# 22. PETROLOGY AND GEOCHEMISTRY OF NAURU BASIN IGNEOUS COMPLEX: LARGE-VOLUME, OFF-RIDGE ERUPTIONS OF MORB-LIKE BASALT DURING THE CRETACEOUS<sup>1</sup>

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#### ABSTRACT

The 16 samples of Deep Sea Drilling Project (DSDP) Leg 89 basalts that we analyzed for whole rock major and trace elements and for mineralogic compositions are identical to some of the basalts recovered during Leg 61. Leg 89 samples are mostly olivine-plagioclase-clinopyroxene sparsely phyric basalts and exhibit a wide variety of textures. These basalts have lower TiO<sub>2</sub> at a given Mg/(Mg + Fe<sup>2+</sup>) × 100 than MORB (midocean ridge basalt). We recognize three major chemical types of basalts in the Nauru Basin. We believe that different degrees of partial melting, modified by fractional crystallization and possibly by magma mixing at shallow depths, can explain the chemical differences among the three groups. This petrogenetic model is consistent with the observed downhole chemical-chronostratigraphic relations of the samples.

New <sup>87</sup>Sr/<sup>86</sup>Sr and <sup>143</sup>Nd/<sup>144</sup>Nd analyses of basalt samples from DSDP Site 462 indicate that the Nauru Basin igneous complex is within the Sr-Nd isotopic range of ocean island basalt. Thus the Nauru Basin igneous complex resembles MORB in many aspects of its chemistry, morphology, and secondary alteration patterns (Larson, Schlanger, et al., 1981), but not in its isotopic characteristics. If it were not for the unambiguous evidence that the Nauru Basin complex was erupted off-ridge, the complex could easily be interpreted as normal oceanic layer 2. For this reason, we speculate that the Nauru Basin igneous complex was produced in an oceanic riftlike environment when multiple, fast-propagating rifts were formed during the fast seafloor spreading episode in the Cretaceous.

## INTRODUCTION

Midocean ridges commonly produce light-rare-earthelement (LREE) depleted basalts known as "normal midocean ridge basalt," or N-type MORB. Their trace element abundances and isotope ratios indicate that they are produced by melting of a mantle source rock, probably peridotite, which has previously been depleted of large-ion lithophile (LIL) or incompatible trace elements such as U, Rb, K, and La. Previous melting to produce continental crust is widely believed to be a likely cause of this observed depletion of certain portions of the mantle. Instead of producing normal MORB, some ridge crest segments erupt voluminous basalt that apparently is produced by melting of mantle sources relatively less depleted or even enriched (relative to chondritic meteorites) in LREE and other incompatible trace elements (Schilling et al., 1983). These less-depleted mantle sources are similar to those that feed large off-ridge linear island chains and are assumed to be located deeper in the mantle than the strongly depleted source of normal MORB (Gast, 1970; Schilling, 1973).

Recently, this simple picture has been complicated in two major ways. First, additional isotope data, especially <sup>3</sup>He/<sup>4</sup>He data, suggest that the mantle contains at least three and possibly more distinct reservoirs capable of producing basalt (Zindler et al., 1982; Hamelin et al., 1984; Allegre et al., 1983). Second, isotope ratios of small non-hot spot volcanoes near ridge crests provide evidence that the upper mantle source of normal MORB is very heterogeneous and may be capable of producing the range of observed oceanic basalt types (Batiza and Vanko, 1984; Zindler et al., 1984).

The picture that emerges is one of a variably mixed but not completely homogenized upper mantle that contains a variety of ultramafic rocks with diverse and distinct histories. In addition, because the upper mantle is essentially a high-grade metamorphic regime, open-system metasomatic redistribution of volatile chemical components may occur. These superimposed secondary processes can add further complications and hinder simple interpretation of mantle history from basalt compositions and isotope ratios. Despite these complications, however, there is apparently a first-order simplicity to the distribution of oceanic volcanic rocks: mainly depleted tholeiite at ridge crests and mainly less-depleted alkalic basalts off-ridge.

The thick basalt complex in the Nauru Basin is very interesting in this context: whereas most mineralogic and chemical composition features of the basalts of this complex resemble MORB, in others they differ from MORB. Even so, it is apparent from many independent lines of evidence that the Nauru Basin basalts did not originate at a ridge crest. Nauru Basin basalts are, for the most part, depleted in LREE and other incompatible trace elements. However, their isotopic ratios are not in the range of N-type MORB values, and their TiO<sub>2</sub> contents and certain trace element ratios are somewhat unusual for N-type MORB. Furthermore, the Nauru Basin basalts

<sup>&</sup>lt;sup>1</sup> Moberly, R., Schlanger, S. O., et al., *Init. Repts. DSDP*, 89: Washington (U.S. Govt. Printing Office).

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have not built up massive volcanic edifices. Instead, the Nauru Basin basalts form a thick and probably extensive tabular unit. Because the complex consists predominantly of volcanic flows, it has been suggested that it may represent the submarine equivalent of continental flood basalts (see Saunders, this volume). Thick tabular (nonedifice-building volcanism) oceanic basalt complexes are also known to occur in the Caribbean (Bence et al., 1975; Burke et al., 1978) and may be more common on a global basis than previously thought. It is thus possible that MORB-like basalts can erupt in off-ridge environments under certain circumstances.

This chapter presents new mineralogic and chemical data for Leg 89 Nauru Basin basalts and new isotopic data for Leg 61 Nauru Basin basalts. We use these new data, together with previously published data for Leg 61 samples, to interpret the origin of the Nauru Basin complex. Finally, we attempt to integrate our petrogenetic interpretations of the Nauru Basin complex with chronologic information and geophysical characteristics to interpret the tectonic setting of the igneous complex in the context of the geologic history of the central Pacific.

## BACKGROUND

Drilling in the Nauru Basin was initiated at Site 462 (Fig. 1) during DSDP Leg 61 (Larson, Schlanger, et al., 1981); Hole 462A, a deep multiple reentry hole, penetrated about 560 m of pelagic sediments, turbidites, and volcaniclastic sediments and about 500 m of the igneous complex. The site was revisited during DSDP Leg 89; continued drilling at Site 462 recovered an additional 140.5 m of basalt flows. Figure 2 shows the simplified stratigraphy of Hole 462A. The upper part of the igneous complex consists of sills that intrude claystones, silt-stones, and shales containing late Albian (100–105 Ma) fossils. These sills comprise two distinct chemical types (Types 2 and 3), but because they are intrusive bodies, their relative ages are not known. Nevertheless, the base of Type 3 sills (Core 462A-32) was dated by the <sup>40</sup>Ar/<sup>39</sup>Ar method and yielded a reasonably good age of 110  $\pm$  3 Ma (Ozima et al., 1981).

Below the sills and separated by several meters of sediments is a thick sequence of flows that makes up the bulk of the Nauru Basin volcanic complex. Rare sediment horizons within the flow complex are thought to be Aptian (114-108 Ma) (Site 462 report, this volume) but could be as old as late Tithonian (~135 Ma) (Schaaf, this volume). The total 40Ar/39Ar fusion age of a sample from near the top of the flow sequence is  $131 \pm 15$  Ma (Ozima et al., 1981), in agreement with a Rb-Sr isochron age for secondary zeolites and smectites in the flows (127 ±9 Ma, S. Hart, personal communication, 1983). These radiometric ages, though difficult to interpret with confidence, are consistent with a Hauterivian age of eruption for the flows. Inasmuch as precise fossil and radiometric ages of the flow sequence are not available, it is difficult to determine the age range of the two distinct chemical units in the flow sequence. Nevertheless, it is clear that the Type 2 flows were erupted first. Furthermore, if the inferred basement age at Hole 462A (M-26) is about 155 Ma, the entire complex was erupted offridge, and if some of the flows are dated at about 130



Figure 1. Bathymetry of the western and central Pacific showing DSDP Site 462 location and Mesozoic magnetic-lineation patterns (from Larson, 1976). (F.Z. = fracture zone.) (Numbers in parentheses indicate other DSDP sites.)

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Figure 2. Generalized stratigraphy of DSDP Hole 462A, showing the stratigraphic-chemical subdivisions of the lower igneous complex. Core descriptions are from the Site 462 report (this volume). Vertical ruling pattern is for sills and horizontal ruling for flows; unruled areas are sediment. (See Larson, Schlanger, et al., 1981, for criteria used to distinguish basalt types.)

Ma, then this Pacific lithosphere was about 20–25 m.y. old when volcanism occurred. Alternatively, if the radiometric ages are incorrect and if the Aptian sediment ages date the volcanism, the lithosphere was about 40 to 45 m.y. old at the time of off-ridge volcanism. In any case, a second pulse of volcanism (to produce the sills) occurred later: this may have occurred either as much as 20 m.y. after the eruption of the flows or else immediately after their eruption.

Age ambiguities aside, the Nauru Basin igneous complex represents a voluminous and widespread Cretaceous off-ridge magmatic event. Based on seismic reflection data, the igneous complex covers approximately 400,000 km<sup>2</sup> of the western Pacific (Larson, Schlanger, et al., 1981). Hole 462A penetrated at least 600 m of basalts; hence, assuming an average thickness of 0.5 km, Nauru Basin volcanism represents an outpouring of at least 200,000 km<sup>3</sup> of magma. Previous work on the petrologic characteristics of the igneous rocks may be found in Larson, Schlanger, et al. (1981) and Batiza et al. (1980). Additional data and interpretation of Leg 61 and Leg 89 basalts from the bottom of Hole 462A are included here and in other chapters in this volume (e.g., by Saunders and by Floyd).

# **RESULTS AND INTERPRETATION**

We analyzed 16 new samples of basalt recovered during Leg 89. Figure 3 shows their relative positions on the stratigraphic column defined by the Leg 89 shipboard scientists. We analyzed samples from all the igneous cool-



Figure 3. Summary of petrographic characteristics of the Hole 462A samples analyzed in this study. Ol = ol-ivine; Pl = plagioclase; Px = pyroxene; listing of minerals indicates relative abundances of phenocrysts. Arrows denote the locations of samples we analyzed. Dashed line at the bottom of the Unit column indicates the inferred contact between Units 55 and 56.

ing units except for Units 47, 53, and 55. For most units we have only a single sample, but for Units 45, 46, 48, and 52 we have multiple samples. Chemically, the sample set is remarkably homogeneous. We find that chemical differences among samples from the same cooling unit are about as large as the differences among different units. In this chapter we emphasize the homogeneity of the flows, although Floyd (this volume) recognizes subtle distinctions between groups of Leg 89 flows.

