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Origin of Nauru Basin igneous complex: Sr, Nd and Pb isotope and REE constraints

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ABSTRACT

The tholeiitic basalts and microdolerites that comprise the Cretaceous igneous complex in the Nauru Basin in the western equatorial Pacific have moderate ranges in initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70347–0.70356), initial $^{143}\text{Nd}/^{144}\text{Nd}$ (0.51278–0.51287), and measured $^{206}\text{Pb}/^{204}\text{Pb}$ (18.52–19.15), $^{207}\text{Pb}/^{204}\text{Pb}$ (15.48–15.66) and $^{208}\text{Pb}/^{204}\text{Pb}$ (38.28–38.81). These isotopic ratios overlap with those of both oceanic island basalts (OIB) and South Atlantic and Indian mid-ocean ridge basalts (MORB). However, the petrography, mineralogy, and bulk rock chemistry of the igneous complex are more similar to MORB than to OIB. Also, the rare earth element contents of Nauru Basin igneous rocks are uniformly depleted in light elements ($\text{La}/\text{Sm}_{\text{ch}} < 1$) indicative of a mantle source compositionally similar to that of MORB. These results suggest that the igneous complex is the top of the original ocean crust in the Nauru Basin, and that the notion that the crust must be 15 to 35 m.y. older based on simple extrapolation and identification of the M-sequence magnetic lineations [1,2] may be invalid because of a more complicated tectonic setting. The igneous complex most probably was extruded from an ocean ridge system located near the anomalously hot, volcanically active, and isotopically distinct region in the south central Pacific which has been in existence since ~ 120 Ma.

1. Introduction

The Nauru Basin complex is a thick (> 600 m) sequence of igneous rocks forming the upper part of the volcanic crust of the Nauru Basin in the western equatorial Pacific (Fig. 1). The complex was initially penetrated at Deep Sea Drilling Project (DSDP) Site 462 during Leg 61 [1], and then deepened during Leg 89 [2]. To date, the petrography, mineralogy and bulk chemistry of Nauru igneous rocks have been well characterized (e.g. [3–8]) but the origin of the complex remains a very interesting problem for two main reasons. First, the complex is assumed to be located on magnetic anomaly M-26 formed at about 145–165 Ma [9,10], but the complex ranges in age from 131 to only about 75 Ma based on $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb-Sr dating of igneous samples as well as

paleontologic dating of sparse sedimentary horizons within the complex [1,2,52]. Although it has been suggested that the complex was extruded ~ 15–35 m.y. after the formation of the Late Jurassic basement [1], the emplacement of such a thick (at least 600 m) and laterally extensive (~ 400,000 km²) igneous body without disturbing the well-preserved magnetic anomalies of the underlying oceanic crust raises additional interesting speculations. If the complex was erupted off-axis, it *has* to be assumed that there were multiple, tensional volcanic conduits in the entire basin so that the M-series anomalies were not displaced, and that the eruption of the Cretaceous magma did not raise the temperature of the Late Jurassic basement above the Curie point (~ 150–200 °C) due to the penetration of abundant seawater into the complex [1,11].

Second, the Nauru Basin igneous complex consists of an upper series of basalt sills intruded ~ 100 to 75 Ma and a lower series of basalt sheet flows and rare pillow lavas erupted ~ 130 to 115

