# 22. IGNEOUS ROCKS OF DEEP SEA DRILLING PROJECT LEG 61, NAURU BASIN<sup>1</sup>

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#### ABSTRACT

During Leg 61 of the Deep Sea Drilling Project the deepest (1068.5 m) hole was drilled in the Nauru Basin. It penetrated rocks of two magmatic cycles. The first ranged from Pleistocene to Oligocene and is represented by thin ash layers, composed of fragments of fresh scoriaceous alkalic and tholeiitic basalts, and crystal fragments of olivine, chrome-diopside, spinel, and feldspars. Specific features of the rocks are high calcium content (up to 14 wt.% CaO) and titanium content (up to 4 wt.% TiO<sub>2</sub>), accompanied by high alkalinity. Rare varieties of titanium-rich (up to 30 wt.% TiO<sub>2</sub>) magnetite and Fe-Ca-anorthoclase are present among the fragments. According to the rock and mineral assemblage, the fragments from the ash layers may be considered to be derivatives of a subaerial, Hawaii-type volcano.

In the interval from Cenomanian to Hauterivian, a tholeiite sill complex was formed, the upper part of which (562–728 m) is represented by essentially holocrystalline dolerites alternating with the hyaloclastites, whereas in the lower part (728–1068 m), thin-layered, pillow-like basalt sills are dominant. Rocks of the upper part are characterized by high iron and titanium contents, and show considerable fractionation (differentiated tholeiites) as compared with the homogeneous, low-titanium and magnesia-rich basalts of the lower part (primitive tholeiites). Consolidation of dolerites was culminated by the formation of quartz-potassium feldspar granophyric aggregates. According to the compositions of liquidus spinel and olivine, crystallization of the magma began at  $T \sim 1210$  to  $1240^{\circ}$ C and  $f_{02} \approx 10^{-8.5}$  atm. Within the low-temperature veins in dolerites, silica-bearing magnetite (up to 3.5% SiO<sub>2</sub>) was discovered. On the basis of mineralogical-geochemical features, the Nauru sill complex is classified as an oceanic trap formation.

### INTRODUCTION

During the DSDP Leg 61 and part of Leg 62, two closely spaced holes (462, 462A) were drilled in the Nauru Basin, western equatorial Pacific. They penetrated igneous rocks of two magmatic cycles. From 30 to 120 meters below sea floor, three thin ash layers composed of products of alkali-basalt eruptions were cored. Lower, ashes consisting of redeposited material of tholeiite basalts were recovered from 562 to 1068.5 meters. Inasmuch as vertical sections of both holes are identical, a joint characterization of them is given.

#### ANALYTICAL METHODS

Before grinding, all samples are rinsed in distilled water for 1 hour and then dried for 2 to 3 hours at 105 °C to remove impurities (dissolved components of sea water, and partly clay-manganous minerals filling cavities and cracks). Dried material was ground either in a cobalt-tungsten mortar for major-element analyses and X-ray study, or in an agate mortar for trace-element analyses. Because of the presence of chemically unstable minerals (smectites, carbonates, sulfides, zeolites), the major element determinations, the spectrographic (Ni, Cr, V, Co, Zr, Sc, Zn, Sn), atomic-absorption (Ni, Cr, Co, Zn, Cu), and XRF (Rb, Sr, Zr, Ba) methods were applied using USA and DDR standards. Sensitivity of these methods is about 1 to 20 ppm, relative errors  $\pm 5$  to 17%. The specific features of magnetite investigation have been described in Shcheka and Pyatkov (1978).

X-ray microanalysis was carried out in thin and polished sections with a JXA-5a microprobe at an accelerating voltage of 10 kv (glasses) and 25 kv (other minerals). The order-disorder state of plagioclases was studied with a DRON-1 diffractometer, CuK $\alpha$ , at 0.5°/min. Magnetite lattice parameters were determined with filtered CoK $\alpha$ X-ray and Pt internal standard.

#### ALKALIC ASSOCIATION

Thin (5-8 cm) ash layers recovered within the interval 30 to 120 meters (Pleistocene-late Oligocene) attracted our attention, because of the abundance of coarse (up to 4 mm) fragments of alkalic basalt rocks, unusual for oceanic structures similar to Nauru Basin. The sharpedged outlines of the fragments, their uncommon freshness, and the absence of the slightest signs of magma-sea-water interaction, as well as the scoriaceous textures of most rocks, led us to the conclusion that the fragments were products of explosive eruptions of a subaerial volcanism. Cavities and cracks within the fragments are usually filled with authigenic carbonate. Shipboard thin-section observations revealed the following:

1) Phyric clinopyroxene-plagioclase ( $An_{60-65}$ ) glassy basalts. The glass of the matrix is brown, and the plagioclase laths show distinct flow alignment. Phenocrysts are not zoned. The plagioclase and pyroxene content of these rocks is about 15 to 20%.

2) Scoriaceous glassy alkaline basalts with perfectly shaped crystals of olivine and titanaugite. The palebrown glass is very fresh. Small (0.1-0.5 mm) inclusions of titanaugite dolerite, which are often present in the glass, probably belong to the early subvolcanic phase of a single volcano.

3) Nepheline-anorthoclase dolerites with titanaugite, kaersutite, magnetite, and apatite needles. Nepheline is partly replaced by cancrinite and calcite.

4) Coarsely phyric magnetite-plagioclase  $(An_{60-62})$  dolerites with titanaugite and kaersutite. Coarse Tiaugite phenocrysts are strongly zoned and colored (pinkish-brown), in contact with the groundmass.

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5) Coarse (>1 mm) fragments of colorless olivine, enstatite, and pale-green Cr-diopside, sometimes coated by glass. The minerals are strongly zoned in contact with glass and replaced by brown smectite, i.e., they are unstable relative to the enclosing melt. Small inclusions of brown Cr-spinel occur commonly within the olivine grains. These features characterize the minerals as fragments of lherzolite inclusions in basalts.

Inasmuch as the author could not collect from the ash layers, a limited number of fragments was analyzed (Tables 1 and 2). Both tholeiite (analysis 1) and alkali basalts are present among the glasses. The wide variation of rock composition shows consierable fractionation of the initial magmas. Therefore, the glasses characterize intermediate melt compositions. Nevertheless, that the glasses belong to derivatives of alkali basalt volcanoes, widespread on the most of Pacific islands, is clearly established. A composition specific to the alkaline glasses is high calcium and alkali contents, along with reduced silica and alumina contents, i.e. picritic affinity. Normative recalculation of analysis 2 (Table 1). using the real mineral compositions (Table 2), gives us the following formula: Or 7.1%; Ab 8.5%; An 8.9%; Cpx 58.6%; Mt 8.4%. The nearest analogs, including Iherzolite nodules, and possible sources of the analyzed rocks may be considered to be volcanoes of the Caroline Islands (Yagi, 1960), 700 to 800 km north of Site 462. The same features are usual for Tahiti rocks (Table 1). The tholeiite glass (analysis 1) is characterized by features of island-arc basalts (higher alumina and lower titanium content); however, they differ strongly from the former by low potassium and iron contents, which may be a result of fractionation.

A single analyzed orthopyroxene grain (Table 2, analysis 1) is iron-rich, alumina-poor, and enriched in calcium—qualities inherent in island-arc basalts, and extremely unusual for alkali basalts. Low-iron chromebearing clinopyroxene (analysis 2) and anorthitic plagioclase (analysis 7) probably belong to a single

Table 1. Chemical compositions of glasses from ash layers, Site 462.

Ovides		Sample											
(wt. %)	1	2	3	4	5	6							
SiO <sub>2</sub>	51.57	46.03	45.28	44.89	42.37	43.18							
TiO <sub>2</sub>	0.99	3.85	4.29	4.33	3.64	3.76							
Al2O3	16.31	13.32	15.04	13.24	14.61	13.41							
FeÕ	7.82	10.83	11.31	11.44	12.86	12.51							
MnO	0.13	0.17	0.18	0.16	0.17	0.16							
MgO	8.53	7.18	5.67	6.23	8.65	8.61							
CaO	12.35	14.16	11.19	12.86	11.25	12.32							
Na <sub>2</sub> O	2.32	3.06	2.69	3.19	2.83	2.84							
K <sub>2</sub> Õ	0.15	1.30	1.84	1.35	1.25	1.40							
Total	100.18	99.88	97.49	97.70	97.63	98.19							
f	34.0	45.9	52.8	50.7	45.5	51.2							
A	0.24	0.48	0.43	0.51	0.41	0.46							

Notes: 1-4 = Sample 462-21-1. FeO = total Fe as FeO. Microprobe analyses by V. M. Chubarov. 5, Ponape Island. 6, Tahiti. 5, 6 after Yagi (1960). f = Fe/ (Fe + Mg) (atomic %). A = (K + Na)/Al (atomic %). association. The other clinopyroxenes are represented by high-titanium augites associated with anorthoclase enriched in calcium, iron, and titanium, in kaersutite dolerites (analysis 6), and with high-titanium magnetite (analysis 3) in plagioclase varieties. According to titanium content, the magnetite is close to ulvospinel; however, low "totals" in analysis that cannot be explained by analytical errors allow us to suppose the presence of considerable maghemite component in the magnetite. Exsolution lamellae in the magnetite are commonly absent or very fine.