## Petrography

Thirteen of the sixteen specimens we examined are sparsely phyric (<3% phenocrysts) and the remaining three are aphyric and coarse grained (see Fig. 3). All samples including the coarse-grained aphyric samples from Units 48 and 52 show clear petrographic evidence of having been multiply saturated with olivine, plagioclase, and clinopyroxene at the time of eruption. All the samples we examined have euhedral to subhedral olivine phenocrysts and microphenocrysts that are now entirely pseudomorphed by secondary minerals. In addition, all but the coarse-grained samples from Unit 48 and Unit 52 (Core 462A-106) have clearly recognizable phenocrysts and microphenocrysts of plagioclase and clinopyroxene. The latter are distinguished by their larger size, subhedral form, common twinning, and concentric or sector zonation from groundmass crystals that may be either granular or interstitial.

Average grain sizes and textures vary from fine-grained quench textures to intergranular, and holocrystalline, equigranular, and subdiabasic textures (e.g., Unit 52, Section 462A-106-2). We recognize no systematic mineralogic or textural variations downhole. The textures of all the rocks we examined, including the three coarse-grained samples, are patchy. In hyalopilitic to intersertal-texture samples, this patchiness is defined by zones that differ greatly in the abundance of groundmass clinopyroxene. In medium to coarse-grained rocks, pyroxene-rich and pyroxene-poor patches can also be distinguished, but, in addition, patches of different grain sizes and textures are present. The majority of samples are hyalopilitic to intergranular and have about 10 to 20% interstitial mesostasis that is now entirely replaced by secondary minerals. Groundmass phases in the samples are clinopyroxene, plagioclase, Fe-Ti oxides, rare pigeonite, plus a variety of secondary phases (see Floyd, this volume).

## Plagioclase

As expected, plagioclase phenocrysts are more calcic than groundmass plagioclase in the same rock (see Table 1 and Fig. 4), but both are usually zoned. Phenocrysts and microphenocrysts range from  $An_{83}$  to about  $An_{50}$ . Individual crystals are usually normally zoned, with a range of 6 mole% An from core to rim. Groundmass plagioclase laths vary from  $An_{70}$  to about  $An_{46}$ , with a range of about 16 mole% An among groundmass crystals from the same rocks. In all these characteristics, including very low K<sub>2</sub>O content, the Leg 89 plagioclase resembles plagioclase from basalts recovered by Leg 61.

### Pyroxenes

Electron microprobe analyses of pyroxene are given in Table 2 and summarized in Figure 5. As with Leg 61 pyroxenes, the Leg 89 samples exhibit systematic relationships between pyroxene texture and chemistry. With only two exceptions (Unit 46, Sections 462A-96-1 and 462A-98-1), clinopyroxene phenocrysts are more Mg- and Ca-rich than groundmass crystals in the same rock. Section 462A-96-1 has coexisting diopsidic augite and magnesian pigeonite in the groundmass, whereas in Section 461A-98-1, phenocrysts and groundmass crystals are of the same composition (diopsidic augite). Augite phenocrysts exhibit minor (about 2 mole% En) chemical zoning that is both normal and reverse. In contrast, usual

Table 1. Representative microprobe analyses of plagioclase from DSDP Hole 462A.

					S	Sample (co	re-section, (Unit)	interval in	cm)					
	1	93-1, 103-1 (45)	04	95-1, (4	38-42 15)	96-1, 39-43 (46)				103-1, 91–95 (50)	108-2, 12-16 (52)		109-3, 33-35 (56)	
		м		Р			Р	м			м		м	
	С	R	G	Ē	G	С	R	c	G	G	c	G	C	G
Component	(wt.%)													
SiO <sub>2</sub>	51.98	54.43	52.36	48.50	56.43	47.56	49.17	49.82	53.35	52.20	50.82	51.60	53.36	53.03
Al2O3	29.99	29.68	30.24	32.73	27.28	32.81	32.37	31.51	28.44	30.17	31.98	30.82	29.07	30.04
FeO	0.80	0.82	0.97	0.54	0.91	0.57	0.50	0.58	1.09	1.05	0.62	0.84	1.13	0.95
MgO	0.14	0.17	0.21	0.22	0.19	0.23	0.23	0.20	0.10	0.40	0.25	0.24	0.57	0.32
CaO	12.91	12.36	12.87	16.07	9.22	16.45	15.29	14.28	11.58	13.14	14.20	13.42	12.72	12.80
Na <sub>2</sub> O	3.98	4.36	3.91	2.64	5.95	1.98	2.64	3.46	4.61	3.32	3.32	3.75	3.92	4.10
K2Ō	0.04	0.04	0.07	0.03	0.08	0.00	0.02	0.03	0.10	0.04	0.00	0.03	0.05	0.03
Total	99.86	100.90	100.65	100.73	100.08	99.61	100.25	99.90	99.29	100.32	101.19	100.72	100.82	101.27
Cations (O	= 8)													
Si	2.368	2.404	2.367	2.211	2.538	2.193	2.243	2.280	2.439	2.365	2.290	2.335	2.407	2.381
Al	1.611	1.574	1.611	1.759	1.447	1.783	1.741	1.700	1.532	1.611	1.699	1.643	1.545	1.590
Fe	0.031	0.031	0.037	0.021	0.034	0.022	0.019	0.022	0.042	0.040	0.023	0.032	0.043	0.036
Mg	0.010	0.012	0.014	0.015	0.013	0.016	0.016	0.014	0.007	0.027	0.017	0.016	0.038	0.022
Ca	0.630	0.596	0.624	0.785	0.445	0.813	0.748	0.700	0.567	0.638	0.686	0.651	0.615	0.616
Na	0.352	0.381	0.344	0.234	0.520	0.177	0.234	0.307	0.409	0.292	0.291	0.330	0.343	0.358
K	0.002	0.003	0.004	0.002	0.004	0.000	0.001	0.002	0.006	0.002	0.000	0.001	0.003	0.002
An‰	64.0	60.9	64.2	76.9	45.9	82.1	76.1	69.4	57.8	68.5	70.2	66.3	64.0	63.1
Ab%	35.8	38.9	35.4	22.9	53.7	17.9	23.8	30.4	41.6	31.3	29.8	33.6	35.7	36.7
Or%	0.2	0.3	0.4	0.2	0.4	0.0	0.1	0.2	0.6	0.2	0.0	0.1	0.3	0.2

Note: P = phenocryst; M = microphenocryst; G = groundmass; C = core; R = rim. Probe conditions for these and data in Table 2 are 15 kV accelerating voltage; 20-40 namp beam current; counting times for minor elements (<1 wt.%) were 20 to 25 s, and for major elements were 10 to 25 s. The matrix correction procedure is that described by Bence and Albee (1968) and uses the correction parameters calculated by the procedure given by Albee and Ray (1970).



Figure 4. Albite (Ab)-anorthite (An)-orthoclase (Or) contents of DSDP Leg 61 (upper diagram) and DSDP Leg 89 (lower diagrams) plagioclases. Leg 61 data are from Tokuyama and Batiza (1981). Inset shows a composite of plagioclase compositions (P = phenocrysts) for the oceanic crust (Basaltic Volcanism Study Project, 1981).

differences between phenocrysts and groundmass pyroxene are much larger (up to 20 mole% En, 12 mole% Wo). Leg 61 pyroxenes exhibit very similar trends (Fig. 5).

Phenocrysts and groundmass pyroxene also differ greatly in Cr content as shown by Figure 6. Furthermore, Cr content is systematically related to Fe/Mg. Phenocrysts are generally Cr- and Mg-rich, whereas corresponding groundmass crystals are Cr-poor and Fe-rich. Table 2 shows that Cr content and Ti content are generally correlated in Leg 89 pyroxenes.

## **Chemical Composition**

### **Major Element Abundances**

Table 3 gives major element chemical analyses for 16 Leg 89 samples along with trace element abundances and partial normative mineralogy. The ranges of SiO<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, MgO, and CaO contents are remarkably narrow and barely exceed analytical uncertainty. Variations of Fe<sub>2</sub>O<sub>3</sub>, Fe<sup>2+</sup>/Fe<sup>3+</sup>, MnO, and K<sub>2</sub>O are a bit greater, but these may be partly the result of alteration (see Floyd, this volume; Saunders, this volume). The samples are moderately fractionated [Mg/(Mg + Fe<sup>2+</sup>) × 100 = 57-62] and are all quartz normative (using measured Fe<sub>2</sub>O<sub>3</sub> and FeO) or both olivine-hypersthene and quartz normative (assuming that Fe<sub>2</sub>O<sub>3</sub>/FeO = 0.2; see Fig. 7).

Figure 8 shows variation patterns for P<sub>2</sub>O<sub>5</sub>, FeO\*/ MgO, CaO/TiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> versus TiO<sub>2</sub> for Leg 89 and Leg 61 basalts with fields for midocean ridge basalt (MORB) for reference. TiO2 is a useful reference element because it is relatively insensitive to low temperature alteration (Bryan et al., 1981; Sun et al., 1979; Pearce and Cann, 1973). Figure 8 shows that Nauru Basin basalts share some, but not all, characteristics of their major element composition with MORB. Moreover, these plots show very clearly that the Nauru basin basalts comprise three distinct chemical groups (see Fig. 2): Type 1-low (0.85-1.06%) TiO<sub>2</sub> basalts from about Cores 43-Core 80; Type 2-an intermediate (1.03-1.30%) TiO<sub>2</sub> group that occurs in the lower sill complex (Cores 35-42) and below Core 80 (i.e., Type 2 includes all Leg 89 samples); and Type 3-high (1.34 to 2.18%) but variable TiO<sub>2</sub> contents from the upper sill complex of Holes 462A and 462. In general, Nauru Basin basalts are systematically lower in TiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> contents but higher in CaO contents than MORB for a given Mg/(Mg +  $Fe^{2+}$  × 100 (not shown in the figure).