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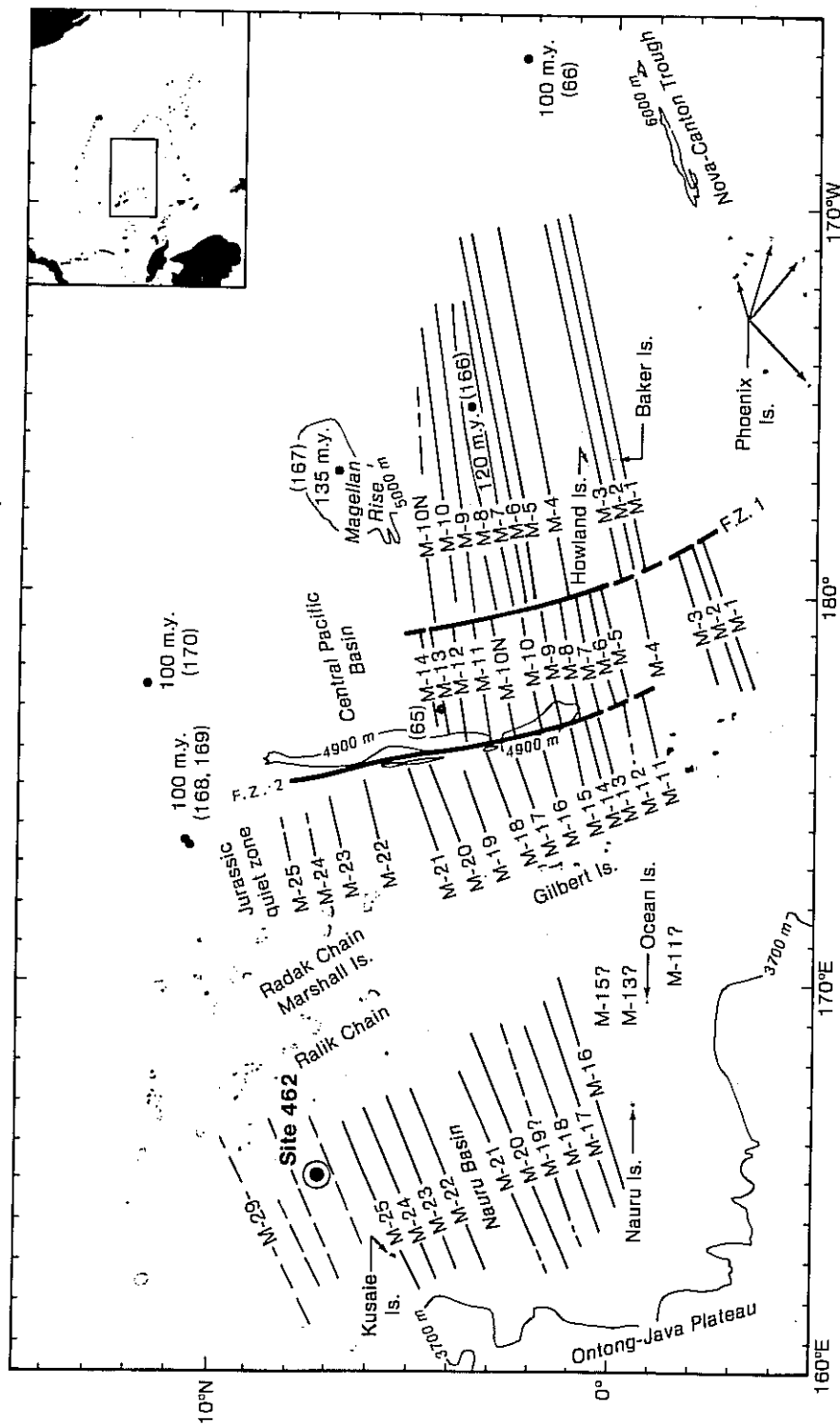


Fig. 1. Sketch map of the western and central Pacific showing DSDP Site 462 location and Mesozoic magnetic lineation patterns [7]. FZ = fracture zone; numbers in parentheses indicate other DSDP sites. Figure from Larson, Schlanger et al. [1].

Ma. A few late-stage granophyric patches are present in the top sills, and the interiors of most sills and flows are microdolerites [3,4]. Chemically, all the basalts and most microdolerites are quartz-normative and olivine-normative tholeiites that resemble MORB in their mineralogy, bulk-chemistry and alteration patterns. Nauru Basin tholeiites, however, differ from normal, incompatible element-depleted MORB because of their slightly greater contents of high field strength elements Nb, Ta and Ti, and ratios of certain trace elements such as La/Yb and Ta/Zr [4–7]. Perhaps, most importantly, the $^{87}\text{Sr}/^{86}\text{Sr}$ of Nauru tholeiites are higher than those of the modern East Pacific Rise (EPR) MORB [4,12,13]. As a result of this unique composition, the Nauru igneous complex has been proposed to represent a new kind of oceanic rock [1], variably referred to as oceanic trap basalt [8], ocean-plateau tholeiite [7], or ocean flood basalt [6]. Floyd [5] suggested that Nauru basalts resemble island-arc tholeiites. Castillo et al. [4], on the other hand, showed that the overall similarities between Nauru Basin basalts and MORB in terms of mineralogy and chemical composition are more striking than their differences. Thus, if it were not for the discrepancy between the basement magnetic age and the radiometric-paleontologic age of the complex, one could easily interpret that the Nauru basaltic flows as MORB that were erupted in a unique tectonic environment.