Joint location of the tholeiitic and alkalic fragments in the thin ash layers, the scoriaceous texture of the rocks, the absence of phenomena of interaction with sea water, and the sharp-edged fragment shapes allow us to conclude that the studied fragments were transported to the drill site by a single explosion of a Hawaii-type subaerial volcano. Inasmuch as such volcanoes in all oceans are on islands characterized by thicker crust, we may suppose the presence of similar structures within the Nauru Basin. All this gives us valid material for interpretation of the main regularities of transformation of the oceanic crust into continental crust.

## THOLEIITE ASSOCIATION

The tholeiitic basalts and dolerites were recovered from 562 to 1068.5 meters. The uppermost basalt sill is overlain by a thin layer of a dark porcellanite with Cenomanian fossils. The lowermost interlayer of finepebble conglomerates and sandstones has deep-water Hauterivian fossils. Thus, the formation of the thick (about 400 meters) basalt sheet proceeded for at least 25 m.y. Because of poor recovery within the sedimentary rocks, the observed position of the layer boundaries was corrected using density and gamma-ray logging data. The author has no such data for the lowest sedimentary interlayer (Core 80); therefore, its position is shown approximately (Fig. 1).

In accordance with the core observation sedimentary rocks lie horizontally and dip gently  $(15^{\circ})$  towards the contact with the top basalt sill. The same inclination  $(8-15^{\circ})$  is characteristic of the dominant joints in basalts.

The parent rocks are transformed into hematite-mullite hornfelses near contacts with the top of the sills, which is evidence of basalt intrusion into the sedimentary rocks. In the lower part (below 728 m), one can observe distinct signs of intrusion of basalt bodies into each other.

The structure of the basalt interval shown in Figure 1 is very approximate. This is caused both by poor recovery across unit contacts and by specific crystallization of magma in contact with water. Two large cycles of the basalt magmatism are distinctly distinguished. The later one (562-728 m) is represented by a series of sills enveloped by thin (3-10 cm) rims of the glass or glass-bearing rocks in contact with the enclosing hyaloclastites. The series below 728 meters is composed of thin (0.2-1.5 m), multiple, pillow-like sills, divided by thicker (up to 30 m) dolerite sills. A specific feature of the Nauru pillowlike basalts is their mostly holocrystalline textures. Even Table 2. Chemical compositions of minerals from ash layers, Site 462.

Sample	Oxides (wt. %)	1	2	3a	4a	5	6a	6b	4b	3b	7	3c	4c
1	SiOn	55.06	50.47	50.65	48.16	48 58	51.30	63.40	53.61	51.68	47.87	0.01	0.01
2	TiO	0.09	1.49	2.89	3.40	2.76	1.89	0.65	0.18	0.21	0.02	29.53	29.30
3	Al2O2	1.25	4.23	3.07	6.34	6.12	2.86	21.68	30.21	31.24	33.10	1.59	2.05
4	FeO	15.87	5.16	6.27	7.68	6.62	10.40	0.44	0.63	0.70	1.12	61.32	59.93
5	MnO	0.53	0.09	0.16	0.15	0.08	0.21	0.04	0.00	0.00	0.05	0.77	0.88
6	MgO	25.72	15.04	13.31	12.24	13.11	11.49	0.02	0.04	0.09	0.11	2.41	2.42
7	CaO	1.78	22.38	22.81	22.25	22.93	22.30	2.31	12.57	13.59	16.55	0.11	0.14
8	Na <sub>2</sub> O	0.05	0.32	0.37	0.44	0.35	0.39	7.36	4.34	3.76	2.06	0.00	0.01
9	K2Õ	0.00	0.03	0.03	0.00	0.01	0.83	4.93	0.29	0.29	0.04	0.02	0.01
10	Cr2O3	n.a.	0.56	n.a.	n.a.	n.a.	n.a.	0.00	0.00	0.00	0.00	0.00	0.31
11	Total	100.34	99.76	98.76	100.66	100.56	100.86	100.82	101.87	101.51	100.88	95.76	95.06
			Ion	s on the b	asis of 6 o	xygens		lons of	n the basis	of 8 oxyge	ens		
1	Si + 4	1.985	1.872	1.919	1.787	1,797	1.915	2.829	2.992	2.322	2.189		
2	Ti +4	0.003	0.042	0.059	0.095	0.077	0.053	0.024	0.006	0.008	_		
3	A1 + 3	0.053	0.185	0.137	0.277	0.267	0.123	1.140	1.588	1.653	1.780		
4	Fe <sup>+2</sup>	0.479	0.160	0.199	0.238	0.205	0.324	0.016	0.029	0.027	0.041		
5	Mn + 2	0.017	0.003	0.005	0.005	0.003	0.007		-		-		
6	$Mg^{+2}$	1.381	1.831	0.695	0.677	0.723	0.639		0.008	0.008	0.008		
7	$Ca^{+2}$	0.069	0.889	0.925	0.884	0.909	0.891	0.110	0.600	0.655	0.809		
8	Na <sup>+1</sup>	0.003	0.023	0.027	0.032	0.025	0.028	0.634	0.375	0.326	0.181		
9	$K^{+1}$		0.001	0.001	-	$\rightarrow$	0.001	0.281	0.016	0.013	0.003		
10	Cr + 3					-	-	100			-		
11	f	25.8	16.2	22.3	26.0	22.1	33.6				-		
12	Or	<u></u>			_	—	—	27.4	1.6	1.3	0.3		
13	Ab				_	-	_	61.9	37.8	32.7	18.2		
14	An			-	-	_	_	10.7	62.6	66.0	81.5		

Notes: 1-orthopyroxene. 2-6a, clinopyroxenes. 6b-7, feldspars. 3c-4c, magnetites. 4a-c, Sample 462-6-3, 77 cm, the others, Sample 462-21-1. Numbers with indices a, b, c are from a single fragment. f = Fe/(Fe + Mg) (atomic %).

thin sills (25-35 cm) which have thick (5-10 cm), glassy margins grade abruptly (2-5 cm) into holocrystalline microdoleritic-textured rock. The phenomenon might be explained by magma emplacement into water-saturated rocks (but not into water directly), resulting in formation of a heat-insulating glass cover. For example according to the shipboard measurements, pore-water content of sediments is more than 20% at depths of up to 600 meters below sea floor. High water pressure (as indicated by the deep-water fauna) was favorable for crystallization of the magma under intrusive conditions.

The change in eruption mechanism and magma composition at the boundary between the cycles (728 m) allows us to suppose the existence of a time interval between them. In addition, formation rate of the lower basalt complex was higher than that of the upper one.

Three joint systems are commonly distinguished in the rocks; one sub-horizontal  $(8-15^{\circ})$  and two vertical  $(75-95^{\circ})$ . Some intervals are strongly fractured. The fractures are filled with saponite, pyrite, opal, and calcite, often occurring jointly in the thickest veins. Within the glassy margins, zeolites, apophyllite, and ocenite are dominant (for details, see the paper by V. B. Kurnosov in this volume).

Petrographic features of the Nauru basalts are caused by magma contact with sea water. The appearance of the vertical, vein-like glass injections into holocrystalline rocks, and the presence of glassy and variolitic patches in coarse-grained dolerites, show convincingly the possibility of water penetration into crystallizing magmatic bodies. This phenomenon makes perfect layering in the oceanic-basalt bodies improbable. The penetration of sea water into magma evokes a microliquation, resulting in separation within glass of more-melanocratic globules which crystallize as variolitic pyroxene aggregates. The first microlite phase of the rocks is plagioclase, whereas pyroxene forms the spinifex-like aggregates.