### **Trace Element Abundances**

Saunders (this volume) and Floyd (this volume) give trace element data for Leg 89 and Leg 61 basalts from Hole 462A. To these and previously available data in

							5	Sample (con	re-section, (Unit)	interval in	n cm)								
	95-1, (4	38-42 15)	2	96-1, 39–4 (46)	3	103-1.	, 91-95 50)	1	04-2, 75-7 (51)	9	1	108-2, 12- (52)	16		108-3, 44-4 (54)	48		109-3, 33-3 (56)	35
		м		м		м		N	4		1	м		м			1	м	
	G	G	с	R	G	c	G	С	R	G	С	R	G	С	R	G	С	R	G
Component	(wt.%)																		
SiO <sub>2</sub>	49.97	49.98	52.26	51.90	53.05	52.07	49.84	51.86	52.37	50.38	51.50	52.27	50.23	51.15	52.53	51.21	51.24	52.42	48.45
TiO <sub>2</sub>	0.77	0.75	0.30	0.05	0.42	0.24	0.74	0.29	0.15	0.61	0.23	0.26	0.12	0.66	0.30	0.54	0.14	0.61	1.03
Al <sub>2</sub> O <sub>3</sub>	1.62	2.02	2.36	2.39	1.52	2.10	3.11	2.46	1.72	2.62	2.41	2.29	2.71	3.55	1.91	3.09	3.45	1.96	4.48
FeO	19.17	18.43	7.09	7.13	14.53	6.85	11.63	7.35	7.70	15.68	7.82	6.78	12.91	8.14	7.91	9.12	7.67	7.60	16.48
MnO	0.41	0.55	0.18	0.15	0.34	0.18	0.27	0.17	0.20	0.30	0.19	0.27	0.30	0.17	0.18	0.25	0.32	0.18	0.37
MgO	11.49	15.00	17.32	17.25	22.72	17.07	15.07	17.59	18.67	16.56	17.64	17.43	16.04	16.88	17.61	17.29	17.57	17.70	14.43
CaO	17.15	13.68	19.50	19.62	6.92	19.13	17.89	17.99	17.62	12.76	18.11	19.25	16.41	17.90	18.36	17.05	18.08	18.56	13.63
Na <sub>2</sub> O	0.18	0.19	0.19	0.18	0.08	0.19	0.19	0.18	0.15	0.14	0.17	0.20	0.20	0.22	0.19	0.17	0.20	0.18	0.24
K <sub>2</sub> O	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr2O3	0.00	0.02	0.48	0.46	0.04	0.39	0.03	0.49	0.25	0.02	0.36	0.44	0.03	0.48	0.21	0.21	0.36	0.20	0.03
NiO	0.10	0.03	0.22	0.02	0.01	0.07	0.04	0.04	0.02	0.02	0.00	0.04	0.03	0.17	0.01	0.07	0.04	0.05	0.09
Total	100.87	100.68	99.91	99.17	99.66	98.29	98.84	98.42	98.85	99.13	98.46	99.25	99.01	99.18	99.24	99.03	99.11	99.48	99.17
Cations (O	= 6)																		
Si	1.921	1.900	1.925	1.926	1.949	1.943	1.891	1.932	1.943	1.910	1.924	1.933	1.905	1.898	1.945	1.908	1.901	1.936	1.854
Ti	0.022	0.022	0.008	0.001	0.012	0.007	0.021	0.008	0.004	0.018	0.007	0.007	0.004	0.018	0.009	0.015	0.004	0.017	0.030
Al	0.073	0.091	0.102	0.104	0.066	0.092	0.139	0.107	0.075	0.117	0.106	0.100	0.121	0.155	0.083	0.136	0.151	0.085	0.202
Fe	0.616	0.586	0.219	0.222	0.446	0.214	0.369	0.229	0.241	0.497	0.244	0.210	0.409	0.253	0.245	0.284	0.238	0.235	0.527
Mn	0.013	0.018	0.006	0.005	0.011	0.006	0.009	0.005	0.006	0.010	0.006	0.009	0.010	0.005	0.006	0.008	0.010	0.006	0.012
Mg	0.658	0.851	0.951	0.955	1.245	0.950	0.853	0.977	1.032	0.936	0.983	0.961	0.907	0.934	0.972	0.960	0.972	0.975	0.818
Ca	0.706	0.557	0.770	0.780	0.272	0.765	0.727	0.718	0.701	0.518	0.725	0.763	0.667	0.712	0.728	0.680	0.719	0.734	0.559
Na	0.013	0.014	0.013	0.013	0.006	0.014	0.014	0.013	0.011	0.011	0.012	0.014	0.015	0.016	0.013	0.012	0.015	0.013	0.018
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cr	0.000	0.001	0.014	0.013	0.001	0.012	0.001	0.014	0.007	0.000	0.011	0.013	0.001	0.014	0.006	0.006	0.011	0.006	0.001
Ni	0.003	0.001	0.007	0.000	0.000	0.002	0.001	0.001	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.002	0.238	0.001	0.003
En‰	33.0	42.3	48.9	48.7	63.1	49.1	43.6	52.3	53.0	47.7	50.2	49.5	45.5	49.1	49.8	49.7	50.1	50.0	42.7
Fs%	31.6	30.0	11.5	11.5	23.2	11.3	19.3	12.5	13.3	25.8	12.8	11.2	21.0	13.6	12.9	15.1	12.8	12.3	28.1
Wo %	35.4	27.7	39.6	39.8	13.8	39.5	37.2	35.3	33.7	26.4	37.0	30.3	33.5	37.4	37.3	35.2	37.1	37.7	29.2

Table 2. Representative microprobe analyses of pyroxene from DSDP Hole 462A.

Note: Abbreviations as in Table 1.

Larson, Schlanger, et al. (1981) we add 16 trace element analyses determined by instrumental neutron activation (Table 3). In general, the trace element abundances of Nauru Basin basalts fall well within the range for MORB. For example, Figure 9 shows that Nauru Basin basalts are depleted in LREE. As for the major elements and mineralogic characteristics (almost all are Ol-Pl-Cpx sparsely phyric), the trace elements of Leg 89 basalts do not vary greatly: Sc = 47-52 ppm, Cr = 120-200 ppm, Hf = 1.81-2.12 ppm, Ta = 0.17-0.27 ppm. Figure 10 shows that the average chondrite-normalized (Haskin et al., 1968) La/Sm of Nauru Basin basalts is roughly constant (about 0.69) for the two chemical types (Types 1 and 2) and also that as a group they are slightly less depleted in LREE than N-type MORB samples. The three distinct chemical types recognized on the basis of major elements can also be clearly distinguished on the basis of trace elements. For example, Figure 11 shows the three distinct types on a plot of (La/Sm)<sub>N</sub> versus Sm abundance.

## **Stratigraphic Trends**

As stated earlier, the three distinct chemical types of basalts in Hole 462A are stratigraphically restricted (see Fig. 2). Figure 12 shows in greater detail that Leg 61 samples plus Leg 89 samples from Core 462A-80 to the bottom of the hole belong to Type 2 (intermediate TiO<sub>2</sub> and La) flows. Overlying these flows, from Core 462A-43 to Core 462A-79, are flows of Type 1 (lowest TiO<sub>2</sub> and La). The sill complex, which must be younger than the flows, consists of a lower part of Type 2 sills and an upper part of Type 3 (highest TiO<sub>2</sub> and La) sills. To a first

order, the pattern displayed in Hole 462A is of a 250-mthick unit of low  $TiO_2$  and La basalts more or less symmetrically sandwiched between thinner packets of more  $TiO_2$ - and La-rich basalts.

The stratigraphic trends shown in Figures 2 and 12 are consistent with those presented by Saunders (this volume) and Seifert (1981) except for the twofold subdivision of the upper sill complex. It should be noted that we did not base this subdivision on chemistry and volcanic stratigraphy alone, but also on the (1) different mean stable inclinations of Cores 14 to 32 (upper sills) and Cores 36 to 41 (lower sills) ( $-51.8 \pm 7.2^{\circ}$ , N = 35, and  $-42.5 \pm 11.2^{\circ}$ , N = 12, respectively), and (2) distinct and systematic differences in the Curie temperature, magnetic inclinations, and NRM paleomagnetic intensities of the opaque mineral contents of the upper and the lower sills (Steiner, 1981a and 1981b).

# **Isotopic Ratios**

Table 4 gives isotope dilution values of Rb, Sr, Ba, Ce, Nd, and Sm as well as <sup>87</sup>Sr/<sup>86</sup>Sr and <sup>143</sup>Nd/<sup>144</sup>Nd for a Type 2 flow from Hole 462A and a Type 3 sill from Hole 462. Present-day values are indistinguishable from age-corrected values of Sr and Nd isotopes. The <sup>87</sup>Sr/ <sup>86</sup>Sr values we present here are identical to those reported by Fujii et al. (1981) for Leg 61 samples and the uniform <sup>87</sup>Sr/<sup>86</sup>Sr ratio for these basalts is an excellent indication that the Nauru Basin igneous complex came from a common source. Figure 13 shows that the Nauru Basin isotope values are outside the range for <sup>87</sup>Sr/<sup>86</sup>Sr but near typical N-type MORB values for <sup>143</sup>Nd/<sup>144</sup>Nd. The slight displacement from the mantle array toward higher



Figure 5. Pyroxene compositions for DSDP Site 462 basalts. Diopside (DI)-hedenbergite (HD)-enstatite (EN)-ferrosilite (FS) quadrilateral components were calculated on the basis of Fe as FeO. Upper diagram shows pyroxene compositions for DSDP Leg 61 basalts (Tokuyama and Batiza, 1981) with the Skaeergaard igneous complex trend of pyroxene crystallization as reference. In lower diagram, DSDP Leg 89 pyroxene compositions are shown, with symbols as in Figure 4.

<sup>87</sup>Sr/<sup>86</sup>Sr could be due to Sr exchange with seawater, but two lines of evidence argue against this possibility. First, leaching experiments do not affect the measured <sup>87</sup>Sr/ <sup>86</sup>Sr (Fujii et al., 1981), and, second, the measured values for 18 samples (see Table 4; and Fujii et al., 1981) are very similar, not highly scattered as would be expected from seawater exchange. These isotope values are similar to those of oceanic island type basalts (Fujii et al., 1981; Mahoney, 1984). The data of Table 4, therefore, show the most striking differences between Nauru Basin basalts and N-type MORB.

## PETROGENESIS

In this section we focus on the evolution of the Nauru Basin basalts. First, we discuss possible petrogenetic relationships among the three chemical groups of Hole 462A basalts. We consider the possibilities that the three groups could be either related by simple shallow fractionation processes or represent distinct mantle melts with shallow fractionation effects superimposed. Second, we discuss some of the possible causes of the observed chemical differences between Nauru Basin basalts and MORB. Later, in the discussion section, we consider the origin of the Nauru Basin basalts in the broader context of their tectonic setting by comparison with off-ridge eruptive products in other oceanic regions.

In the following discussion, we assume that the compositions of Nauru Basin basalts are close to their original magmatic compositions. This assumption is clearly violated for volatile elements and perhaps also certain other components that are sensitive to secondary alteration processes (like K, Na, Mn, FeO/Fe<sub>2</sub>O<sub>3</sub>). Nevertheless, for most elements of interest, it is reasonable to assume that the composition of these basalts has not been greatly affected by phenocryst accumulation or by alteration processes, because Nauru Basin basalts are generally aphyric and only moderately altered; this is shown by the low water content (see Table 3; and Batiza et al., 1981), low oxidation state of opaques (Steiner, 1981b), and the small variation of major and trace elements of most of the samples analyzed (see Figs. 8-10; also Shcheka, 1981; Seifert, 1981; Tokuyama and Batiza, 1981). Coherent behavior of many of these elements would not be expected if these rocks had been subjected to great extents of seawater weathering (Ludden and Thompson, 1979; Seyfried and Bischoff, 1979). Whole Rock  $\delta^{18}$ O analyses (Batiza et al., 1981) also indicate that Nauru Basin basalts had been subjected to only about 5% al-



Figure 6. Variation of  $Cr_2O_3$  (wt.%) with the  $Fe^{2+}/(Fe^{2+} + Mg)$  ratio of pyroxenes, DSDP Leg 89 samples. Area enclosed by dashed lines is for DSDP Leg 61 samples (Tokuyama and Batiza, 1981); symbols are as in Figure 4. Solid lines connect phenocrysts and groundmass crystals. Broken lines connect cores and rims of zoned phenocrysts.

teration on the average, which is low compared to oceanic layer 2 samples of comparable age in the Atlantic (Muehlenbachs, 1980). Hence, the chemical effects of alteration on Site 462 basalts are not expected to be large, which means that the systematic geochemical variations of the basalts are most probably the result of primary magmatic processes and not of postsolidification alteration or other processes. The only possible exceptions to this are some of the rocks from the upper parts of the sill complex. Some of the upper sills contain granophyric patches and two generations of amphiboles produced by late magmatic alteration (Batiza et al., 1981).

