect to such characteristic components as silica, iron, magnesium, nickel, and chromium. This probably indicates similar, but somewhat different, initial compositions of the parent magmas from which the two rock



Figure 5. Basalts of three holes plotted on a normative Ol-Pl-Di diagram. Mean Ocean Ridge Basalt is indicated by stars (Dmitriev et al., 1976); other symbols are explained in Figure 1.

		Basalts	of Leg 58 (from	Table 2)				
		Hole 442B					MORP	
New	Upper 59 meters (14 samples)	Lower 102 meters (11 samples)	Average, Hole 442B (25 samples)	Average, Hole 443 (12 samples)	Holes 446A and 446 (24 samples)	TOPS (Hart, 1976)	(Hart, 1976)	(Dmitriev et al., 1976)
SiO ₂ (%)	49.16	50.76	49.72	48.72	48.35	49.09	49.92	49.96
TiO ₂	1.35	1.60	1.49	1.39	4.14	1.55	1.46	1.48
Al203	15.70	15.90	15.81	16.11	13.54	15.48	16.08	15.74
Fe ₂ O ₃ FeO	5.16	9.70	9.39	4.31	6.04 7.83	9.43	9.26	2.48
MnO	0.12	_		0.14	0.22	0.18	0.17	0.18
MgO	7.14	6 4 9	6.78	8.03	5.55	6.72	7.75	7.97
CaO	10.90	11 74	11.36	10.85	9.81	10.66	11.21	11.36
NapO	2.94	2.87	2.91	2.83	2 70	2.73	2.79	2.63
KaO	0.29	0.29	0.29	0.15	0.66	0.49	0.17	0.23
P205	0.103	-	-	0.12	0.39	0.18	0.15	-
H20+	1.96	-	144	1.08	0.00	2.65	0.77	-
H20-	0.62		12	0.79	1.24	-	_	-
cõ ₂	0.15	—	-	0.16	0.12	-		
Na (ppm)			2.21	2.14	2.02	2.01	2.06	-
K		-	0.25	0.16	0.61	0.41	0.14	-
K/Na	-	-	0.11	0.075	0.30	0.20	0.06	-
Li	-	· — ·	16	10.5	7.52	9.81	5.44	14
Rb	-		9.2	6.8	14.9	5.44	1.94	-
K/Rb	-	—	268	236	407	750	720	-
Sr	-	_	183	171	490	445	121	
В	-	-	<11	<10	<10	_	—	-
F	-		255	244	488	-	—	-
Cr	_		207	271	66	260	291	-
V			277	364	272	316	286	-
Cu		0-0	74	61	119	56	79	
Ni			73	92	56	128	123	
Co	-	—	67	50	46	46.4	43.7	-
Zn		$\sim - 1$	90	112	151	101	91	-
U	<u></u>	2 <u>—</u> 2	0.2-0.7	< 0.1	0.3-0.7	0.35	0.28	
Th	-		0.3	0.3	1.9	0.21		-
Cr/Ni	-		2.4	3.0	1.2	2.0	2.4	-
Ti/Cr	1222		80	50	620	60	50	8 <u>150</u>

TABLE 3 Average Chemical Composition of Some Basalts

types originated. By parent magma, we mean the magma which has given rise to a series of igneous rocks, whether or not it was primitive or underwent a certain evolution. To a larger extent, this may be applied to the Hole 446A basalts which are all characterized by a high iron content. Their distinctive trend shows no relationship with the Hole 442B and Hole 443 basalts. We think that



Figure 6. Variations among some Leg 58 basalts.

this conclusion is correct, because the presence of thick sills of similar composition at Site 446, in the complete absence of oceanic basalts, may indicate a parent magma already enriched in iron and titanium. Magma evolution has given rise to the whole range of Site 446 ferrobasalts and alkaline rock varieties (Table 2; Figure 7).

In Figure 7, one may notice an interesting fact: the Site 446 basalts have the same differentiation index as the Hole 442B basalts, but a higher magnesium content. In other words, despite the high content of iron and titanium (suggesting extensive magma differentiation, in which a great decrease in magnesium content is common), the rocks under discussion have a higher magnesium content. This may point to a higher magnesium content in the parent magma (and to a considerable depth of its formation) which, in the process of magma evolution, has given rise to rocks described as ferrobasalts. This is in agreement with conclusions at which Bass (1971) and Scheidegger (1973) have arrived.