Olivine and Cr-spinel are primary liquidus phases in the Nauru basalts; however, they remain unaltered only within fresh glass. In holocrystalline rocks, they are replaced by secondary minerals, or completely resorbed by pyroxene and magnetite. Sporadic coarse crystals and glomerophyric clusters of pyroxene and plagioclase show signs of crystallization in situ. Besides the listed phases, coarse (1-2 mm), perfectly shaped magnetite crystals appear in coarse-grained dolerites from the interiors of differentiated sills. A remarkable feature of the Nauru Basins rocks, unknown earlier in oceanic basalts, are granophyric patches in ophitic pyroxene-plagioclase aggregates. The latter are graphic intergrowths of orthoclase and quartz and isolated quartz grains, enriched in fluorapatite needles. Plagioclase and pyroxene adjacent to quartz granophyre are strongly zoned. Autometasomatic-stage minerals include kaersutite, green hornblende, biotite, and sulfides (pyrrhotite, pentlandite, chalcopyrite). The lower-temperature stage of the process is remarkable for the formation of veins of octahedral magnetite, actinolite, and talc. The described phenomena are characteristic of all differentiated bodies related to continental trap formations.

Fresh olivine is preserved only in the lower part of the section. The analyses (Table 3) show an invariable composition, either within a single grain or in different samples. No zonation within a grain is observed. The relatively high Fe/(Mg + Fe) ratio correlates with that of the rocks. Analyzed olivine is richer in calcium than in the intrusive analog.



Figure 1. Schematic vertical section of the basalt interval in Hole 462 and 462A.

Being the latest phases, pyroxenes show wide chemical variations (Table 4). They are the most iron-rich and alumina-depleted in the granophyric dolerites (462-69-1, 17-21 cm). In zoned grains (462A-38-2, 43-46 cm), the margins are more iron-rich and display a pigeonite affinity. A chrome-bearing, magnesian variety occurs in the lower part of the section (462A-68-1, 19-21 cm).

Analyzed plagioclases are mostly from phenocrysts (Table 5). Their compositions show a limited range (An<sub>71-82</sub>). The stable higher concentrations of magnesia and iron are remarkable. According to optical properties microlites are more sodium-rich (up to 10-15% An) than the phenocrysts. The same range is characteristic of the individual phenocryst zonation. Strong zonation is revealed in plagioclases from the granophyric dolerites (462-69-1, 17-21 cm): core, An<sub>53</sub>; margin in contact with granophyre, An<sub>35</sub>. These plagio-clases are magnesia-free, and enriched in iron and potassium. Feldspar from the granophyre is calcium-bearing orthoclase.

X-ray investigations of the bulk plagioclase separations show an extremely disordered structure in granophyric varieties (Table 6; 462-65, 462-69), whereas partial ordering of the plagioclases is observed in the thick dolerite sill. These are confirmed by optical measurements, which show more-perfect ordering of the grain margins in the granophyre-free dolerites. The extreme disordering of the intermediate (Ca-Na) plagioclases from granophyric dolerites, as compared with plagioclase of autonomous granite phases, probably is caused by crystallization of granitoid residue of basalt magma at high temperature.

Magnetite is widely represented in holocrystalline rocks, whereas only a dust-like impregnation occurs in glass-bearing varieties. The character of the solid-solution breakdown depends on the degree of crystallinity of the rocks: in microdolerites and glassy basalts, magnetite grains are homogeneous, whereas in coarsegrained dolerites a dense network of ilmenite exsolution lamellae appears. Distribution of ilmenite lamellae within the magnetite matrix is rather inhomogeneous

Oxides (wt. %)	462A	-44-2, 12-1	6 cm	462A-47-1,	95-98 cm
(wt. %)	1	2	3	1	2
SiO <sub>2</sub>	39.76	39.25	59.98	39.88	39.91
TiO <sub>2</sub>	0.01	0.01	0.01	0.01	0.01
Al2O3	0.08	0.07	0.06	0.07	0.07
FeO	15.10	15.25	15.24	15.03	15.25
MnO	0.24	0.22	0.23	0.26	0.23
MgO	44.05	44.21	44.95	44.66	44.11
CaO	0.34	0.32	0.31	0.32	0.33
Na <sub>2</sub> O K <sub>2</sub> O	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Total	99.92	99.33	100.78	100.22	99.91
	Ions	on the ba	sis of 4 ox	ygens	
Si + 4	1.004	0.999	0.997	1.000	1.005
A1 + 3	0.003	0.001	0.001	0.001	0.001
$Fe^{+2}$	0.318	0.324	0.317	0.315	0.320
$Mn^{+2}$	0.006	0.006	0.006	0.006	0.006
$Mg^{+2}$	1.655	1.658	1.670	1.668	1.654
$Ca^{+2}$	0.009	0.009	0.009	0.009	0.009
f	16.1	16.3	16.0	15.9	16.2

Table 3. Selected chemical compositions of olivines from Hole 462A basalts.

Notes: Microprobe analyses by I. M. Romanenko; FeO = total Fe as FeO; f = Fe/(Fe + Mg) (atomic %).

Table 4. Selected chemical compositions of pyroxenes from Leg 61 basalts.

	462			462A	
Oxides		38-2, 4	3-46 cm		
(wt. %)	69-1, 17-21 cm	core	margin	48-4, 46-48 cm	63-1, 19-21 cm
SiO <sub>2</sub>	52.51	49.09	49.86	50.31	51.69
TiO <sub>2</sub>	0.22	1.59	1.14	1.05	0.38
Al2O3	0.32	5.28	6.08	3.54	2.94
FeO	16.36	8.29	10.58	19.42	5.67
MnO	0.49	0.18	0.18	0.29	0.15
MgO	9.55	15.33	16.96	13.74	16.65
CaO	19.00	18.95	14.03	16.63	20.68
Na <sub>2</sub> O	0.68	0.20	0.18	0.22	0.20
K2Ô	0.02	0.01	0.01	0.01	0.01
Cr2O3	n.a.	n.a.	n.a.	n.a.	0.90
Total	99.95	98.92	99.01	99.20	99.26
	1	ons on the	e basis of	6 oxygens	
Si +4	2.020	1.837	1.850	1.908	1.907
Ti+4	0.007	0.045	0.031	0.032	0.011
A1+3	0.014	0.234	0.265	0.157	0.128
Fe+2	0.527	0.259	0.328	0.426	0.175
$Mn^{+2}$	0.016	0.007	0.007	0.009	0.004
$Mg^{+2}$	0.571	0.854	0.938	0.776	0.515
$Ca^{+2}$	0.784	0.760	0.559	0.676	0.817
$Na^{+1}$	0.051	0.013	0.013	0.016	0.013
Cr + 3		_	_		0.027
En	30.3	45.6	51.4	41.3	48.0
Wo	41.7	40.6	30.6	36.0	42.8
Fs	28.0	13.8	18.0	22.7	9.3
f .	48.0	23.2	25.9	35.4	16.0

Notes: Microprobe analyses by I. M. Romanenko: FeO = total Fe as FeO; n.a. = not analyzed; f = Fe/(Fe + Mg) (atomic %).

(Fig. 2). Inasmuch as titanium content in zones in ilmenite lamellae and between them is the same (Table 7, Nos. 3-6), a sharp change of thermodynamic conditions during growth of the magnetite crystals might be supposed. However, the possibility of leaching of titanium from the ilmenite lamellae by residual fluids from granophyre is not excluded. The high titanium content in the residual magnetite  $(6.19-6.65\% \text{ TiO}_2)$  indicates a

high temperature of the process. Chemical analyses of the bulk magnetite separations (Nos. 1, 2, Table 7, 8) show that the degree of iron oxidation corresponds to the simultaneous presence of ilmenite and ulvospinel components in the magnetite; it is also confirmed by cell parameters. However, it should be noted that recalculation of the analyses of components (assuming stoichiometry of magnetite) on the basis of an estimated Fe<sup>+2</sup>/Fe<sup>+3</sup> ratio shows that most Ti, even in homogeneous magnetite (No. 8), is included in ilmenite, not ulvospinel. This however is contradicted by the large value of  $a_0$  (8.46 Å). Calculation of Ti in probe analyses of ulvospinel shows a constant deficit (1-2%) in analysis totals. These cited features can be explained to a certain extent by the predominance of Fe2O3 over FeO, i.e., by the enrichment of magnetite in the magnetite component. All this is commonly noted in most maghemites from oceanic basalts (e.g., see Stoesser, 1975), and it deserves to be investigated in detail.

Ilmenite of exsolution lamellae is characterized by higher magnesia and manganese content compared with the analog from individual grains.