## **Fractional Crystallization**

Qualitatively, the chemical differences among Types 1, 2, and 3 basalts are similar to those exhibited by many suites of oceanic basalts that are thought to be related by low pressure differentiation processes like loss of early-formed mineral phases. The expected chemical effects of such processes displayed by the groups of Nauru Basin basalts include: (1) increase of alkalies, and incompatible trace elements with decreasing  $Mg/(Mg + Fe^{2+})$  $\times$  100; (2) decrease of CaO and compatible trace elements with decreasing Mg/Fe; and (3) little change of most incompatible element ratios. Figure 14 shows that Nauru Basin samples are multiply saturated with olivine, plagioclase, and clinopyroxene in agreement with petrographic observations, suggesting that subtraction of these phases from relatively primitive liquids to yield more evolved liquids is reasonable. However, Figure 14 shows that samples from each type display a great deal of scatter: no consistent relationships among the types of basalts are evident on this diagram. In contrast, Figures 8, 10, and 11 suggest that Types 1, 2, and 3 may be related to each other by a simple process. Figure 15 shows that the Zr and Ni abundances of Site 462 basalts are only questionably consistent with the hypothesis that they could all be related by fractional crystallization. It shows that the samples exhibit a great deal of scatter and that many Type 2 samples deviate significantly from the expected Zr-Ni "crystallization" trend.

To test this hypothesis quantitatively we employed a mixing program similar to that of Bryan et al. (1969). In these model calculations we used the chemical compositions of phenocrysts observed in the parental liquid. Table 5A shows that the residuals obtained in the production of average Type 2 basalt from average Type 1 basalt by the subtraction of olivine, spinel, clinopyroxene, and plagioclase are very small ( $R^2 = 0.086$ ). So it is reasonable to assume that Type 2 melt could be derived from Type 1 parent magma through fractional crystallization. The residuals obtained in the production of average Type 3 basalt from average Type 1 basalt are relatively much larger (Table  $6A-R^2 = 1.094$ ). We have tried other models, including the production of Type 3 by fractionating Type 2 basalts, but all give fairly poor results. Part of the problem could be in averaging analyses for the highly variable Type 3 basalts. In any case, simple fractional crystallization alone does not give a satisfactory solution for the derivation of Type 3 melt from Type 1 or Type 2 parent magma.

We tested this hypothesis further by computing the predicted trace element abundances for derived liquids. For this we computed bulk partition coefficients for the

							Sample	e (core-secti (U	on, interval nit)	in cm)							_		
	93-1, 103-104 (45)	94-4, 69-75 (45)	95-1, 38-42 (45)	96-1, 39-43 (46)	96-4, 105-106 (46)	97-2, 33-37 (46)	98-1, 46-50 (46)	100-3, 15-20 (48)	101-2, 64-68 (48)	102-5, 19-21 (49)	103-1 91-95, (50)	104-2 75-79, (51)	106-2 75-80, (52)	108-2 12-16, (52)	108-3 44-48, (54)	109-3 33-35, (56)	Average type 1 (N = 18)	Average type 2 (N = 22)	Average type 3 (N = 19)
Major element (wt.%)																			
	49.8 1.23 13.6 8.63 4.11 0.20 6.97 11.4 2.12 0.03 0.12 0.29 0.96 0.02 99.48	49.9 1.22 13.8 7.99 3.82 0.19 6.96 11.6 2.15 0.04 0.11 0.31 0.90 0.02 99.01	50.2 1.18 13.6 8.79 3.63 0.21 7.26 11.5 2.16 0.05 0.10 0.29 0.83 0.01 99.81	49.9 1.23 13.6 9.52 0.21 7.03 11.5 2.13 0.06 0.11 0.51 0.62 0.02 99.56	49.2 1.20 13.8 7.87 4.05 0.21 7.31 11.7 2.22 0.03 0.11 0.39 1.12 0.04 99.25	49.8 1.21 13.7 8.76 0.19 7.03 11.5 2.10 0.04 0.12 0.38 0.92 0.02 99.53	49.9 1.22 13.6 9.29 3.17 0.21 7.02 11.6 2.11 0.03 0.11 0.39 0.68 0.02 99.35	49.3 1.20 14.1 8.32 4.05 0.20 7.10 11.4 2.42 0.02 0.11 0.63 0.02 99.60	50.5 1.18 13.9 8.21 3.47 0.20 6.99 11.3 2.48 0.02 0.11 0.45 0.52 0.02 99.35	48.4 1.21 13.9 8.98 3.62 0.23 7.08 11.8 2.18 0.06 0.11 0.42 0.68 0.03 98.70	49.1 1.20 14.0 8.94 3.66 0.23 7.11 11.8 2.30 0.04 0.12 0.33 0.71 0.02 99.56	48.8 1.20 13.8 8.53 4.22 0.23 7.24 11.6 2.37 0.03 0.12 0.35 0.92 0.03 99.44	50.2 1.18 13.7 8.93 3.57 0.21 6.96 11.2 2.19 0.19 0.11 0.57 0.58 0.02 99.61	50.0 1.18 13.6 8.81 3.51 0.20 7.02 11.4 2.24 0.03 0.11 0.42 0.72 0.04 99.28	48.7 1.26 13.8 8.88 3.93 0.23 7.05 11.6 2.40 0.03 0.12 0.42 0.42 0.42 0.42 0.99.26	48.9 1.30 13.4 9.27 3.90 0.25 7.06 11.1 2.63 0.03 0.13 0.66 0.79 0.02 99.44	49.37 1.00 14.50 10.71 0.20 8.08 11.75 2.06 0.05	49.60 1.20 13.28 12.00 0.21 7.30 11.50 2.22 0.05	49.51 1.60 13.98 12.4 0.22 7.04 10.61 2.36 0.20
Trace element (ppm) La Ce Sm Eu Tb Yb Lu Sc Cr Cr Co Hf Ta Th	3.29 9.21 2.62 0.976 0.82 2.71 0.427 49.0 181 49 2.05 0.232 0.15	3.11 9.97 2.64 0.999 0.83 2.78 0.434 50.1 190 51 2.06 0.270 0.25	2.82 8.79 2.46 0.987 0.82 2.69 0.416 48.7 189 49 1.81 0.217 0.15	3.36 9.89 2.63 1.041 0.73 2.69 0.436 49.3 192 50 2.02 0.234 0.27	3.21 9.57 2.58 1.007 0.80 2.72 0.438 49.5 202 50 1.82 0.219 0.17	3.25 9.45 2.61 1.010 0.76 2.72 0.436 49.5 195 50 2.00 0.233 0.18	3.16 9.34 2.56 0.928 0.68 2.69 0.419 47.2 180 48 1.81 0.202 0.28	3.43 9.77 2.6 1.023 0.85 2.78 0.434 51.8 161 52 2.02 0.235 0.19	3.23 9.91 2.57 1.015 0.84 2.74 0.423 50.4 168 51 1.95 0.171 0.21	3.23 9.50 2.6 1.026 0.75 2.77 0.428 49.8 151 50 2.00 0.185 0.36	3.30 9.21 2.53 1.095 0.75 2.71 0.431 50.2 145 51 2.05 0.207 0.23	3.10 9.23 2.55 1.009 0.80 2.71 0.427 49.4 147 50 1.93 0.225 0.19	3.44 10.66 2.6 0.981 0.76 2.74 0.424 49.4 142 50 2.03 0.173 0.37	3.21 9.83 2.54 0.980 0.76 2.58 0.422 49.1 152 50 1.95 0.177 0.20	3.45 10.66 2.68 1.060 0.87 3.02 0.432 50.2 127 51 2.00 0.23 0.17	3.56 10.44 2.81 1.130 0.86 2.86 0.459 51.8 121 53 2.12 0.158 0.23	2.47 6.81 2.06 0.76 0.54 2.12 0.33 46 354 50	3.28 9.72 2.66 1.01 0.76 2.78 0.43 49 176 50	4.77 12.89 3.50 1.24 0.86 3.21 0.49 47 182 51
Partial CIPW norms Q Or + Ab + An Di Hy Mg/(Mg + Fe <sup>2+</sup> ) × 100 (for Fe <sup>2+</sup> as analyzed)	4.07 45.63 22.99 16.94 59.0	4.09 46.32 23.48 15.77 60.8	3.28 45.85 23.76 18.07 59.6	2.70 45.74 23.70 19.14 56.8	2.64 46.57 23.95 16.10 62.3	3.64 45.85 23.16 17.54 58.9	3.00 45.58 23.94 18.56 57.5	1.86 48.15 22.96 16.83 60.3	3.02 47.85 23.25 16.71 60.3	1.00 46.77 24.30 17.68 58.4	1.12 47.76 24.46 17.59 58.6	1.22 47.17 24.18 16.88 60.2	3.28 46.64 22.72 18.11 58.2	3.22 46.11 23.43 17.73 58.7	0.89 47.28 24.42 17.04 58.6	0.42 47.11 24.12 17.90 57.6	1.97 47.90 22.70 18.11 66.4	2.71 45.21 25.17 16.78 60.4	2.60 48.11 20.89 17.76 59.0

Note: 1. Leg 89 samples have been analyzed for major elements by X-ray fluorescence (XRF) techniques and for FeO, H<sub>2</sub>O<sup>+</sup>, H<sub>2</sub>O<sup>-</sup>, and CO<sub>2</sub> by wet chemical methods at U.S.G.S., Branch of Analytical Chemistry, Lakewood, Colorado 80225 (courtesy of Dr. D. Clague). Trace element analyzes were carried out using the instrumental neutron-activation analysis (INAA) methods described by Jacobs et al. 91977). Analytical precision for the trace elements has been reported by Batiza (1981). Major element data used in calculating the average compositions of the three basalt types are from Shcheka (1981), Tokuyama and Batiza (1981) and this chapter; trace element data are from Batiza (1981), Seifert (1981), and this chapter.