This paper presents new Sr, Nd, and Pb isotopic compositions and elemental concentrations of representative samples from the Nauru Basin igneous complex. The main purpose of the study is to constrain the mantle source of the complex and to compare this with sources of modern-day oceanic lava analogues. Because these are old oceanic rocks, we first examine the possible effects of seawater alteration on the samples. Then, we integrate the isotope data with previously published rare earth element (REE) data [4,14,15] in order to better understand the mantle source composition of the igneous complex. Essentially, we find that the Nauru Basin lavas are MORB that have an isotopic signature that is distinct from that of normal, depleted-type ocean ridge lavas, but is similar to the signature of some of the lavas erupted along the modern Indian Ocean Ridges and southern Mid-Atlantic Ridge. This indicates

that the Nauru Basin igneous complex could have been erupted at a normal ridge crest, most probably at one which was formed when the Late Jurassic basement drifted near the thermally and isotopically anomalous region in the south central Pacific. This tectonic model can be tested easily when drilling in the Nauru Basin is resumed and/or when new magnetic lineation data become available.

2. Sample locations

Figure 2 shows the simplified stratigraphy of Hole 462A. Based on stratigraphic occurrence, bulk TiO_2 and La contents, and paleomagnetic inclinations, the sills and flows have been grouped into three major types [4]. Type 3 is characterized by high TiO_2 and La content and occurs at the top of the section. Type 1 has low TiO_2 and La and occurs in the middle of the section whereas Type 2, which has intermediate TiO_2 and La, occurs above and below Type 1. A detailed evaluation of the data suggests that the differences among the three types can be ascribed to different degrees of partial melting in the mantle source region followed by shallow-level fractional crystallization of phenocryst phases and possibly magma mixing [4–6,8,13]. To a first order, the igneous complex can be modelled as a product of moderate degree of partial melting (Type 2 flows) at the onset, followed by high degree of melting (Type 1 flows) at the peak and finally by moderate (Type 2 sills) to low (Type 3 sills) degree of melting at the waning of volcanism in the Nauru Basin [4].

Samples analyzed for Sr, Nd and Pb isotopic composition are powdered holocrystalline rocks taken from different horizons of the 640 m section of Hole 462A (Fig. 2). Each of the three types of lavas is represented. All samples analyzed are slightly to moderately altered (2 to 40% alteration), mostly to smectite, zeolite and pyrite. The samples are aphyric to slightly phytic with < 3% phenocrysts of olivine (almost always pseudomorphed by clay), clinopyroxene, and plagioclase. A sample containing granophyric patches (sample 462-69-1, 20-24) and a microdolerite from a sheet flow interior (sample 462A-100-3, 15-20) were also analyzed in order to evaluate the effects of differentiation and grain size on isotopic composition.

3. Methodology

Visible alteration and drill or saw marks were removed from exposed surfaces of core samples with a diamond lap wheel. Samples were then washed, dried and crushed into cm-sized chips in a stainless steel Plattner mortar. Whenever possible, secondary vein materials were picked off the chips. Rock powders (< 100 mesh size) were prepared by grinding the chips in an alumina ceramic shatterbox.

To evaluate the effects of seawater alteration on Sr and Nd isotopic composition, the powders were subjected to a harsh, multi-step acid-leaching procedure (H. Staudigel, pers. commun., 1986; [16]). A 15 ml PFA beaker containing ~ 1 gram of powder was filled with high-purity 4 N HCl. The beaker was capped tightly and placed in an ultrasonic bath for approximately 30 minutes. Then, the acid was replaced with quartz-distilled water; the sample "cake" at the bottom of the beaker was stirred into solution by shaking the capped beaker and putting the beaker back into the ultrasonic bath for about 15 minutes. The cycle was repeated several times until acid and water were both clear

and colorless. The procedure generally required 4 to 6 hours depending on the sample and only about 100 mg of the powder remained at this stage. Finally, beakers with wet samples were capped lightly and placed overnight inside an oven at ~ 90 °C to dry. The acid and water solutions of two samples (462A-56-1, 131-134; 462A-108-2, 12-16) were collected and saved as leachates in separate beakers and were dried over a hot plate.