Besides the primary magmatic magnetite, wellshaped octahedrons of magnetite from saponite or talcsaponite veins were analyzed. This magnetite was found to be the extremely rare silica-bearing variety (Table 8), recently discovered by the author (Shcheka et al., 1977). Unlike earlier occurrences, silica in the Nauru magnetite is not associated with the other isomorphous elements. Remarkable variations of silica content from grain to grain and within a single grain commonly are observed. In contact with later silicates, magnetite lacks silica, which is extracted from its structure by solutions. As in all previous occurrences, magnetite from Nauru is characterized by an Fe<sub>2</sub>O<sub>3</sub> excess.

Nauru magnetites have a trace-element assemblage shown by Table 9. Along with the elements of basic to ultrabasic magmas (Ni, Co, V, Ti), they are enriched in the lithophile elements of acid melts: Mn, Zr, Sn. Using a special method (Shcheka and Pyatkov, 1978), calculation of the similarity of the Nauru magnetites and magnetites of the other genetic groups was carried out (Table 10). In this method, the coefficient  $K_i$  is the indicator of similarity; it characterizes generally a quota of the estimated object properties (in this case, traceelement association) in each of the standard objects. The calculations show (Fig. 3) either that magnetites of the upper complex or lower one are closest to magnetites of continental granophyric diabases (group 8), along with a strong contribution of tholeiitic basalt (group 5) and granite- acid-volcanic (groups 18, 19) properties. These indicate the specific features of Nauru basalt differentiation. Silica-bearing magnetite from the veins shows a similarity to magnetites from alcalime basalts, which probably indicates a high alkalinity of mineralforming solutions.

Investigations of recent years reveal a wide distribution of Cr-spinel in oceanic basalts (Sigurdsson and Schilling, 1976; Shcheka et al., 1978; and others). It is established that spinel may be considered as an effective indicator of temperature and oxygen fugacity of crystal-

		462			462A								
Oxides	6	9-1, 17-2	1	38-2, 4	3-46 cm	44-2, 12	2-16 cm	47-1, 95-98 cm	48-4, 46-48 cm	63-1, 19-21 cm			
(wt. %)	1	2	3	1	2	1	2	1	1	1	1		
SiO <sub>2</sub>	57.99	53.46	-	50.45	49.52	51.61	48.43	47.90	50.35	46.70	48.78		
TiO <sub>2</sub>	0.01	0.04		0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.04		
Al2O3	25.53	28.06		29.95	31.94	30.45	32.07	32.84	31.20	31.65	31.85		
FeO	0.72	0.80		0.74	0.70	0.82	0.72	0.73	0.93	0.90	0.60		
MnO	0.01	0.01		0.01	0.02	0.02	0.01	< 0.01	< 0.01	< 0.01	< 0.01		
MgO	0.06	0.06		0.28	0.24	0.29	0.18	0.31	0.36	0.30	0.27		
CaO	7.80	10.94	1.28	14.42	15.43	14.36	16.81	15.83	14.21	15.22	15.04		
Na <sub>2</sub> O	7.80	5.25	1.15	3.15	2.63	2.81	2.02	2.23	3.21	2.34	2.51		
K <sub>2</sub> Õ	0.14	0.06	12.49	0.06	0.01	0.01	0.02	0.01	0.02	0.02	0.01		
Total	100.05	98.68		99.07	100.50	100.38	100.26	99.87	100.29	99.18	99.10		
						lons on	the basis o	of 8 oxygens					
Si + 4	2.610	2.455		2.306	2.257	2.348	2.222	2.204	2.289	2.252	2.252		
A1+3	1.354	1.515		1.609	1.713	1.631	1.732	1.778	1.672	1.723	1.731		
Fe <sup>+2</sup>	0.027	0.030		0.027	0.027	0.030	0.028	0.028	0.036	0.033	0.022		
$Mg^{+2}$	0.003	0.003		0.019	0.016	0.019	0.011	0.022	0.025	0.019	0.019		
$Ca^{+2}$	0.376	0.537	0.071	0.705	0.755	0.699	0.826	0.782	0.694	0.755	0.745		
Na + 1	0.681	0.466	0.113	0.280	0.233	0.221	0.179	0.199	0.284	0.208	0.224		
K + 1	0.008	0.003	0.816	0.003	-	_			777	_	-		
An	35.3	53.4	7.1	71.4	76.4	75.9	82.2	79.7	70.9	78.4	76.9		
Ab	63.9	46.3	11.3	28.3	23.6	24.1	17.8	20.3	29.1	21.6	23.1		
Or	0.8	0.3	81.6	0.3	-	100 AU	-		1	_	-		

Table 5. Selected chemical compositions of feldspars from Leg 61 basalts.

Table 6. X-ray and optical order-disorder characteristics of Leg 61 plagioclases.

Parameter	462-65-1, 120-124 cm	462-69-1, 17-21 cm	462A-66-1, 143-147 cm	462A-66-3, 143-148 cm	462A-67-7, 21-25 cm
An (204 - 113)	44	40	61	61	61
An (chemical)		38			61.6
An (optical)	42 (m), 58 (c)		—	—	56 (m), 80 (c)
131 - 131	1.99	1.98	2.03	2.00	2.02
Deviation from Slemmons					
(1962)	0.0	0.0	0.1	0.2	0.2
220 + 131 -					
2 (131)	0.87	0.88	1.00	0.91	0.96
Deviation from Smith and	0.0	0.0	0.2	0.3	0.25
Deviation from Marfunin	0.0	0.0	0.2	0.5	0.20
(1962)	0 (m), 0 (c)			-	0.5 (m)

Note: m, c indicate margin and core of a single grain.



Figure 2. Magnetite grain with exsolution texture. A. Back scattered electrons. B. TiK $\alpha$ . Vertical side of print is equivalent approximately to 1 mm.

Table 7. Representative chemical compositions of magmatic magnetites and ilmenites from Leg 61 basalts.

Oxides	462-68-8, 55-60 cm		4	62-69-1,	17-21 c	m		462-69-2, 85-89 cm	462A-81-2, 15-16 cm
(wt. %)	1	2	3	4	5	6	7	8	9
SiO <sub>2</sub>	-		1.17	0.12	0.75	0.14	0.00	_	0.21
TiO <sub>2</sub>	20.47	10.07	6.44	6.19	6.35	6.65	47.63	18.43	48.11
Al2O3	2.54	1.44	0.20	0.17	0.64	0.49	0.10	2.81	0.13
Fe2O3	38.08	55.51	-	-	-	—	-	41.00	-
FeO	37.07	30.76	85.62	86.35	85.81	86.15	50.34	35.57	48.42
MnO	0.45	0.40	0.41	0.46	0.46	0.42	0.93	0.60	0.55
MgO	0.93	0.90	0.45	0.41	0.59	0.46	1.55	11.06	0.77
CaO	0.10	0.20	0.07	0.18	0.01	0.00	0.00	0.19	0.03
Cr2O3	—	0.00	0.00	0.00	0.00	0.00	0.00		0.02
Total	99.62	99.28	94.36	93.88	94.61	94.31	100.55	100.26	98.24
$a_0(Å)$	8.428	8.398	-	—	-	_		8.456	_

Notes: 1, 2, 8 are wet chemical analyses, analyst V. G. Kohanova; others are microprobe analyses by I. M. Romanenko: 3, 4, fine grains from groundmass; 5, part of a coarse grain lacking ilmenite lamellae; 6, interior of ilmenite; 7, lamellae in the same grain as in 5; 9, fine, isolated grain of ilmenite; FeO in microprobe analyses represents total Fe as FeO.

Table 8. Chemical compositions of silica-bearing magnetites from Leg 61 basalts.

Table 10. Computer estimation of magnetite genetic type, Leg 61 basalts.

	462	2-69-1, 17	-21 cm	46	52A-85-4	, 78-80 (	cm
Oxides (wt. %)	1	2 (core)	2 (margin)	3	4	5	6
SiO <sub>2</sub>	3.60	3.47	1.53	3.50	2.62	2.32	2.03
TiO <sub>2</sub>	0.22	0.11	0.30	1.34	0.84	0.74	0.63
Al <sub>2</sub> O <sub>3</sub>	0.30	0.27	0.19	0.42	0.21	0.15	0.22
FeO	88.29	28.22	91.44	87.8	88.80	88.40	89.00
MnO	0.23	0.20	0.23	0.37	0.31	0.28	0.31
MgO	0.19	0.32	0.14	0.36	0.30	0.22	0.35
CaO	0.16	0.40	0.02	0.36	0.05	0.15	0.23
Cr <sub>2</sub> O <sub>3</sub>	0.04	0.00	0.04	0.07	0.08	0.07	0.07
Total	93.05	32.99	93.91	94.22	93.21	92.33	92.84
<i>a</i> <sub>0</sub> Å	_	8.395	_	_	×^	_	

Notes: FeO = total Fe as FeO. Microprobe analyses by I. M. Romanenko. Additionally, Fe<sub>2</sub>O<sub>3</sub> was determined in sample 2 (core): 65.43%.