Figure 7. Projection of the normative basalt tetrahedron for representative DSDP site basalts. Filled circles are for DSDP Leg 89 samples; open circles for DSDP Leg 61 samples (Shcheka, 1981; Tokuyama and Batiza, 1981).

solid assemblages that gave the best fit for major elements. These solid assemblages consist mostly of labradorite and augite with small amounts of olivine and Fe-Ti oxides, which are consistent with experimental basalt crystallization data (Basaltic Volcanism Study Project, 1981; Bender et al., 1978) and models for the producing MORB ferrobasalts (Clague and Bunch, 1976). Tables 5B and 6B also show that the predicted trace element abundances, using literature values for crystal-liquid partition coefficients and a perfect fractional crystallization model, closely match the observed abundances for average Type 2 basalt but not for average Type 3 basalt.

Therefore, based on the preceding calculations, we can conclude that a simple crystal fractionation model seems to explain the compositional differences between Types 1 and 2 basalts. However, this explanation is not supported by the data for differences between Types 1 and 3 and between Types 2 and 3 basalts. Furthermore, three other observations keep us from suggesting that such a model is an adequate explanation for the petrogenesis of the Nauru Basin basalts. First, the La/Sm (Fig. 10) and Rb/Sr (Table 4; and Fujii et al., 1981) ratios for Type 3 basalts are higher than those for Types 1 and 2 basalts. Many workers have argued that fractional crystallization, especially at only about 35% crystallized (from Table 6A and B), cannot effectively change these ratios (Basaltic Volcanism Study Project, 1981; Haskin, 1983). Second, the Nauru Basin basalts comprise three distinct groups, rather than a continuous series of basalts with smoothly varying compositions, as expected for a simple model of continuous fractionation. The third problem has to do with the observed stratigraphicchemical relations. Instead of more and more fractionated basalts being younger than the most primitive (parental) composition, the most primitive Nauru Basin basalts are sandwiched between series of fractionated basalts.

It could be argued that the increase in La/Sm and Rb/Sr values is probably due to alteration. Altered samples of Site 462 basalts though, have lower total REE contents than the unaltered samples (Seifert, 1981). Almost all of the Type 3 basalts that have higher La/Sm ratios also have the highest total REE concentrations.

#### **Partial Melting**

Previous melting studies have shown that Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> and CaO/TiO2 ratios increase as TiO2 decreases with increasing amount of partial melting of peridotite (Jacques and Green, 1980; Sun et al., 1979). As shown by Figure 8B and D, the Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> and CaO/TiO<sub>2</sub> increase as TiO<sub>2</sub> decreases from basalt Types 3 to 2 to 1 of Nauru Basin. Each of the basalt types forms a discrete cluster and the overall trend parallels the inferred partial melting trend of MORB (Sun et al., 1979). Partial melting is also more effective in increasing the La/Sm and Rb/Sr values than fractional crystallization (Basaltic Volcanism Study Project, 1981; Haskin, 1983), especially for rocks that do not show a wide range of compositional variation like the Nauru Basin basalts. And because the three basalt types have identical 87Sr/86Sr values, we suggest that Types 1, 2, and 3 could represent different degrees of partial melt of a common peridotite source.

We recognize that this model cannot explain all aspects of the observed chemical variation of Nauru Basin basalts as there are no basalts in either Types 1, 2, or 3 that could be primary melts of peridotite on the basis of some of the commonly accepted criteria for recognizing



Figure 8. Variations in FeO\*/MgO(A), Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub>(B), P<sub>2</sub>O<sub>5</sub>(C), and CaO/TiO<sub>2</sub>(D) as functions of TiO<sub>2</sub> for representative DSDP Site 462 basalts. Open triangles are for samples from Lithologic Units 22 to 39 (Type 1), filled circles are for samples from Units 13 to 21 and 40 to 56 (Type 2), and open circles are from samples from Units 1 to 12 (Type 3). Fields for mid-ocean ridge basalts (MORB), ocean island tholeites (OIT) and oceanic island basalts (OIB) in C are from Bass et al. (1973); the field for FAMOUS area basalts in A is from Bryan et al. (1976); and the MORB fields in C and D are from Sun et al. (1979). DSDP Site 462 data are from Shcheka, (1981), Tokuyama and Batiza (1981), Site 462 report, DSDP Leg 61 volume, Larson, Schlanger, et al. (1981); and this chapter.

primitive liquids: (1) Mg number  $\sim$  70, and (2) Ni contents >210 ppm (Basaltic Volcanism Study Project, 1981; Frey et al., 1978; Fujii and Bougault, 1983). All Site 462 samples are somewhat fractionated. Nevertheless, the most primitive analyzed compositions of Types 1 and 2 basalts closely approach inferred primary melt compositions and could be only slightly modified by early crystallization of olivine and possibly minor amounts of spinel  $\pm$  plagioclase  $\pm$  clinopyroxene. Thus to a first order, adding olivine (Fo<sub>90</sub>) until the Mg number approached 70 will create "model" primary liquid composition for each basalt type (Frey et al., 1978). The results of such calculations are presented in Table 7. We recognize that this exercise is not strictly correct, but the firstorder models that we explore are not sensitive to these simplifying assumptions, as shown by the work of Frey et al. (1978) and Wright and Fisk (1971).

Table 8 shows the results of some very simple melting calculations for the major elements. We have started with a fairly refractory pyrolite composition from Sun et al. (1979) as a source. Because TiO<sub>2</sub> shows fairly good correlation with La (Figs. 12 and 16), we assume that Ti is perfectly incompatible during melting and compare the TiO<sub>2</sub> abundances of our "primitive" Types 1, 2, and 3 basalts to the peridotite source to determine percent partial melt for batch melting. After that, using a mass balance, we compute the chemical composition of the residue from partial melting to determine whether this residual composition is reasonable both chemically and in terms of normative CIPW mineralogy. This simple model suggests that Types 1, 2, and 3 could be produced by batch melts of 22%, 19%, and 17%, respectively, leaving a depleted olivine-rich harzburgite residue. These results are in good agreement with the results of experimental partial melting studies for oceanic tholeiites (Jacques and Green, 1980; Presnall et al., 1978).

To test further whether the partial melting model can also explain the differences in trace element concentra-



Figure 9. A. Chondrite-normalized REE abundances for MORB showing percent of analyzed MORB samples in each field (Basaltic Volcanism Study Project, 1981) and field of REE abundances for DSDP Leg 89 basalts. B. Chondrite-normalized REE abundances for DSDP Site 462 basalts (Batiza, 1981; Seifert, 1981; and this chapter). Note that Leg 89 basalts REE content (dots) plot within the REE range at 40% of MORB, and Site 462 basalts REE concentrations plot within the REE range of 90% of MORB (symbols as in Fig. 8).

tions of the three basalt types, we made batch melting calculations involving the REE. We opted to use a hypothetical spinel lherzolite with a reasonable mineralogy (0.65 olivine, 0.20 orthopyroxene, 0.10 clinopyroxene, and 0.05 spinel; Basaltic Volcanism Study Project, 1981) and of slightly depleted LREE composition as source of the basalts (see lower panel—Fig. 17A). Modal batch melting of this source gives plausible results and suggests that they could be produced by about 20 to 35% (Type 1), 17 to 20% (Type 2), and 10 to 18% (Type 3) batch partial melting (see Figs. 17B and 9B).

The partial melting models just presented are probably too simple to be realistic. Nevertheless, most of the results of our calculations are in agreement with previous studies (e.g., Frey et al., 1978; Jacques and Green, 1980; Sun et al., 1979), hence we view our results as useful guides for understanding possible differences among the three Nauru Basin basalt types. In any case, the differences in the extents of partial melting cannot fully explain all the features of the Nauru Basin basalts (Fig. 17). The melting process involved is most probably more complicated than the very simple formulation presented here. For example, Smewing and Potts (1976) have used incremental partial melting to explain the REE variations in



Figure 10. Chondrite-normalized La-Sm relationships for DSDP Site 462 basalts. Reference lines for Mauna Loa and N-MORB are from Basaltic Volcanism Study Project (1981). Note the slight deviation of the Type 3 data from the inferred "constant" La/Sm ratio for Nauru Basin. Sources of DSDP Site 462 data as in Figure 9 and symbols as in Figure 8.



Figure 11. Chondrite-normalized La/Sm versus Sm abundance for DSDP Site 462 basalts. N (normal)- and T (transitional)-MORB fields are from Sun et al. (1979). Sources of DSDP Site 462 data as in Figure 9 and symbols as in Figure 8.



Figure 12. Downhole variations of TiO<sub>2</sub> and La in the lower portion of DSDP Hole 462A. Note the stratigraphic-chemical subdivisions of the igneous complex shown in Figure 2. Dashed lines serve as rough boundaries between basalt types. S indicates sediments. Sources of data as in Figure 9. Type 1 basalts have lowest TiO<sub>2</sub> and La; Type 3 samples have highest TiO<sub>2</sub> and La, and Type 2 samples are intermediate.

the pillow lavas at the top of Troodos ophiolite. That suite of pillow lavas is similar in many respects to the Nauru Basin igneous complex. Furthermore, if melting differences are really important, then superimposed on these are the chemical effects of some fractionation process and possibly mixing (see Fig. 15) to lower the Ni content and Mg/(Mg + Fe<sup>2+</sup>) × 100 of the primitive melts. Discussions on the effects of fractional crystallization plus mixing of magmas for each basalt type are presented in detail by Floyd (this volume) and by Shcheka (1981).

## Differences and Similarities between Nauru Basin Basalts and MORB

Nauru Basin basalts are isotopically more similar to oceanic island-type basalts than to N-type MORB. They also differ from N-type MORB in the following respects: (1) spinels in Nauru Basin basalts have a higher Cr num-

	Sample (inte	rval in cm)	
	462A,72-3, 21-23	462,68-1	, 86-100
	Whole rock	Whole rock	Plagioclase
Trace elements			
Rb	0.25	1.20	0.22
Sr	95.1	136.4	234.4
Ba	19.5	27.3	
Ce	8.14	14.60	
Nd	6.61	11.37	
Sm	2.21	3.52	
Isotope ratios			
<sup>87</sup> Rb/ <sup>86</sup> Sr	0.008	0.026	0.003
<sup>87</sup> Sr/ <sup>86</sup> Sr	$0.70370 \pm 5$	$0.70358 \pm 4$	$0.70350 \pm 6$
${}^{87}\text{Sr}/{}^{86}\text{Sr}$ ( $t = 1 \times 10^8$ yr.)	0.70370	0.70356	0.70350
147 <sub>Sm</sub> /144 <sub>Nd</sub>	0.202	0.187	
143 <sub>Nd</sub> /144 <sub>Nd</sub>	0.51307 + 4	$0.51301 \pm 4$	
$\epsilon$ Nd ( $t = 1 \times 10^8$ yr.)	$7.6 \pm 0.8$	$6.6 \pm 0.8$	

Table 4. Trace element concentrations and isotope ratios for Site 462 basalts.