Neodymium and Sr isotope measurements and Nd, Sr, Sm and Rb concentration analyses by isotope dilution were made on the majority of leached powders, two leachates and some of the unleached powders. Because our leaching experiment shows that Sr and Nd isotope compositions of Nauru igneous rocks are only slightly modified by alteration (results are presented below), and since Taras and Hart [17] showed that seawater alteration effects on Pb isotopic composition of oceanic lavas are minimal, Pb isotopic composition and elemental concentrations were analyzed on unleached samples. Powders were dissolved in HF-HNO₃-HCl mixture in tightly capped PFA beakers on a hot plate. Sr and Nd were separated on HCl and alpha-hydroxy isobutyric acid ex-

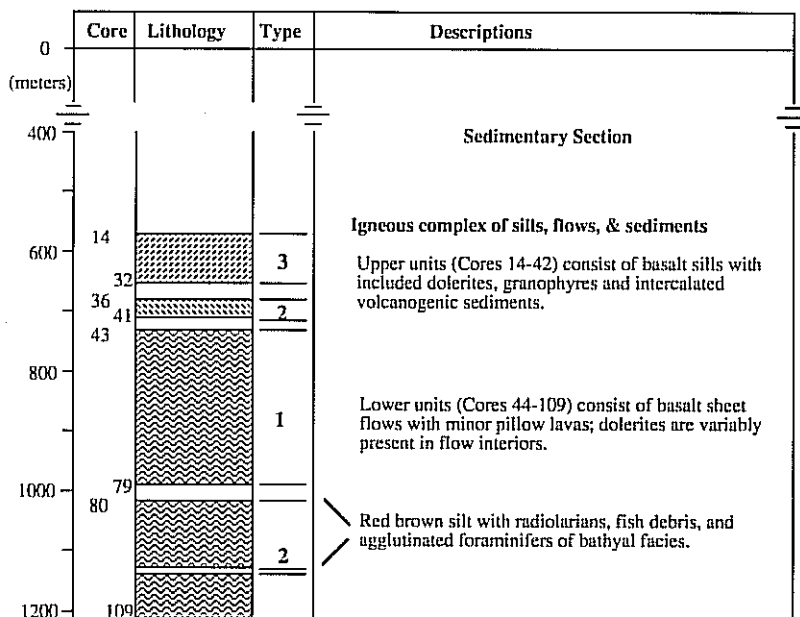


Fig. 2. Generalized stratigraphy of DSDP Hole 462A, showing the stratigraphic-chemical subdivisions of the igneous complex. General core descriptions are from the Site 462 reports [1,2]. Inclined dash pattern is for sills and horizontal wavy pattern is for flows; unruled areas are sediments.

change columns, respectively [18]. Pb was separated using the procedure of Manhès et al. [19] with some modifications [20].

All REE concentration data reported here, except for Nd and a few Sm, were determined previously through instrumental neutron activation (INAA) at Washington University counting facilities [4,14,15]. Sm concentrations determined by isotope dilution and INA analyses of five unleached samples agree to better than 1% and thus, previously determined Sm concentrations by INAA were used for the rest of the unleached samples.

4. Results and interpretation

Isotope and trace element data are presented in Tables 1–3 and are shown graphically in Figs. 3–8. In general, leached and unleached Nauru tholeiites have a fairly moderate range in both $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70348–0.70395) and $^{143}\text{Nd}/^{144}\text{Nd}$ (0.51292–0.51307) (Table 1). The only exception is sample 462A-41-4, 86-90 which has high $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70504 U; 0.70515 L) despite “normal” $^{143}\text{Nd}/^{144}\text{Nd}$. Previously published isotope data for Nauru igneous rocks [12,13,16] show similar ranges. Sm and Nd concentrations in unleached