Table 9. Trace-element contents of magnetites from Leg 61 basalts.

Sample (interval in cm)	TiO <sub>2</sub>	Cr	v	Ni	Co	MnO	Zr	Sn	Zn	Cu
462-65-1, 120-124	16.0	76	4800	150	180	5000	170	4	630	260
66-3, 93-97	20.0	54	5700	100	190	14000	250	10	650	76
66-4, 97-101	18.0	30	5100	110	150	10000	200	6	870	66
67-1, 63-67	20.0	57	7200	110	230	5000	260	10	430	120
68-1, 81-85	17.0	52	8300	200	260	2800	250	11	370	320
68-2, 105-110	16.0	45	5700	190	230	2700	240	8	560	210
68-3, 55-60	18.0	52	5000	220	260	3200	310	7	370	200
69-1, 17-21	6.5	11	1300	73	130	2400	98	10	320	58
69-1, 17-21	0.79	1700	560	130	220	4800	96	48	630	52
69-2, 85-89	14.0	33	4400	170	230	4400	130	6	370	160
Average of above	17.38	50	5775	156	216	5430	226	8	531	177
462A-65-1, 1-6	14.0	45	3800	190	200	3400	240	7	300	250
66-1, 143-147	10.0	130	4700	160	210	3900	300	12	460	300
66-3, 143-148	13.0	36	5400	110	190	5500	320	10	300	52
66-5, 145-150	14.0	48	7200	130	230	6000	260	23	630	170
67-4, 107-112	18.0	40	5500	150	260	2700	320	20	370	140
67-7, 21-25	16.0	130	5200	160	200	3400	190	12	380	380
68-2, 72-74	17.0	48	5500	160	260	4000	240	72	650	320
68-2, 104-106	13.0	140	3000	200	170	5000	320	15	540	380
Average of above	14.38	77	5038	158	215	4238	271	14	454	249

Notes: Low-temperature magnetite veins, analyst T. V. Lankova. TiO2 in wt. %; others in ppm.

lization processes (Hill and Roedder, 1974). The general features of spinel from Nauru basalt are high Fe/ (Fe + Mg) and Cr/(Cr + Al) ratios (Table 11; Fig. 4), characteristic of the rocks. Inclusions in plagioclase are greatly enriched in titanium. The other characteristics (enrichment in titanium and high iron oxidation) are the

Sample			S	imilarity	Ord	ler		
(interval in cm)	I		II			III		IV
462-65-1, 120-124	14	(0.05)	5	(0.04)	9	(0.04)		
66-3, 93-97	8	(0.05)	18	(0.03)				
66-4, 97-101	8	(0.04)	18	(0.02)	19	(0.02)		
67-1, 63-67	8	(0.05)	19	(0.04)	5	(0.03)		
68-1, 81-85	8	(0.05)	5	(0.04)	19	(0.03)		
68-2, 105-110	8	(0.04)	5	(0.04)	19	(0.03)		
68-3, 55-60	5	(0.03)	8	(0.03)	19	(0.02)		
69-1, 17-21	8	(0.03)	5	(0.03)	19	(0.02)		
69-1, 17-21	6	(0.11)				10000000		
69-2, 85-89	8	(0.03)	5	(0.03)	19	(0.03)		
Average of above	8	(0.04)	5	(0.03)	19	(0.03)		
462A-65-1, 1-6	8	(0.04)	5	(0.03)	19	(0.03)	18	(0.03)
66-1, 143-147	5	(0.09)	19	(0.07)	8	(0.07)	22	(0.07)
66-3, 143-148	8	(0.05)	19	(0.03)	18	(0.02)		
66-5, 145-150	8	(0.10)	4	(0.04)	19	(0.04)		
67-4, 107-112	8	(0.05)	5	(0.03)	14	(0.03)	19	(0.02)
67-7, 21-25	5	(0.08)	11	(0.07)	8	(0.07)	19	(0.06)
68-2, 72-74	8	(0.08)	4	(0.06)	19	(0.03)	19	(0.07)
68-2, 104-105	8	(0.11)	5	(0.09)	18	(0.08)		
Average of above	8.519	(0.07)		10		2		

Notes: Numerals before brackets (1-22) indicate numbers of magnetite genetic types: 1, 2, ultrabasic volcanics (1) and intrusives (2); 3, serpentines; 4, low-temperature ores from alcalime ultrabasics; 5, 6, tholeiitic (5) and alkaline (6) basalts; 7, 8, tholeiitic (7) and granophyric (8) diabases; 9, gabbro; 10, monzonite, 11, olivine-anorthite inclusions in basalts; 12, basic hornfelses and xenoliths; 13, Cu-Ni ores, 14, 15, tholeiite (14) and trachyandesites (15); 16, plagiogranites and diorites: 17, granodiorites; 18, acid volcanics; 19, granites: 20, alkaline granites; 21, skarns; 22, propylitized gabbro. Numerals in brackets = similarity coefficient ( $K_i$ ).

same as those for all oceanic basalts (Shcheka et al., 1978). Only in grains was a zonation (enrichment of the grain margin in Mg-Al) observed. No regularities in the compositional change through the section (from 730 to 870 m) are established. The deficit in totals of some analyses is probably caused by non-stoichiometry of the spinels.

On the basis of experimental data (Hill and Roedder, 1974), for melt compositions close to the Nauru basalt, an approximate temperature and oxygen fugacity of crystallization of the liquidus stage are: t = 1210 to  $1220^{\circ}$ C; and  $f_{O2} = 10^{-8}$  to  $10^{-8.5}$  atm. Application of the liquidus-solidus geothermometer of Vaganov and Kuznetsov (1976) shows similar temperature values: sol-



Figure 3. The pattern of genetic links of the Nauru magnetites: 1, "differentiated" range; 2, "primitive" range; 3, low-temperature veins. Genetic groups (as in Table 10) are shown on abscissa.

idus, 1160°C; liquidus, 1240°C. The same order of thermodynamic parameters  $(t, f_{O2})$  are characteristic of spinel crystallization in basalts of rift zones (Fig. 4). In addition (as shown by Shcheka et al., 1978), zonation developed in spinels from the Nauru basalts is not caused by t and  $f_{O2}$  change, but presumably by change of the melt composition, i.e., alumina redistribution between spinel and plagioclase.

Reconstruction of the chemistry of the primary oceanic basalt, as compared with continental basalts, is difficult but elucidated by consideration of melt-seawater interaction. Being heated, sea water becomes a real hydrothermal solution, causing various transformations of the rocks. Hydrothermal alteration is intensively manifested in the Nauru basalts, especially in the upper units, where basalts alternate with sediments. These processes are described in detail in the shipboard report, and because of the limited length of this paper are not discussed here. Suffice it to note that two types of alteration are revealed in the rocks. In the upper complex (562-728 m), rock hydration was accompanied by considerable removal of calcium and addition of potassium (Table 12), along with preservation of titanium content and the Fe/Mg ratio. Calcium zeolites, celadonite, and apophyllite prevail among the secondary minerals within this interval (see Kurnosov, this volume). Apophyllite (also including fluorine) commonly occurs above the thick sills, where differentiation is completed by the formation of a granitic residue enriched in fluorine (fluorapatite), and probably generating K-F-solutions. Deep transformations of rocks within the upper complex were stimulated by carbonic acid, probably from sediment layers, in post-magmatic processes. Within the lower complex, alteration coincides with glassy margins of sills, and has resulted in hydration and enrichment of rocks in potassium, i.e., it proceeded without essential disturbance of primary geochemical associations of elements (Table 12). It is seen that the most stable geochemical characteristics of the rocks are titanium content and the Fe/Mg ratio.

All quench glasses include olivine and spinel as liquidus phases, and there was fractionation of initial melts. This is supported by microprobe analyses of the glasses (Table 13), which show a higher Fe/Mg ratio as compared with the bulk analysis. According to calculations, about 4% olivine is present in Sample 47-3.