Note: Analytical blank is about 2 nanogram Sr and about 0.2 nanogram Rb. <sup>87</sup>Sr/<sup>86</sup>Sr normalized to E + A SrCO<sub>3</sub> = 0.70800. BCR-1 <sup>143</sup>Nd/<sup>144</sup>Nd = 0.51271.



Figure 13. Nd-Sr isotopic variation for DSDP Site 462 (Nauru Basin) basalts. Reference data are from Zindler et al. (1984).

ber and lower Mg number than those in N-type MORB (Tokuyama and Batiza, 1981); (2) coexisting spinel-olivine pairs in Nauru Basin basalts are both lower in Mg number than those in N-type MORB (Tokuyama and Batiza, 1981); (3) Nauru Basin basalts have lower  $Al_2O_3/$ TiO<sub>2</sub> value at any given TiO<sub>2</sub> content than all types of MORB (see Fig. 8B); and (4) they have higher La/Sm values than N-type MORB (see Figs. 9, 10, and 11). Nauru Basin basalts also have lower whole rock TiO<sub>2</sub> and higher FeO\*/MgO contents at any given Mg value than most of the typical N-type MORB (Tokuyama and Batiza, 1981).

On the other hand, except for isotopic values, the overall similarities of the mineralogy and chemical composition and Nauru Basin basalts with those of MORB are more striking than their mineralogic and chemical differences. These differences could be simply due to tapping a source with lower Ti/Fe and Al/Ti values than most MORB. This would result in lower whole-rock TiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> but higher FeO\* values for Nauru Basin basalts than for MORB at the same degree of partial melting. Furthermore, near-primitive liquids with higher FeO\* and lower Mg/Fe contents would be expected to produce spinel and olivine with correspondingly lower Mg number. The Nauru Basin igneous complex also is a tabular, sheetlike body rather than a series of conical volcanoes, and the alteration patterns observed downcore in Hole 462A are very similar to MORB (Larson, Schlanger, et al., 1981; Alt et al., in press). Because the Nauru Basin is an area of smooth oceanic crust characterized by a well-defined magnetic-lineation pattern, Site 462 igneous complex is a very interesting example of MORB-like basalt with oceanic island-type basalt isotopic affinity.

### DISCUSSION

If it were not for the discrepancy between the basement magnetic age and the inferred radiometric-paleontologic age of the Nauru Basin igneous complex (155 Ma and ~135 Ma maximum, respectively: Larson, Schlanger, et al., 1981; Site report, this volume), one could readily interpret that the basaltic flows of Hole 462A below 729 m represent normal oceanic layer 2. These basalts are compositionally similar to those from the Costa Rica Rift (J. Natland, personal communication, 1984), the AMAR area (Stakes et al., 1984), and certain portions of the northern Indian Ocean (Frey et al., 1977). But on the basis of the age constraints, the Nauru Basin igneous complex was clearly not formed at the same ridge crest that produced the M-series anomalies at Site 462. This intraplate volcanism could have been influenced by a mantle plume as evidenced by the thermally induced uplift of the 25 to 40 m.y. old lithosphere (Larson and Schlanger, 1981) and the isotopic data (Table 4; and Fujii et al., 1981; Mahoney, 1984). However, the morphol-



Figure 14. Normative ternary olivine (Ol)-diopside (Di)-silica (Si) for DSDP Site 462 basalts. Curved solid line is the plagioclase saturated olivine-diopside phase boundary at 1 atmosphere (Walker et al., 1979); the low Ca pyroxene boundaries at 10, 15, and 20 kb are also shown (Bryan et al., 1981). Note that each of the basalt types generally exhibits the expected effects of fractional crystallization and perhaps mixing. Data sources as in Figure 9 and symbols as in Figure 8.

ogy, undisturbed magnetic anomalies, and particularly petrology are not consistent with the formation of the complex by a mantle plume. What is required, then, is an off-ridge volcanic-tectonic environment to produce a thick (>600 m), tabular, MORB-like deposit without disturbing the M-series anomalies in the Basin (Larson and Schlanger, 1981). Hence, the volcanic activity should be vigorous but short-lived. It is possible that such an environment could have been created by several and closely spaced rifts propagating rapidly into the 25 to 40 m.y. old Nauru lithosphere. Modern analogies for this case may be the Easter platelet region (Hey et al., 1983; Engeln and Stein, 1984), although the Nauru Basin case would have to be more complex because the lithosphere in the latter case is thicker (25-40 Ma). This "off-ridge" (younger) but ridgelike volcanism may be a consequence of very rapid spreading (Hey et al., 1983) such as is inferred to have occurred at the Pacific-Farallon during the Late Cretaceous (Larson, Schlanger, et al., 1981).

Based on volcanic stratigraphy at Site 462, the ridgecrestlike volcanism and thermal resetting in the Nauru Basin probably started with the eruption of Type 2 lavas; this was followed by the eruption of Type 1 lavas and then by the intrusions of Type 2 and 3 sills. The later edifice-building stage, which covered a wide area in the western Pacific Basin with volcaniclastics and volcanic ash-rich sediments noted by Schlanger and Primoli Silva (1981) probably marked the end of this thermal and volcanic event. The exact timing of each of these short-lived volcanic episodes is not precisely known (Larson, Schlanger, et al., 1981). This chemical-chronostratigraphic sequence is an important consideration for the petrogenesis of Site 462 basalts, because if partial melting differences are the chief cause of the observed geochemical variations in the igneous complex, then the stratigraphic succession could be interpreted as representing the waxing, apex, and waning stages of partial melting in the mantle beneath the Nauru Basin. The eruption of the lowest Type 2 lavas (17-20% melting) may mark the onset of thermal resetting in the area; the eruption of Type 1 lavas (20-35% melting) could represent the peak of volcanism; and the intrusions of Types 2 and 3 sills (17-20% and 10-18% melting, respectively) could represent waning volcanism in the Nauru Basin.

## CONCLUSIONS

The major conclusions of this study are: (1) Leg 89 basalts are very similar mineralogically and chemically



Figure 15. Variation of Ni versus Zr for DSDP Site 462 basalts. For reference, a "crystallization" trend (bulk distribution coefficient of 3.5 for Ni and 0.1 for Zr) for N-MORB from 22-25°N: Mid-Atlantic Ridge and Kane Fracture Zone (Bryan et al., 1981) is shown as a single curved line. "Best-fit crystallization" trend (bulk distribution coefficient of 4.25 for Ni and 0.1 for Zr) for DSDP Site 462 basalts is shown as double curved lines. Data are from Shcheka (1981). Symbols as in Figure 8.

to Leg 61 basalts drilled previously at Site 462. (2) Three distinct stratigraphic and chemical groups of basalt are present in Hole 462A. These three groups could be related either by differences in degree of partial melting or by having undergone different extents of fractional crystallization at shallow depths, or a combination of both. We favor the hypothesis that partial melting differences modified by later fractional crystallization and possibly magma mixing at shallow depths contributed to the petrogenesis of Nauru Basin basalts. (3) The mineralogy and chemical composition of Nauru Basin basalts are within the observed ranges for all types of MORB. (4) Nauru Basin basalts are isotopically similar to ocean island-type basalts. (5) Based on the inferred basement and flow ages, we speculate that the Nauru Basin complex represents the volcanic product of a series of ridgecrestlike tectonic elements that originated on older lithosphere. Fast propagating rifts creating many tiny shortlived microplates during a magnetic quiet period could produce a widespread volcanic complex such as the Nauru Basin. If the series of new ridges produced by rift propagation were short-lived, then much, but not all, of the Nauru Basin would be underlain by older ocean crust and sediments accumulated during the 20 to 40 m.y. before rift propagation occurred.

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#### REFERENCES

- Albee, A. L., and Ray, L., 1970. Correction factors for electron probe microanalysis of silicates, oxides, carbonates, phosphates, and sulfates. Anal. Chem., 42:1408-1414.
- Allegre, C. J., Standacher, T., Sarda, P., and Kurz, M., 1983. Rare gas isotope systematics in oceanic basalts: constraints on the formation of the atmosphere and structure of the mantle. *Trans. Am. Geophys. Union*, 64:18, 348. (Abstract)
- Alt, J. C., Laverne, C., and Muehlenbachs, K., in press. Alteration of the upper oceanic crust: mineralogy and processes in DSDP Hole 504B, Leg 83. In Anderson, R. N., Honnorez, J., Becker, K., et al., Init. Repts. DSDP, 83: Washington (U.S. Govt. Printing Office).
- Basaltic Volcanism Study Project, 1981. Basaltic Volcanism on the Terrestrial Planets: New York (Pergamon Press, Inc.).
- Bass, M., Moberly, R., Rhodes, J., Shih, C.-Y., and Church, S., 1973. Volcanic rocks cored in the Central Pacific, Leg 17, Deep Sea Drilling Project. In Winterer, E. L., Ewing, J. I., et al., Init. Repts. DSDP, 17: Washington (U.S. Govt. Printing Office), 429-503
- Batiza, R., 1981. Trace-element characteristics of Leg 61 basalts. In Larson, R. L., Schlanger, S. O., et al., Init. Repts. DSDP, 61: Washington (U.S. Govt. Printing Office), 689-695.
- Batiza, R., Larson, R. L., Schlanger, S. O., Shcheka, S. A., and Tokuyama, H., 1980. Trace element abundances in basalts of the Nauru Basin (DSDP Leg 61): Late Cretaceous off-ridge volcanism in the western Pacific. *Nature*, 186:476-478.
- Batiza, R., Shcheka, S., Tokuyama, H., Muehlenbachs, K., Vallier, T., Lee-Wong, F., Seifert, K., Windom, K., Book, P., and Fujii, N., 1981. Summary and index to petrologic and geochemical studies of Leg 61 basalts. *In Larson*, R. L., Schlanger, S. O., et al., *Init. Repts. DSDP*, 61: Washington (U.S. Govt. Printing Office), 829-839.
- Batiza, R., and Vanko, D., 1984. Petrology of young Pacific seamounts. J. Geophys. Res., 89:11,235-11,260.
- Bence, A. E., and Albee, A. L., 1968. Empirical correction factors for the electron microanalysis of silicates and oxides. J. Geol., 76: 382-403.
- Bence, A. E., Papike, J. J., and Ayuso, R. A., 1975. Petrology of submarine basalts from the central Caribbean: DSDP Leg 15. J. Geophys. Res., 80:4775-4804.
- Bender, J. F., Hodges, F. N., and Bence, A. E., 1978. Petrogenesis of basalts from the project FAMOUS area: experimental study from 0 to 15 kbars. *Earth Planet. Sci. Lett.*, 41:277-302.
- Bougault, H., 1977. Evidence de la cristallisation fractionnée au hiveau dune ride medio-oceanique: Co, Ni, Cr, FAMOUS, Leg 37 du DSDP. Bull. Soc. Geol. France, 19:1207–1212.
- Bryan, W. B., Finger, L. W., and Chayes, F., 1969. Estimating proportions in petrographic mixing equations by least squares approximation. *Science*, 163:926–927.
- Bryan, W., Frey, F., and Dickey, J., 1976. Inferred geologic settings and differentiation in basalts from the Deep Sea Drilling Project. J. Geophys. Res., 81:4285-4304.
- Bryan, W. B., Thompson, G., and Ludden, J. N., 1981. Compositional variation in normal MORB from 22°-25°N: Mid-Atlantic Ridge and Kane Fracture Zone. J. Geophys. Res., 86:11,815-11,836.
- Burke, K., Fox, P. J., and Sengor, A. M. C., 1978. Buoyant ocean floor and the evolution of the Caribbean. J. Geophys. Res., 83: 3949-3954.