TABLE 1

Sr and Nd isotope and trace element data

Sample	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	Rb	Sr	Sm	Nd	$^{87}\text{Sr}/^{86}\text{Sr}_i$	$^{143}\text{Nd}/^{144}\text{Nd}_i$
<i>Hole 462</i>								
69-1, 20-4L	0.703541	0.512939 ± 19	–	115	–	8.84	–	–
<i>Hole 462A</i>								
17-2, 84-6U	0.703815	0.512924 ± 24	0.28	130	(2.9)	8.78	0.703805	0.512784
17-2, 84-6L	0.703478	0.512998 ± 20	–	108	1.34	2.86	–	0.512798
22-2, 120-4L	0.703599	0.513005 ± 17	–	161	0.49	1.26	–	0.512839
38-2, 53-6U	0.703662	0.512981 ± 18	0.64	111	(2.7)	7.75	0.73636	0.512832
38-2, 53-6L	–	0.513016 ± 23	–	–	–	3.60	–	–
41-4, 86-90U	0.705040	0.513013 ± 23	3.83	102	(1.6)	4.70	0.704870	0.512866
41-4, 86-90L	0.705149	0.512988 ± 16	–	96.1	1.23	3.01	–	0.512814
47-2, 90-4U	0.703689	0.512969 ± 19	0.20	82.7	(1.9)	5.42	0.703678	0.512818
47-2, 90-4L	0.703630	0.513053 ± 16	–	78.2	1.12	2.40	–	0.512854
50-3, 11-4U	0.703614	0.512958 ± 18	0.49	83.3	(1.8)	5.62	0.703580	0.512818
50-3, 11-4L	–	0.512989 ± 22	–	–	0.80	1.74	–	0.512792
50-3, 130-4L	0.703604	0.513006 ± 19	–	78.2	0.96	2.19	–	0.512818
56-1, 131-4U	0.703570	0.512983 ± 21	0.20	90.7	2.07	6.11	0.703560	0.512839
56-1, 131-4L	0.703561	0.513046 ± 18	–	70.9	1.08	2.20	–	0.512837
Leachate	–	0.512890 ± 26	–	–	2.83	9.19	–	0.512759
65-1, 59-61U	0.703586	0.512941 ± 17	0.25	87.7	(2.2)	6.15	0.703573	0.512788
65-1, 59-61L	0.703543	0.513046 ± 14	–	74.3	0.81	1.63	–	0.512833
74-4, 25-31U	0.703949	0.512952 ± 14	1.34	88.5	(2.2)	6.95	0.703881	0.512814
74-4, 25-31L	–	0.512983 ± 20	–	–	1.20	2.61	–	0.512786
94-4, 69-75U	0.703582	0.512996 ± 22	0.32	97.4	2.66	7.90	0.703567	0.512852
94-4, 69-75L	0.703556	0.513037 ± 24	0.11	64.7	1.20	2.61	0.703548	0.512840
96-4, 105-6L	0.703588	0.513006 ± 18	–	–	–	–	–	–
100-3, 15-20L	0.703597	0.513074 ± 17	–	–	–	–	–	–
108-2, 12-16U	0.703709	0.512922 ± 20	0.37	97.2	2.55	7.60	0.703692	0.512779
108-2, 12-16L	0.703692	0.513030 ± 15	0.14	55.3	1.35	2.90	0.703681	0.512831
Leachate	0.703673	0.512954 ± 24	–	112	3.22	11.2	–	0.512831

U = unleached; L = leached; – = not determined. In-run precision of $^{87}\text{Sr}/^{86}\text{Sr}$ measurements is ± 0.000007 but the 2 sigma of the population for multiple determinations of NBS 987 gives analytical uncertainty of ± 0.00002 ; the 2 sigma of the population for multiple determinations of La Jolla Nd standard gives analytical uncertainty of ± 0.000023 for $^{143}\text{Nd}/^{144}\text{Nd}$. All isotopic and concentration measurements were made according to the procedure described in [18,20]. Sr isotopic ratios were fractionation corrected to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and normalized to $^{87}\text{Sr}/^{86}\text{Sr} = 0.71025$ for NBS 987; Nd isotopic ratios were measured in oxide forms and fractionation corrected to $^{146}\text{NdO}/^{144}\text{NdO} = 0.72225$ ($^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$) and are reported relative to $^{143}\text{Nd}/^{144}\text{Nd} = 0.511860$ for the La Jolla Standard. Initial isotopic compositions were calculated for an assumed age of 110 Ma. All concentration data reported in ppm. Data in parentheses are by INAA.

TABLE 2

REE data by INAA of representative Nauru tholeiites

Sample	La	Ce	Sm	Eu	Tb	Yb	Lu
<i>Hole 462</i>							
69-1, 20-24	4.27	10.8	3.18	1.18	0.76	2.87	0.45
<i>Hole 462A</i>							
17-2, 84-84	3.55	9.24	2.87	1.03	0.74	2.74	0.39
22-2, 120-124	4.98	14.3	3.45	1.35	0.88	-	0.48
38-2, 53-56	3.32	8.90	2.70	0.96	0.68	2.47	0.37
41-4, 86-90	1.60	5.56	1.62	0.59	0.42	1.59	0.25
47-2, 90-94	2.26	6.39	1.92	0.69	0.46	2.08	0.31
50-3, 11-14	1.94	6.09	1.84	0.72	0.51	1.91	0.32
50-3, 130-134	-	7.08	2.11	0.81	0.54	-	0.36
56-1, 131-134	2.59	6.07	2.06	0.76	0.53	2.10	0.33
65-1, 59-61	2.60	6.06	2.20	0.74	0.55	2.14	0.34
74-4, 25-31	2.93	6.31	2.24	0.84	0.61	2.45	0.38
94-4, 69-75	3.11	9.97	2.64	0.99	0.83	2.78	0.43
96-4, 105-106	3.21	9.57	2.58	1.01	0.80	2.72	0.44
100-3, 15-20	3.43	9.77	2.60	1.02	0.85	2.78	0.43
108-2, 12-16	3.21	9.83	2.54	0.98	0.76	2.58	0.42