Because of numerous XRF analyses carried out aboard ship, only samples from thick sills of the upper and lower complexes and selected samples from the other intervals had been analyzed (Table 14). All XRF and wet-chemical results are the same, excluding a negligible divergence (2-5 relative per cent) in iron determination.

Study of the distribution of the very immobile titanium through the vertical section shows (Fig. 5) that above-classified complexes are diverse, either by initial content of the element or by its behavior during local differentiation of the individual bodies. A distinct petrochemical boundary (728 m) divides the lower por-

	44	-2, 12-16	cm	47-1, 9	5-98 cm	47-3,	74-77 cm	48-4, 46-48 cm	63-1, 19-21 cm	
Oxides (wt. %)	1	2	3	4	5	6 (core)	6 (margin)	7	8	
TiO <sub>2</sub>	0.69	0.70	0.68	0.72	0.69	0.57	0.53	0.59	0.89	
Al2O3	18.57	18.44	18.04	18.03	18.10	15.27	17.33	14.21	18.51	
Fe2O3	11.58	11.90	11.82	12.54	11.98	10.86	10.86	9.18	11.74	
FeO	16.45	16.24	16.38	16.24	16.31	16.81	16.02	17.68	18.11	
MnO	0.26	0.21	0.25	0.22	0.24	0.30	0.28	0.26	0.29	
MgO	12.04	12.17	12.08	12.19	12.19	11.37	11.86	10.89	11.09	
Cr2O3	39.35	39.31	40.21	39.26	39.72	43.81	40.98	46.76	38.64	
Total	98.94	98.97	99.48	99.20	99.23	98.99	98.45	99.53	99.27	
				Ions on	the basis	of 4 oxyg	gens			
Ti +4	0.017	0.017	0.015	0.017	0.015	0.014	0.014	0.016	0.021	
A1+3	0.696	0.692	0.676	0.678	0.680	0.584	0.662	0.542	0.698	
Fe+3	0.278	0.286	0.284	0.300	0.288	0.266	0.266	0.266	0.288	
Fe <sup>+2</sup>	0.422	0.430	0.435	0.416	0.418	0.429	0.422	0.465	0.485	
Mn <sup>+2</sup>	0.008	0.006	0.008	0.006	0.008	0.008	0.008	0.008	0.008	
$Mg^{+2}$	0.572	0.581	0.573	0.578	0.577	0.549	0.573	0.527	0.526	
Cr <sup>+3</sup>	0.992	0.988	1.012	0.988	1.000	1.122	1.050	1.200	0.978	
f	55.0	55.2	55.6	55.3	55.0	55.9	54.6	56.7	59.4	
Y	58.8	58.8	60.0	59.3	59.5	65.8	61.3	68.9	58.6	
f'''	39.7	39.9	39.9	41.9	40.8	38.3	38.9	32.3	37.3	

Table 11. Selected chemical compositions of spinels from Hole 462A basalts.

Notes: Microprobe analyses by I. M. Romanenko. FeO and Fe<sub>2</sub>O<sub>3</sub> are calculated assuming stoichiometry of spinel. Number 8 is an inclusion in plagioclase, the others in glass.  $\gamma = Cr/(Cr + Al)$  (atomic %);  $f' = Fe^{+3}/\Sigma Fe$  (atomic %); f = Fe/(Fe + Mg) (atomic %).



Figure 4. Compositions of Cr-spinels from basalts and ultrabasic rocks: 1-4, basalts: 1, Nauru; 2, upper and, 3, lower rift complexes of Indian and Atlantic Oceans; 4, inner Hebrides; 5, oceanic gabbro and troctolites; 6, oceanic ultrabasic rocks of the upper rift complexes; 7, 8, fields of spinels from ultrabasic rocks of the alpine type (7) and layered intrusives (8). Number 4 according to Ridley (1977). Zonation of spinels from core to margin is shown by arrows.

Table 12. ical c the tw tered	Average composit vo types basalts.	e chem- ion of of al-
Oxides		
(wt. %)	1 (5)	II (8)
SiO <sub>2</sub>	50.26	49.79
TiO <sub>2</sub>	1.60	1.21
Al2O3	15.15	14.23
F 6		

Fe <sub>2</sub> O <sub>2</sub>	13.22	11.94
MnO	0.30	0.14
MgO	7.23	7.47
CaO	7.25	11.42
K <sub>2</sub> O	0.95	0.42
L.o.i.	3.30	2.72
Total	99.49	99.57
f	49.4	44.5

Notes: Fe<sub>2</sub>O<sub>3</sub> = total Fe as Fe<sub>2</sub>O<sub>3</sub>; figures in parentheses are analysis numbers; f = Fe/(Fe + Mg) (atomic %).

tion, lacking in sedimentary layers, and the upper one, enriched in such layers. It is remarkable that sharp changes of titanium concentrations are observed near sedimentary layers, indicating the dependence of local sill differentiation on the presence of a sedimentary cover.

Table 13. Microprobe analyses of glasses from Hole 462A.

Oxides			47-3, 74-77 cm		
(wt. %)	44-2, 12-16 cm	47-1, 95-98 cm	1	2*	
SiO <sub>2</sub>	51.35	51.17	50.30	50.20	
TiO <sub>2</sub>	0.95	0.94	0.95	0.95	
Al2Õ3	13.37	13.72	13.83	14.14	
FeO	10.75	10.54	10.74	7.36	
MnO	0.21	0.19	0.20	0.20	
MgO	6.97	7.40	7.11	8.76	
CaO	11.65	12.15	12.12	11.79	
Na <sub>2</sub> O	2.06	1.97	2.05	1.99	
K <sub>2</sub> Õ	0.11	0.12	0.13	0.11	
Total	97.43	98.19	97.44	100.34	
Fe/(Fe + Mg)	46.4	44.4	46.0	39.7	
(K + Na)/Al	0.26	0.25	0.26	0.24	

\* Wet chemical analyses by T. I. Bortina; also determined: Fe<sub>2</sub>O<sub>3</sub> (3.18%), H<sub>2</sub>O<sup>+</sup> (1.15%), H<sub>2</sub>O<sup>-</sup> (0.13%), CO<sub>2</sub> (0.38%).

General features of differentiation in thick sills are shown in Figure 6, which shows that the Fe/Mg ratio and Ti content of rocks within Unit 14 (462A) varies from the roof (No. 1) to the bottom (No. 15) irregularly, i.e., perfect layering in the body is not observed. This is explained by sporadic penetration of sea water into the crystallizing magma. Rock composition both in the roof (No. 1) and the bottom of the sill (No. 15), is the same. The Fe/Mg ratio and Ti content of the rocks increase as coarse-grained textures and granophyre patches appear, indicating deep magma fractionation at some levels of the sill. Fractionation is not observed within a thick sill from the lower complex (No. 113; 462A), but it occurs in sills (Nos. 135-139) underlying the lowest sediment layer (Fig. 1). Local differentiation trends of sills from the lower and upper complexes are the same, but differ in primary Ti content of the consequent magma portions. General differences of rock composition and their differentiation paths in Nauru Basin and oceanic rift zones are clearly outlined in Figure 6, besides an equal Fe/Mg ratio, the rift basalts are richer in titanium.

Comparison of average compositions of the rocks from Nauru and other oceanic complexes (Table 15) shows that the closest analogs of Nauru basalts are those from the Pacific oceanic plateaus. Basalts of the upper differentiated complex correlate with analogs of the Ontong-Java Plateau (Stoesser, 1975), whereas "primitive" tholeiites of the lower complex are analogous to the Manihiki Plateau (Jackson et al., 1975).

Review of voluminous DSDP data from the Pacific leads us to the conclusion that, according to composition, rocks of the Nauru Basin are remarkably close to pre-Paleogene basalts of a vast area of the sea floor distant from geological structures of continents, island arcs, and rift zones.

Recent investigations of dredged material show a stratification of the "basalt layer" in oceanic rift zones (Shcheka and Kurentsova, 1980). Essentially, lava of the upper complex is composed of differentiated, lowalcalime and magnesia-rich basalts, whereas the lower one (pre-Paleogene) is represented by sills of iron-rich

Table 14. Chemical compositions of the Nauru basalts.