- Clague, D. A., and Bunch, J. E., 1976. Formation of ferro-basalt at East Pacific midocean spreading centers. J. Geophys. Res., 81: 4247-4256.
- Engeln, J. F., and Stein, S., 1984. Tectonics of the Easter Plate. Earth Planet. Sci. Lett., 68:259-270.
- Frey, F. A., Dickey, J. S., Thompson, G., and Bryan, W. B., 1977. Eastern Indian Ocean DSDP sites: correlations between petrography, geochemistry, and tectonic setting. *In* Heirtzler, J., Bolli, H., Davies, T., Saunders, J., and Sclater, J. (Eds.), *Indian Ocean Geology and Biostratigraphy:* Washington (Am. Geophys. Union), pp. 189-257.
- Frey, F. A., Green, D. H., and Roy, S. D., 1978. Integrated models of basalt petrogenesis: a study of quartz tholeiite to olivine melititizes from southeast Australia utilizing geochemical and experimental petrologic data. J. Petrol., 19:463–513.
- Fujii, T., and Bougault, H., 1983. Melting relations of a magnesian abyssal tholeiite and the origin of MORBs. *Earth Planet. Sci. Lett.*, 62:283-295.
- Fujii, N., Notsu, K., and Onuma, N., 1981. Chemical compositions and Sr isotopes of Deep Sea Drilling Project Leg 61 basalts. In Larson, R. L., Schlanger, S. O., et al., Init. Repts. DSDP, 61: Washington (U.S. Govt. Printing Office), 97-700.
- Gast, P. W., 1970. Dispersed elements in oceanic volcanic rocks. Phys. Earth Planet Int., 3:246.
- Hamelin, B., Dupre, B., and Allegre, C., 1984. Lead-strontium isotopic variations along the East Pacific Rise and the Mid-Atlantic Ridge: a comparative study. *Earth Planet. Sci. Lett.*, 67:340-350.
- Haskin, L. A., 1983. Petrogenetic modelling—use of rare earth elements. In Henderson, P. (Ed.), Rare Earth Element Geochemistry. Developments in Geochemistry, 2. The Netherlands (Elsevier Science Publishers B. V., Amsterdam), 115-152.
- Haskin, L. A., Haskin, M. A., Frey, F. A., et al., 1968. Relative and absolute abundances of the rare earths. In Ahrens, L. H. (Ed.), Origin and Distribution of the Elements: New York (Pergamon Press), pp. 889-912.
- Haskin, L., and Korotev, R., 1977. Test of a model for trace element partition during closed-system solidification of a silicate liquid. *Geochim. Cosmochim. Acta*, 41:921-939.
- Hey, R. N., Naar, D. F., Kleinrock, M. C., Morgan, J. P., Morales, E., and Johson, C., 1983. Microplate tectonics and fast rifts propagation along the superfast spreading East Pacific Rise near Easter Island. *Trans. Am. Geophys. Union*, 65:58. (Abstract)
- Irving, I., 1980. Petrology and geochemistry of composite ultramafic xenoliths in alkalic basalts and implications for magmatic processes within the mantle. Am. J. Sci., 280-A:389-426.
- Jacobs, J. W., Korotev, R. L., Blanchard, D. P., and Haskin, L. A., 1977. A well-tested procedure for instrumental neutron activation analysis of silicate rocks and minerals. J. Radioanal. Chem., 40: 93-114.
- Jacques, A. L., and Green, D. H., 1980. Anhydrous melting of peridotite at 0-15 kb pressure and the genesis of tholeiitic basalts. *Contrib. Mineral. Petrol.*, 73:287-310.
- Larson, R. L., 1976. Late Jurassic and Early Cretaceous evolution of the western Pacific Ocean. J. Geomagnet. Geoelec., 28:219–236.
- Larson, R. L., and Schlanger, S. O., 1981. Geological evolution of the Nauru Basin, and regional implications. *In Larson*, R. L., Schlanger, S. O., et al., *Init. Repts. DSDP*, 61: Washington (U.S. Govt. Printing Office), 841-862.
- Larson, R. L., Schlanger, S. O., et al., 1981. Init. Repts. DSDP, 61: Washington (U.S. Govt. Printing Office).
- Ludden, J. N., and Thompson, G., 1979. An evaluation of the behavior of the rare earth elements during the weathering of sea-floor basalts. *Earth Planet. Sci. Lett.*, 43:85–92.
- Mahoney, J. J., 1984. A Nd and Sr isotopic study of Pacific Oceanic plateaus. Trans. Am. Geophys. Union, 65:297. (Abstract)
- Muehlenbachs, K., 1980. The alteration and aging of the basaltic layer of the seafloor: oxygen isotope evidence from DSDP/IPOD Legs 51, 52, and 53. *In* Donnelly, T., Francheteau, J., Bryan, W., Robinson, P., Flower, M., Salisbury, M., et al., *Init. Repts. DSDP*, 51, 52, 53. Pt. 2: Washington (U.S. Govt. Printing Office), 1159-1167.
- 52, 53, Pt. 2: Washington (U.S. Govt. Printing Office), 1159-1167.
  Ozima, M., Saito, K., and Takigami, Y., 1981. <sup>40</sup>Ar-<sup>39</sup>Ar geochronological studies on rocks drilled at Holes 462 and 462A, Deep Sea

Drilling Project Leg 61. In Larson, R. L., Schlanger, S. O., et al., Init. Repts. DSDP, 61: Washington (U.S. Govt. Printing Office), 701-703.

- Paster, T. P., Schauwecker, D. S., and Haskin, L. A., 1974. The behavior of some trace elements during solidification of the Skaergaard layered series. *Geochim. Cosmochem. Acta*, 38:1549-1577.
- Pearce, J. A., and Cann, J. R., 1973. Tectonic setting of basic volcanic rocks determined using trace elements analyses. *Earth Planet. Sci. Lett.*, 19:290-300.
- Presnall, D. C., Dixon, J. R., O'Donnell, T. H., and Dixon, S. A., 1978. Generation of mid-ocean ridge tholeiites. J. Petrol., 20:3-35.
- Schilling, J.-G., 1973. Iceland mantle plume: geochemical study of Reykjanes Ridge. Nature, 242:565-571.
- Schilling, J.-G., Zajac, M., Evans, R., Johnston, T., White, W., Devine, J. D., and Kingsley, R., 1983. Petrologic and geochemical variations along the Mid-Atlantic Ridge from 29°N to 73°N. Am. J. Sci., 283:510-586.
- Schlanger, S. O., and Premoli Silva, I., 1981. Tectonic, volcanic and paleogeographic implications of redeposited reef faunas of Late Cretaceous and Tertiary age from the Nauru Basin and the Line Islands. In Larson, R. L., Schlanger, S. O., et al., Init. Repts. DSDP, 61: Washington (U.S. Govt. Printing Office), 817-827.
- Seifert, K., 1981. Geochemistry of Nauru Basin basalts from the lower portion of Hole 462A, Deep Sea Drilling Project Leg 61. In Larson, R. L., Schlanger, S. O., et al., Init. Repts. DSDP, 61: Washington (U.S. Govt. Printing Office), 705-708.
- Seyfried, W. E., and Bischoff, J. L., 1979. Low temperature basalt alteration by seawater: an experimental study at 70°C and 150°C. *Geochim. Cosmochim. Acta*, 43:1937-1947.
- Shcheka, S., 1981. Igneous rocks of Deep Sea Drilling project Leg 61, Nauru Basin. In Larson, R. L., Schlanger, S. O., et al., Init. Repts. DSDP, 61: Washington (U.S. Govt. Printing Office), 633-646.
- Smewing, J. D., and Potts, P. J., 1976. Rare earth abundances in basalts and metabasalts from the Troodos Massif, Cyprus. Contrib. Mineral. Petrol., 75:245-258.
- Stakes, S. S., Shervais, J. W., and Hopson, C. A., 1984. The volcanictectonic cycle of the FAMOUS and AMAR valleys, Mid-Atlantic Ridge (36°47'N): evidence from basalt glass and phenocryst compositional variations for a steady-state magma chamber beneath the valley midsections. J. Geophys. Res., 89:6995-7028.
- Steiner, M., 1981a. Paleomagnetism of the igneous complex, Site 462. In Larson, R. L., Schlanger, S. O., et al., Init. Repts. DSDP, 61: Washington (U.S. Govt. Printing Office), 717-729.
- \_\_\_\_\_\_, 1981b. Magnetic and mineralogical investigations of opaque minerals: preliminary results. *In* Larson, R. L., Schlanger, S. O., et al., *Init. Repts. DSDP*, 61: Washington (U.S. Govt. Printing Office), 731-742.
- Sun, S., Nesbitt, R., and Sharaskin, A., 1979. Geochemical characteristics of mid-ocean ridge basalts. *Earth Planet. Sci. Lett.*, 44: 119-138.
- Tokuyama, H., and Batiza, R., 1981. Chemical composition of igneous rocks and origin of the sill and pillow-basalt complex of Nauru Basin, Southwest Pacific. *In* Larson, R. L., Schlanger, S. O., et al., *Init. Repts. DSDP*, 61: Washington (U.S. Govt. Printing Office), 673-687.
- Walker, D., Shibata, T., and DeLong, S., 1979. Abyssal tholeiites from the Oceangrapher Fracture Zone, II. Phase equilibria and mixing. *Contrib. Mineral. Petrol.*, 70:111-125.
- Wright, T., and Fisk, R., 1971. Origin of the differentiated and hybrid lavas of Kilauea volcano, Hawaii. J. Petrol., 65:1-65.
- Zindler, A., Jagoutz, E., and Goldstein, S., 1982. Nd, Sr and Pb isotopic systematics in a three-component mantle: a new perspective. *Nature*, 298:519-523.
- Zindler, A., Staudigel, H., and Batiza, R., 1984. Isotope and trace element geochemistry of young Pacific seamounts: implications for the scale of upper mantle heterogeneity. *Earth Planet. Sci. Lett.*, 70:175-195.