Ferrobasalts are comparatively widespread on a global scale. They are encountered in the eastern Indian ocean (Hekinian, 1974; Thompson et al., 1974; Robinson and Whitford, 1974), in the central and eastern

Pacific ocean, within the Juan de Fuca submarine ridge (Jackson et al., 1976; Clague and Bunch, 1976). Similar rock types are described by Sigursson et al. (1968) from Iceland. Such rock types also occur within continents in plateau basalts, both as independent intrusions of dolerites and as final products of their differentiation, exemplified by ferrogabbro of the Skaergaard intrusion, described in detail by Wager (1968).

Bass (1971) and Scheidegger (1973) attribute ferrobasalt to a considerable depth of magma formation. However, Clague and Bunch (1976) consider these rock types to be the result of intensive subsurface magma differentiation. Generally, ferrobasalt formation resembles the in-chamber differentiation hypothesized by Wager (1968) for the Skaergaard intrusion and supported by experimental data obtained by Kennedy (1955) and Osborn (1959), who showed that magma evolution resulting in iron accumulation in the final products of differentiation should proceed under a constant bulk composition of the dry melt (constant oxygen content). A high water content should result in a calc-alkaline trend of differentiation, with silica accumulation. Hamilton and Anderson (1967) arrived at the conclusion that water content in magma does not greatly influence magma differentiation.

The last conclusion is of principal importance, because melts producing the Shikoku and Daito basalts were characterized by various (including high) water contents, which nevertheless ensured the tholeiitic trend of magma evolution, resulting in accumulation of iron and not silica at the end of the process.

WATER CONTENT IN MAGMA

Basalts of the Shikoku Basin and Daito Basin have different vesicularities; Site 442 basalts are most vesicular, with average vesicularity of 20 to 25 per cent in lava flows and 25 to 30 per cent in pillow basalts.

Hole 443 basalts have vesicularity values of 3 and 15 per cent (in places up to 30%), for flows and pillow basalts respectively. The bulk of the Hole 446A basalts are characterized by a vesicularity of 0 to 10 per cent (3% average); in five units with amphibole vesicularity amounts to 15 to 30 per cent. Visual determination of vesicularity is in agreement with the porosity of the rock (site reports, this volume).

The high vesicularity of the Hole 442B basalts is not a sign of near-surface effusion, as hypothesized for the Reykjanes basalts (Moore and Schilling, 1973). High vesicularity is also typical of some Hole 443 and Hole 446A basalts which definitely formed at depths exceeding 4000 meters. Rock density in all cases is a function of porosity, rather than depth. Therefore, the different vesicularities of rocks from one hole and the high vesicularity of Hole 442B basalts were predetermined by different water contents in the magmas. The melts may have contained relatively high water concentrations, which is indicated by amphibole in the most-vesicular Hole 446A basalts.

Assuming that the density of the water gaseous phase is 0.09 g/cm³ (Vakulovitch, 1965) at 1000°C and 500 atm (at a depth of 5 km), the concentration of free water



Figure 7. Behavior of major oxides and minor elements in the process of magma differentiation. $\Sigma Fe(FeO)/[\Sigma Fe(FeO) + MgO]$ is an index of differentiation. Symbols are explained in Figure 1.

equals 0.27, 1.35, 2.25, and 2.7 per cent at vesicularities of 3, 15, 25, and 30 per cent, respectively. Noting the 0.3 per cent of water dissolved in basalts (Moore, 1970; Bryan and Moore, 1977), the total water content in the magma should be 0.6, 1.6, 2.5, and 3.0 per cent. Therefore, minimum water content (0.6%) is characteristic of the basalts of Hole 443 and the bulk of Hole 446A basalts, while the maximum content (2.5-3.0%) is determined for the Hole 442B basalts. Such high and inter-

mediate water contents are also typical of the Hole 443 pillow basalts, as well as of the sills with amphibole in Hole 446A.

The data on rock chemical composition (Table 3) and the low vesicularity (relative dryness) of Hole 443 basalts enable us to attribute them to ridge basalts (Moore, 1970).

The high water content in the Hole 442 basalts with a tholeiitic trend of evolution apparently reflects the deci-

sive influence of water upon magma differentiation (Hamilton and Anderson, 1967). This raises the question of the absence of amphibole in these rocks, as opposed to similar rocks in Hole 446 which contain amphibole. With due regard for experimental data (Yoder and Tilley, 1962; Lambert and Wyllie, 1972), this can be accounted for by high magma temperature (Hole 442B), outside the amphibole stability field. At the same time, the presence of amphibole in the Hole 446A basalts indicates either a lower magma temperature (compared with that for Hole 442B basalts) or a greater depth (higher pressure) of amphibole formation. The last interpretation is based on experimental data showing that amphibole is stable in a basaltic melt at a temperature somewhat lower than 1000°C and at 10 to 15 kbar (Lambert and Wyllie, 1972). These data, as well as those obtained by Yoder and Tilley (1962), prove that amphibole crystallization in situ is impossible, because the stability field is above a pressure range of 1 to 1.5 kbar. This indicates that the amphibole was crystallized at depth, possibly in an intermediate chamber. Erupting onto the surface, such magma could produce rock with amphibole.