Ovide		Oxide Hole 462											
Nos	(wt. %)	65-1, 120-124	66-3, 93-97	66-4, 97-101	66-5, 52-55	67-1, 63-67	68-1, 82-85	68-2, 105-110	68-3, 55-60	69-1, 17-21			
1	SiO <sub>2</sub>	49.60	50.15	50.45	49.20	50.10	49.95	49.90	49.85	49.85			
2	TiO <sub>2</sub>	1.54	1.60	1.46	1.99	1.75	1.58	1.60	1.71	1.79			
3	Al2Õ3	14.04	13.04	13.86	12.56	13.63	14.01	13.87	14.03	14.23			
4	Fe2O3	3.73	3.82	3.20	6.01	4.40	2.73	3.17	3.15	5.47			
5	FeO	8.99	9.95	8.91	9.66	9.13	9.52	9.45	9.30	6.74			
6	MnO	0.22	0.26	0.23	0.24	0.22	0.23	0.23	0.22	0.19			
7	MgO	7.10	7.45	7.68	6.55	6.68	7.28	7.45	7.09	6.75			
8	CaO	11.18	10.04	10.53	9.40	10.27	10.85	10.69	10.84	11.17			
9	Na <sub>2</sub> O	2.20	2.26	2.20	2.44	2.44	2.26	2.31	2.50	2.56			
10	K2Õ	0.09	0.09	0.11	0.09	0.16	0.11	0.10	0.09	0.19			
11	H20+	1.19	1.41	1.57	1.60	1.69	1.64	1.46	1.44	0.82			
12	$CO_2$	0.40	0.28	0.14	0.89	0.42	0.16	0.33	0.24	0.31			
13	Total	99.76	99.78	99.85	99.98	100.34	99.82	100.04	99.95	99.73			
14	f	49.4	50.1	46.2	57.3	52.3	48.3	48.0	49.1	49.1			
15	f'''	27.7	25.7	24.7	35.9	29.9	20.1	23.0	23.4	43.1			
16	A	0.27	0.29	0.27	0.33	0.31	0.27	0.28	0.30	0.31			

Notes: f = Fe/(Fe + Mg);  $f''' = \text{Fe}^{3+}/\Sigma\text{Fe}$ ; A = (K + Na)/Al; all in atomic %.

Table 14. (Continued).

Hole 462	Hole 462A										
69-2, 85-89	66-5, 145-150	67-4, 107-112	67-7, 21-25	68-2, 72-74	68-2, 104-106	75-3, 112-114	78-3, 40-43	79-5, 144-14			
49.50	49.90	49.30	49.95	49.85	49.95	49.65	49.20	48.95			
1.71	1.03	0.94	0.95	1.03	1.01	0.95	1.03	1.06			
14.16	14.16	14.29	14.24	14.50	14.45	13.79	14.43	14.80			
5.02	6.40	3.51	2.72	3.36	4.44	2.90	4.03	4.23			
7.77	4.69	7.84	7.96	8.19	6.99	8.27	7.48	6.64			
0.21	0.20	0.21	0.21	0.21	0.20	0.20	0.20	0.22			
6.63	8.28	8.61	8.26	8.12	7.82	8.15	8.10	7.92			
10.53	11.56	12.15	12.15	11.91	11.66	12.35	11.83	11.99			
2.75	2.20	1.97	2.01	2.08	2.00	2.10	2.22	2.32			
0.09	0.13	0.03	0.05	0.07	0.03	0.05	0.03	0.03			
1.82	1.59	1.23	1.46	0.90	1.16	1.30	1.37	1.96			
0.33	0.30	0.44	0.24	0.49	0.63	0.70	0.62	0.34			
99.99	99.99	100.52	99.76	100.73	100.34	100.31	100.54	100.46			
50.8	41.6	41.8	41.4	43.7	44.1	42.9	43.4	42.6			
36.6	55.2	28.8	23.4	26.9	36.6	23.8	32.4	37.1			
0.31	0.26	0.22	0.23	0.23	0.22	0.34	0.24	0.24			

basalts. Pre-Paleogene basalts of the Nauru Basin are very similar to lower rift complexes (Table 15), differing slightly in their higher alkalinity. Continental traps, occupying vast territories, differ from Nauru basalts in their higher K contents and Fe/Mg ratios (Kutolin, 1972). The closest continental analog of the oceanic sill basalt is the Karroo trap.

The distribution of most trace elements in Nauru rocks is ruled by their major-element chemistry (Table 16). Cr-content is minimum in granophyric varieties (462-66-3; 66-5; 69-1) and maximum in magnesia-rich glass (462A-47-3). Clear correlations of Cr and Ni content with the Fe/Mg ratio of the rocks (Fig. 7A), and Zr with Ti (Fig. 7B) are observed. Vanadium concentrations are controlled by oxidation degree of the rocks (Fig. 7C). Points on the plot in Figure 7 deviate from the curve representing rocks which underwent low-temperature alteration.

The differences and similarity of the Nauru and other oceanic basalts mentioned above are totally supported by the distribution of trace elements (Table 17). A specific feature of the Nauru rocks is their higher vanadium content, which might be caused by a specific oxidation state of the initial magma. Simultaneous increase of Zr, Ni, and Sr in Fe-basalts from rift zones, which is contrary to their low alkalinity, probably indicates the higher-temperature character of melts in rift zones. It should be noted that, despite the presence of granophyre, Ba concentrations in Nauru basalts remain on a low "oceanic" level (20-40 ppm) as compared with continental basalts, in which these values are much higher. These differences are in agreement with the potassium content of the rocks. Finally, according to rock composition and emplacement mode, basalts of the Nauru Basin are mostly close to tholeiites which compose vast areas of the world ocean floor, and might be considered to belong to the pre-Paleogene basement of either rift zones or more-stable geological structures.

Two main aspects must be discussed in interpretation of the geological nature of the Nauru sill complex. The first is that the basalts recovered from Holes 462 and 462A represent a typical oceanic tholeiite basement.

Table 14. (Continued).

	Ovide	Hole 462A								
Nos	(wt. %)	80-5, 91-93	81-2, 15-16	85-4, 78-80	27-2, 71-76	28-2, 81-83	29-6, 86-88	30-1, 98-100	30-3, 14-17	47-3, 74-77
1	SiO <sub>2</sub>	50.10	49.00	50.40	49.64	49.74	49.82	49.79	49.62	50.20
2	TiO <sub>2</sub>	1.22	1.20	1.14	1.54	1.52	1.45	1.41	1.60	0.95
3	Al2Õ3	14.44	14.18	13.69	14.85	13.89	12.78	13.16	13.81	14.14
4	Fe2O3	3.18	4.60	3.47	6.47	3.68	4.27	4.57	4.64	3.18
5	FeO	9.02	7.29	8.04	5.68	9.03	8.41	8.34	8.41	7.36
6	MnO	0.21	0.21	0.20	0.23	0.22	0.22	0.19	0.22	0.20
7	MgO	7.10	8.03	9.31	6.27	6.79	7.72	7.09	7.00	8.76
8	CaO	11.18	12.02	10.53	11.02	11.09	10.82	9.45	10.52	11.79
9	Na <sub>2</sub> O	2.33	2.02	2.00	2.36	2.30	2.35	2.55	2.40	1.99
10	K2Õ	0.06	0.07	0.05	0.17	0.14	0.39	1.28	0.33	0.11
11	H2O+	1.50	1.35	1.36	1.34	1.40	1.54	1.72	1.30	1.15
12	CÕ2	0.54	0.16	0.12	0.37	0.36	0.52	0.34	0.32	0.38
13	Total	100.88	100.13	100.26	99.94	100.16	100.29	99.89	100.17	100.34
14	f	48.5	44.6	40.0	50.8	50.6	47.2	49.7	50.3	39.7
15	f'''	24.1	36.3	27.2	50.6	26.7	31.2	32.9	33.1	28.0
16	A	0.25	0.24	0.24	0.27	0.28	0.33	0.42	0.31	0.24

Table 14. (Continued).