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Table 5A. Summary of fractional crystallization model calculations (in %) for major elements (R<sup>2</sup> = 0.086).

	Parent: Type 1		Residua	l: Type 2				
Major element	Observed residual comp. <sup>a</sup>	Oliv. <sup>b</sup>	Spinel <sup>C</sup>	Plag.d	Cpx <sup>e</sup>	Observed parent comp. <sup>a</sup>	Calculated parent comp.	
SiO <sub>2</sub>	50.93	38.96	0.09	48.21	51.33	50.50	50.27	
TiO <sub>2</sub>	1.23	0.01	0.65	0.05	0.38	1.02	1.04	
Al2O2	13.64	0.07	17.12	31.39	3.03	14.83	14.85	
FeO*	12.32	15.59	25.96	0.72	6.64	10.95	11.11	
MnO	0.22	0.18	0.42	0.00	0.07	0.20	0.19	
MgO	7.50	44.44	12.47	0.33	17.33	8.26	8.27	
CaO	11.81	0.32	0.11	16.00	19.66	12.02	12.01	
Na <sub>2</sub> O	2.28	0.02	0.00	2.55	0.26	2.11	2.19	
K2Ô	0.05	0.00	0.00	0.04	0.00	0.05	0.05	
Cr2O3	0.03	0.03	42.64	0.00	0.44	0.05	0.05	
Weight fraction (= sum)								
	0.8387	0.0359	0.0003	0.1064	0.0200			

#### Table 5B. Summary of fractional crystallization model calculations (in ppm) for trace elements (16.26% crystallized).

	Parent: Type 1	Residual: Type 2	
Trace element	Observed parent comp.f	Observed residual comp. <sup>f</sup>	Calculated residual comp. <sup>g</sup>
La	2.47	3.28	2.95
Sm	2.06	2.66	2.46
Yb	2.12	2.78	2.53
Sc	46	49	54
Co	50	50	58

Note: We also tried deriving Type 3 basalt using Type 2 as the parent, but the fits are not very good, and we do not include examples here.

amples here. a Data from Table 3, calculated on an anhydrous basis. b Average olivine composition from Tokuyama and Batiza (1981). c Average spinel composition from Tokuyama and Batiza (1981). d Average plagioclase core composition from Tokuyama and Batiza (1981). e Average pyroxene core composition from Tokuyama and Batiza (1981). f From Table 3. g Partition coefficients used in the calculations are from Bougault (1977), Frey et al., (1978), Haskin and Korotev (1977), Irving (1980), and Paster et al. (1974).

	Parent: Type 1		Residua	l: Type 3			
	Observed residual comp. <sup>a</sup>	Oliv. <sup>b</sup>	Cpx <sup>c</sup>	Plag.d	Mag <sup>e</sup>	Observed parent comp. <sup>a</sup>	Calculated parent comp.
SiO2	50.55	38.40	51.82	50.39	3.60	50.50	49.58
TiO2	1.63	0.00	0.32	0.00	0.22	1.02	1.13
Al2Õ2	14.27	0.00	2.70	30.95	0.30	14.83	15.14
FeÕ*	12.66	22.95	7.50	1.00	88.29	10.95	11.11
MnO	0.22	0.00	0.20	0.00	0.23	0.20	0.17
MgO	7.19	38.65	17.69	0.39	0.19	8.26	8.27
CaO	10.83	0.00	18.55	14.23	0.16	12.02	11.70
Na <sub>2</sub> O	2.41	0.00	0.18	3.25	0.00	2.11	2.19
K <sub>2</sub> Õf	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr2O3	0.03	0.00	0.40	0.00	0.04	0.05	0.06
Weight fraction (= sum)	0.6699	0.0377	0.1086	0.1708	0.0088		

Table 6A. Summary of fractional crystallization model calculations (in %) for major elements ( $\mathbb{R}^2$ = 1.094).

Table 6B. Summary of fractional crystallization model calculations (in ppm) for trace elements (32.59% crystallized).

	Parent: Type 1	Residual: Type 3	
	Observed parent comp. <sup>g</sup>	Observed residual comp. <sup>g</sup>	Calculated residual comp.h
La	2.47	4.77	3.65
Sm	2.06	3.50	3.03
Yb	2.12	3.21	3.11
Sc	46	47	59
Co	50	51	68

Note: We also tried deriving Type 3 basalt using Type 2 as the parent, but the fits are not very good, and we do not include examples here.

<sup>a</sup> Data from Table 3, calculated on an anhydrous basis. <sup>b</sup> Stoichiometric Fo<sub>75</sub>.

<sup>C</sup> Average plagioclase core composition from Table 2. <sup>d</sup> Average plagioclase core composition from Table 1.

e Silica-bearing magnetite from Shchecka (1981).

f Not included in the calculations because Type 3 basalts have highly variable K<sub>2</sub>O contents (0.05-1.28 wt.%) that are most probably due to secondary alteration.

g From Table 3.

h Partition coefficients used in the calculations are from Bougault (1977), Frey et al. (1978), Haskin and Korotev (1977), Irving (1980), and Paster et al. (1974).

Sample (interval in cm) [basalt type]	462A-47-3, 74–77 cm <sup>a</sup> [1]	Type 1 basalt + 8% Fo90 [Model 1]	462A-85-4, 78-80 <sup>a</sup> [2]	Type 2 basalt + 10% Fo90 [Model 2]	462-66-4, 97-101 <sup>a</sup> [3]	Type 3 basalt + 15% Fogo [Model 3]
Major element (%)						
SiO <sub>2</sub>	50.20	50.17	50.45	50.14	50.45	49.83
TiO2	0.95	0.89	1.14	1.05	1.46	1.29
Al <sub>2</sub> Õ <sub>3</sub>	14.14	13.27	13.69	12.59	13.86	12.21
Fe <sub>2</sub> O <sub>3</sub>	1.74	1.63	1.90	1.75	2.00	1.76
FeO	8.69	8.89	9.49	9.63	10.02	10.12
MnO	0.20	0.19	0.20	0.18	0.23	0.20
MgO	8.76	11.93	9.31	13.10	7.68	13.29
CaO	11.79	11.06	10.53	9.68	10.53	9.27
Na <sub>2</sub> O	1.99	1.87	2.00	1.84	2.20	1.94
K <sub>2</sub> Õ	0.11	0.10	0.05	0.05	0.11	0.10
Total		100.00		100.01		100.01
CIPW norm						
Qu	0.11	0.00	0.84	0.00	1.81	0.00
Or	0.65	0.59	0.30	0.30	0.65	0.59
Ab	16.84	15.82	16.92	15.57	18.62	16.42
An	29.33	27.52	28.23	25.95	27.62	24.31
Di	23.75	22.10	19.56	17.83	20.20	17.51
Ну	23.56	22.20	28.00	27.97	23.97	26.16
Ol	0.00	7.79	0.00	7.87	0.00	10.02
Mg	2.52	2.36	2.75	2.54	2.90	2.55
п	1.80	1.69	2.17	1.99	2.77	2.45
Trace element (ppm)						
Ni	170		160		90	
Co	90		68		48	
Cr	540	h	330	h	145	F
$Mg/(Mg + Fe^{2+}) \times 100$	64.3 <sup>c</sup>	68.0 <sup>0</sup> 70.5 <sup>d</sup>	63.6 <sup>c</sup>	67.4 <sup>0</sup> 70.8 <sup>d</sup>	57.7 <sup>c</sup>	60.6 <sup>0</sup> 70.1 <sup>d</sup>

Table 7. Compositions and CIPW norms of DSDP Site 462 "primary" basalts.

a Data from Shcheka (1981). <sup>b</sup> For FeO as analyzed. <sup>c</sup> For FeO = (0.85) (FeO\*). <sup>d</sup> FeO = (0.85) (FeO\*) before the addition of Fo<sub>90</sub>.

Table 8 Pa	rtial melting	model	calculations	for	DSDP	Site 462	hasalts
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	Pyrolite model <sup>a</sup>	25% Model 1 "primitive" basalt	75% residue	21% Model 2 "primitive" basalt	79% residue	17% Model 3	83% residue
Major elem	ent (%)						
SiOn	44.60	50.17	42.74	50.14	43,13	49.83	43.53
TiO	0.22	0.89	0.00	1.05	0.00	1.29	0.00
AlaÖa	4.30	13.27	1.31	12.59	2.10	12.21	2.68
FeaOa	1.41	1.65	1.34	1.75	1.32	1.76	1.34
FeO	7.06	8.89	6.45	9.63	6.38	10.12	6.43
MnO	0.15	0.19	0.14	0.18	0.14	0.20	0.14
MgO	38.00	11.93	46.69	13.10	44.62	13.29	43.06
CaO	3.50	11.06	0.98	9.68	1.86	9.27	2.32
Na <sub>2</sub> O	0.50	1.87	0.04	1.84	0.14	1.94	0.21
K2Õ	0.02	0.10	0.00	0.05	0.01	0.10	0.00
CIPW norn	ns						
Or	0.12	0.59	0.00	0.30	0.06	0.59	0.00
Ab	4.23	15.82	0.34	15.57	1.18	16.42	1.78
An	9.43	27.52	3.40	25.95	5.07	24.31	6.37
Di	6.25	22.10	1.15	17.83	3.27	17.51	4.04
Hy	13.69	22.12	11.16	27.97	10.29	26.16	11.31
OI	63.58	7.79	81.71	7.87	77.92	10.02	74.27
Mg	2.04	2.36	1.94	2.54	1.91	2.55	1.94
11	0.42	1.69	0.00	1.99	0.00	2.45	0.00

<sup>a</sup> Data from Sun et al. (1979).



Figure 16. Variation of TiO<sub>2</sub> (wt. %) with La (ppm) for DSDP Site 462 basalts. Data sources and symbols as in Figures 8 and 9.



Figure 17. The lower panel shows a range of chondrite-normalized REE abundances for analyzed LREE depleted spinel lherzolites (Basaltic Volcanism Study Project, 1981) and calculated REE concentrations for 10%, 15%, 20% and 35% partial melts of the most REE-rich spinel lherzolite superimposed on the REE range of DSDP Site 462 (Nauru) basalts. The upper panel illustrates the computed REE concentrations of 10%, 15%, 25%, and 30% partial melts of our preferred spinel lherzolite source superimposed on the REE range of DSDP Site 462 (Nauru) basalts. Note that the REE range of DSDP Site 462 (Nauru) basalts. Note that the REE range of type 2 basalt is roughly within the REE concentrations of 15% to 22% partial melts of the estimated source. Partition coefficients used in the calculations are from Bougault (1977), Frey et al. (1978), Haskin and Korotev (1977), Irving (1980), and Paster et al. (1974).