RARE ELEMENTS IN THE SHIKOKU AND DAITO BASALTS

The distribution and behavior of rare and minor elements in basalts are governed by regularities typical of basic magma (Table 2; Figure 7) which involve both initial composition of magma and differentiation peculiarities of the basalts in each hole of Leg 58.

Generally, the behavior of minor elements in magma evolution is similar to in-chamber differentiation (Wager and Brown, 1968; Nisterenko and Almukhamedov, 1973). Typical of all the Leg 58 holes is an increase in rubidium, strontium, fluorine, and copper concentration (simultaneous with iron and alkali accumulation) and a decrease in chromium, nickel, and (to a lesser extent) cobalt concentration in the final products of differentiation. Such behavior of elements may be variously accounted for.

Some of the elements are closely associated with petrogenic elements, which predetermine the distribution and behavior of the minor elements. For instance, rubidium and strontium are closely associated with potassium, whose accumulation at the end of the process is accompanied by a gradual increase in minor elements (Figure 7). On the other hand, the distribution of nickel, and to some extent cobalt, is governed by magnesium. Yet, up to 20 per cent of the nickel in basalts can be found in sulfides, and up to 60 per cent of the cobalt in the titanomagnetite (Nisterenko and Almukhamedov, 1973; Nisterenko et al., 1974), presumably in the form of ferrites. The same can also be said of nickel and copper behavior, but only 10 to 20 per cent of these elements in the rock is associated with titanomagnetite.

Copper, with distinct chalcophile properties, occurs in sulfide form, primarily as chalcopyrite and partly as sulfide droplets (Vakhrushev, 1973; Czamanske and Moore, 1977). In the process of basalt alteration, copper is reduced to native copper, which has been identified in many polished sections and is partly removed into carbonate veins (Sample 443-54-3, 108 cm).

Chromium concentration gradually decreases as the final products of differentiation are formed. Minimum chromium content is typical of basalts with the highest iron content (Hole 446A). Such behavior is quite natural, because chromium is removed from the melt at early differentiation stages, chiefly in chrome spinels and partly by substitution in ore minerals and pyroxenes.

The behavior of vanadium is somewhat obscure. It is commonly associated with titanium, and the two elements should accumulate together toward the end of melt evolution. The process of in-chamber magma differentiation is, for instance, characterized by a direct correlation of the two elements and intensive (>1 wt. %) vanadium accumulation in titanomagnetite (Nisterenko and Almukhamedov, 1973). In the Shikoku and Daito basalts, this behavior of vanadium is noted only in rocks from Holes 443 and 446A; in Hole 442B basalts, such behavior is not noted, which defies explanation.

Fluorine (along with phosphorus) gradually accumulates at the end of the magma differentiation process and is seemingly bound with phosphorus in apatite.

The behavior of other minor elements (lithium, boron, zinc, uranium, thorium, rare earths) in the process of magma evolution is either obscure or cannot be definitely traced because of lack of analyses.

On the whole, the behavior and distribution of minor elements in the process of the Shikoku and Daito basalt formation (Figure 7) support the conclusions on the role of major elements in this process and testify to distinct (Hole 446A) or slightly different (Holes 442B and 443) magma compositions and different intensities of magma differentiation.

SUMMARY

1. Basalts from the northern Philippine sea are of different compositions: in Hole 443, they correspond to mid-ocean-ridge basalts; in Hole 442B, to off-ridge basalts with a lower magnesium content; in Hole 446A, to ferrobasalts. These differences are predetermined by the various compositions of the parent magmas, which are slightly different for Sites 442 and 443 and substantially different for Site 446.

In normative composition, the basalts are olivine tholeiites (normative olivine and hypersthene, Holes 442B and 443) and saturated tholeiites (normative hypersthene, Site 446).

2. Off-ridge basalts from Hole 442B have distinct compositions and require additional studies. However, the data obtained by Hart (1976) indicate that their lower magnesium content is typical for the world ocean.

3. Basalts from Hole 443 indicate minimum differentiation, those from Hole 442 considerable differentiation, and those from Site 446 maximum differentiation of parent magma. In all three cases, magma evolution, irrespective of water content, was of a tholeiitic trend, resulting in accumulation of iron, titanium, and alkalis. Melt differentiation was accompanied by fractionation of olivine, plagioclase, and (in Site 446 basalts) pyroxene.