	Hole 462A											
51-4, 27-30	65-1, 1-6	65-3, 18-20	66-1, 143-147	66-3, 143-148	87-1, 70-72	88-2, 74-75	90-3, 88-90					
47.90	49.25	49.60	49.75	49.50	50.20	50.10	48.85					
0.95	0.98	1.01	1.02	1.02	1.10	1.03	1.27					
13.88	14.20	14.21	4.07	14.30	13.59	12.60	14.04					
5.66	4.00	3.67	2.71	3.42	5.52	4.30	4.47					
6.13	6.70	6.92	8.46	8.06	7.29	7.56	8.52					
0.18	0.19	0.20	0.20	0.21	0.21	0.19	0.24					
7.43	8.06	8.05	8.30	8.10	7.21	8.96	6.81					
8.99	12.37	12.31	11.73	11.89	11.73	11.27	12.27					
1.54	2.34	2.13	2.08	2.11	2.03	1.91	2.31					
0.27	0.03	0.03	0.05	0.03	0.05	0.07	0.05					
3.40	1.53	1.72	1.40	1.60	1.03	1.38	1.41					
0.36	1.26	0.49	0.54	0.32	0.30	0.15	0.22					
99.61	100.86	100.34	99.85	100.56	100.26	99.52	99.93					
45.8	41.8	41.6	42.4	43.6	48.7	41.7	50.9					
45.5	35.0	30.8	28.9	27.7	40.0	34.0	32.0					
0.25	0.26	0.23	0.25	0.23	0.25	0.25	0.27					

This is supported by the chemical composition and homogeneity of the magma, and especially by the extremely low K contents (0.05–0.10 wt. % K<sub>2</sub>O), which decreases to 0.001 wt. % K<sub>2</sub>O in the lower portion (below 728 m) of the holes, in both fresh and altered varieties. This casts doubt on the presence of a thick layer of K-bearing sediments and limestones lower in the section, because the presence of such sediments would lead to a high-K type of alteration in the overlying basalts, as observed in the upper differentiated complex. In addition, it is commonly observed in continental basalt complexes that basic rocks overlying a K-rich sedimentary terrane are enriched in K. The reasons for this K enrichment are not yet well understood, but such phenomena are indisputable now.

An additional explanation of the features of the Nauru complex is based on specific conditions of crystallization. The numerous observations listed above are undoubtedly consistent with the idea that the basalts crystallized under a crust of overlying water-saturated rocks. The Nauru sill complex is similar in many respects to the trap complexes of continental platforms, where giant eruptions (sometimes more than 3 km thick) culminate in the formation of layered igneous bodies. These layered complexes commonly include thin granitic layers. Despite the great thickness of many of the Nauru sills, the development of rhythmic layering has been impeded by free access of water to the crystallizing sill.

However, the composition of continental traps is different from that of the Nauru Basin basalts. This is probably due to the fact that continental and oceanic crust differ greatly in composition. It is well known that along the borders of depressions continental traps overlie various sedimentary rocks, but their thickness at a distance is unknown. In this direction the seismic crust becomes reduced, and the basalt component prevails. Therefore, it is possible that eruptions similar to continental trap basalts in all their fundamental characteristics may be present in oceanic regions of specific non-linear spreading zones, but this fundamental simi-



Figure 5. Distribution of titanium in the basalt intervals of Hole 462 and 462A.

larity between the oceanic and continental occurrences may be obscured by chemical differences which result from the different crustal type.

Finally, all these data, and the absence of post-Cretaceous rift complexes in the Nauru Basin, allow us to consider the Nauru Basin and other similar zones (Ontong-Java, Manihiki, and others) as geological structures of mature consolidation of the oceanic floor.

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Figure 6. Correlation of Ti and Fe/(Fe + Mg) in the Nauru basalts. 1, 2, basalts and dolerites of the upper and lower Nauru complexes (larger symbols = averages); 3, Nauru glasses; 4, 5, average compositions, Ontong-Java (4) (Stoesser, 1975) and Manihiki (5) plateau basalts (Jackson, Bargar, et al., 1975).

Table 15. Chemical compositions of Nauru basalts and the major types of oceanic basalts.

Table 16. Trace-element in unaltered basalts of the Nauru Basin.

Oxide (wt. %)	1(15)	2(20)	3(22)	4(2)	5(134)	6(33)	7(51)
SiO <sub>2</sub>	49.69	49.58	50.19	48.85	49.71	49.70	51.88
TiO <sub>2</sub>	1.62	1.05	0.97	1.55	1.11	1.54	1.34
Al <sub>2</sub> O <sub>3</sub>	13.63	14.10	14.70	14.8	16.20	14.64	15.30
Fe <sub>2</sub> O <sub>3</sub>	4.29	3.99	4.21	4.2	2.26	2.60	1.35
FeO	8.62	7.47	6.21	7.85	7.21	8.85	9.12
MnO	0.22	0.20	0.22	0.17	0.17	0.18	0.23
MgO	7.04	8.07	8.43	6.75	8.35	7.50	6.92
CaO	10.56	11.83	11.29	11.1	11.84	11.02	10.03
Na <sub>2</sub> O	2.39	2.10	2.11	2.25	2.35	2.61	2.09
K <sub>2</sub> O	0.15	0.05	0.09	0.40	0.17	0.17	0.78
$H_{2}O^{+}$	1.82	1.82	1.58	1.85	0.40	0.44	-
Total	100.03	100.26	100.09	99.77	100.15	99.22	_
f	49.9	43.5	39.9	49.1	38.3	45.6	45.6
A	0.30	0.25	0.24	0.28	0.20	0.23	0.28

Notes: 1, 2 differentiated (1) and "primitive" (2) Nauru complexes; 3, Manihiki Plateau (Jackson et al., 1975); 4, Ontong-Java Plateau (Stoesser, 1975); 5, 6, upper (5) and lower (6) complexes of ocean rift zones (Kurentsova, 1979); 7, Karroo dolerites (Kutolin, 1972). Figures in brackets are analysis numbers; f = Fe/(Fe + Mg); A = (K + Na)/Al (atomic %).

Sample	Trace Elements (ppm)										
(interval in cm)	Cr	V	Ni	Co	Zr	Zn	Sn	Rb	Sr		
1	2	3	4	5	6	7	8	9	10		
462-65-1, 120-124	130	340	66	45	105	48	5	8	130		
66-3, 93-97	74	420	78	60	120	57	5	7	129		
66-4, 97-101	145	270	90	48	106	60	3	10	128		
66-5, 52-55	30	440	52	51	115	43	3	8	134		
67-1, 63-67	90	420	72	50	110	49	1	8	135		
68-1, 81-85	150	270	90	48	100	45	3	10	132		
68-2, 105-110	160	310	80	50	92	43	3	9	125		
68-3, 55-60	130	300	70	42	90	37	3	10	124		
69-1, 17-21	47	510	72	57	110	53	1	5	122		
69-2, 85-89	90	350	80	35	100	60	4	6	122		
Average of above	105	363	75	49	105	50	3	8	128		
462A-47-3, 74-77	540	280	170	90	70	45	6	_	-		
51-4, 24-30	390	280	120	42	80	41	1	-	-		
65-1, 1-6	460	325	150	70	71	49	4	6	113		
65-3, 18-20	260	230	85	47	58	36	3	7	113		
66-1, 143-147	360	280	110	52	77	53	3	5	112		
66-3, 143-148	360	320	118	63	75	47	1	6	99		
66-5, 145-150	350	340	130	72	78	57	7	7	101		
67-4, 107-112	340	270	120	50	50	45	3	5	101		
67-7, 21-25	380	280	135	64	68	46	4	6	105		
68-2, 72-74	290	360	100	48	73	52	3	10	107		
68-2, 104-106	410	350	140	66	82	52	5	8	109		
75-3, 112-114	450	360	160	60	85	64	4	8	110		
78-3, 40-43	410	430	140	65	90	65	4	6	112		
79-5, 144-146	350	400	100	55	90	73	1	-	_		
80-2, 91-93	140	350	85	40	80	52	1	7	117		
81-2, 15-16	200	350	125	60	100	53	4	—	-		
85-4, 78-80	330	400	160	68	100	54	3	6	109		
87-1, 70-72	240	340	120	56	89	52	4	6	112		
88-2, 74-75	140	320	76	50	70	49	5	7	106		
90-3, 88-90	180	360	100	60	87	52	5	-	-		
Average of above	329	332	122	59	79	52	4	7	108		



Figure 7. Geochemical correlations in the Nauru Basin basalts.

Table 17. Trace-element contents of various oceanic basalts (ppm).

Element	1(10)	2(20)	3(22)	4(2)	5(18)	6(25)
Cr	105	329	360	300	375	283
Ni	75	122	79	175	163	138
Co	49	59	47	50	38	46
v	363	332	201	200	208	262
Zr	105	79	72	70	75	127
Sc	50	52	44	70	34	43
Sn	3	4	n.a.	n.a.	1	2
Ba	44	21	22	13		22
Sr	128	108	100	150	_	190
Rb	8	7	12	-	—	

Notes: 1, 2, Nauru Basin, upper (1) and lower (2) complexes; 3, Manihiki Plateau (Jackson et al., 1975); 4, Ontong-Java Plateau (Stoesser, 1975); 5, 6, upper (5) and lower (6) complexes of oceanic rift zones (Kurentsova, 1979). Figures in parentheses are analysis numbers; n.a. = not analyzed.