4. All basalts of Hole 442B and the Hole 446A sills (with amphibole) are characterized by high (up to 30%) vesicularity, suggesting maximum 3 per cent water content in the erupted magma. The absence of amphibole in Hole 442B basalts may be accounted for by higher magma temperature as compared with that for Site 446 basalts.

5. Site 446 basalts, notable for the highest iron content and intensive enrichment in titanium (ferrobasalts), are not a common rock type. These are, however, normal igneous rocks of oceanic origin. Such rocks occur in the eastern Indian Ocean, in the central and eastern Pacific Ocean, and within the Juan de Fuca ridge. Also, similar rocks are found in Iceland and within continents among plateau basalts and are described as the final products of differentiation of tholeiitic intrusions (ferrogabbros).

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APPENDIX
Chemical Composition of Unrepresentative Basalts (with high carbon-dioxide concentration or extensive oxidation)

Sample (interval in cm)	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na 20	K20	P ₂ O ₅	H ₂ O+	H ₂ O-	CO ₂	Total
442A-31-1 81-86ª	49 40	1.43	15.55	8.8	0	0.16	6.74	13.42	2.94	0.31	141	0.47	-	0.22	99.59
32-1 50-554	49.60	1 42	15.30	8.9	88	0.15	6.55	12.85	2.92	0.32	128	0.78		0.32	99.30
32-2 101-106ª	48.50	1.36	14.65	8.9	7	0.13	6.41	13.41	2.94	0.28	132	1.67	-	0.67	99.14
33-1, 62-66a	48.40	1.24	16.30	8.6	5	0.15	7.00	13.28	2.76	0.32	.137	1.12		2.32	101.74
33-1, 118-122a	47.50	1.28	15.60	8.5	7	0.15	6.23	14.84	2.66	0.24	.137	0.65	-	1.85	99.70
33-3, 81-87a	49.50	1.31	15.32	8.9	3	0.13	6.39	14.41	2.71	0.24	.121	1.17	-	1.21	101.48
33-4, 83-88 ^a	49.20	1.38	14.79	8.8	8.82		6.75	13.07	2.95	0.40	.114	1.79		0.85	100.34
34-1, 5-10 ^a	49.10	1.33	15.52	8.8	15	0.13	5.78	13.01	2.77	0.26	.146	0.97		0.39	98.26
34-1, 110-118 ^a	49.50	1.32	15.24	8.4	8.44		6.21	13.47	2.99	0.42	.107	1.98	122	1.10	100.98
442B-3-3, 30-36 ^a	49.70	1.46	16.02	8.3	8.32		6.22	11.80	2.80	0.27	.141	2.81	-	1.50	101.22
3-4, 26-30a	49.20	1.37	14.80	8.6	6	0.15	6.18	16.02	2.85	0.23	.093	0.46	-	0.05	100.11
3-4, 64-70b	47.20	1.28	15.45	4.89	3.91	0.14	6.42	13.71	2.74	0.25	.141	1.42	0.56	2.17	100.23
5-2, 83-88ª	48.90	1.29	15.15	9.0	6	0.15	8.43	10.81	2.95	0.18	.123	2.58		0.55	100.23
6-2, 25-29	48.90	1.25	15.40	5.51	3.79	0.14	7.47	11.69	2.72	0.36	.119	1.19	0.80	0.61	100.10
9-2, 120-125a	48.80	1.22	15.25	9.0	7	0.14	6.58	12.13	2.86	0.31	.054	3.00		1.01	100.42
12-1,95-100b	48.80	1.68	16.72	10.5	3	0.23	3.87	11.52	3.16	0.73	.114	2.35		0.32	100.02
16-2, 20-28b	49.80	1.29	16.46	8.0	6	0.11	6.71	12.13	2.85	0.43	.137	1.39	-	0.03	99.42
443-50-2, 130-135	49.00	1.71	17.05	3.48	6.41	0.25	5.35	11.50	2.98	0.17	.132	1.00	0.25	0.72	100.00
57-1, 71-75	44.20	1.57	13.25	5.21	5.30	0.19	6.65	14.10	2.43	0.43	.155	1.42	0.83	4.21	99.94
57-2, 114-118	47.10	1.82	14.60	6.34	5.55	0.22	5.86	11.70	2.88	0.56	.229	0.79	0.95	1.03	99.63
446A-12-4, 47-53	44,70	3.60	10,90	5.27	5.98	0.22	10.20	11.75	2.07	0.85	.389	2.	17	1.32	99.50
13-1, 17-23	42.50	3.35	13.30	5.64	5.81	0.22	6.86	14.10	2.51	1.22	.412	1.	48	2.30	99.70

^aX-Ray-fluorescence method. ^bStrongly oxidized basalts.