- = not determined. Analytical uncertainty for measurements is $\pm 2\%$ except that for Sm which is probably better than 1%.

samples range from ~ 8 to 20 times chondritic (Table 2; Fig. 3) but most important, the range of Sm/Nd is fairly small (0.31–0.36). The upper sills (Type 3 lavas; Fig. 2) are slightly more enriched in light REE's and these samples have the lowest Sm/Nd. Nevertheless, there is no systematic difference between the $^{143}\text{Nd}/^{144}\text{Nd}$ of sills and flows; $^{143}\text{Nd}/^{144}\text{Nd}$ of the granophyric patch and the microdolerite are also indistinguishable from

TABLE 3

Pb isotopic compositions of Nauru tholeiites

Hole 462a	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	Pb (ppb)
22-2, 120-124	18.519	15.479	38.28	-
38-2, 53-56	18.925	15.529	38.43	662
47-2, 90-94	18.710	15.593	38.56	392
56-1, 131-134	18.993	15.620	38.68	432
56-1, 131-134 (dup)	19.059	15.609	38.73	
94-4, 69-75	19.007	15.557	38.76	221
108-2, 12-16	19.151	15.643	38.70	878
108-2, 12-16 (dup)	19.131	15.664	38.81	

Pb element concentration analyzed by isotope dilution using ^{205}Pb spike. Isotopic compositions of Pb were corrected for mass fractionation based on average measured values for NBS 981 using the values given in Catanzaro et al. [21]. Uncertainties on Pb isotopic compositions are approximately $^{206}\text{Pb}/^{204}\text{Pb} \pm 0.015$, $^{207}\text{Pb}/^{204}\text{Pb} \pm 0.019$, and $^{208}\text{Pb}/^{204}\text{Pb} \pm 0.06$.

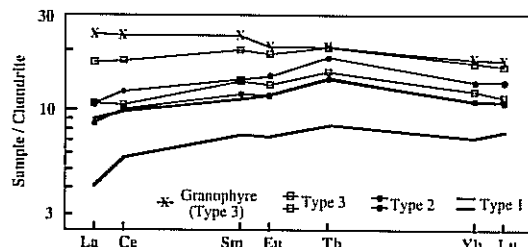


Fig. 3. Range of REE abundances of Nauru tholeiites normalized to chondritic values. Only the maximum and minimum values for each lava type are plotted except for a sample of type 3 basalt, which has a granophyric patch. Note that all samples have fairly similar abundance patterns.

those of the other samples. Strontium concentration in unleached samples (~ 85 – 135 ppm) shows minimal variation but Rb concentration (~ 0.20 – 3.8 ppm) varies by a factor of almost 20. This big difference in Rb concentration gives a fairly wide range, but still generally low Rb/Sr (0.002–0.037) for Nauru igneous rocks (see also [5–8,12,13]).

Compared to isotopic compositions of Sr and Nd, those of Pb of samples that were analyzed have a wider range in values ($^{206}\text{Pb}/^{204}\text{Pb} = 18.52$ – 19.15 ; $^{207}\text{Pb}/^{204}\text{Pb} = 15.48$ – 15.66 ; $^{208}\text{Pb}/^{204}\text{Pb} = 38.28$ – 38.81 ; Table 3). Pb isotope ratios also appear to become more radiogenic with increasing depth which is roughly equivalent to increasing age. The samples analyzed for Pb isotopic compositions have between 0.22 and 0.88 ppm Pb and these values cover the entire range of modern MORB (c.f. [22]). Nauru Basin lavas contain 0.12 to 0.42 ppm Th [4,5,6,21] and 0.5 to 0.11 ppm U [5] which are at the low end of the range of modern MORB values (c.f. [22]).

4.1. Alteration effects

Numerous studies have shown that seawater generally increases $^{87}\text{Sr}/^{86}\text{Sr}$ of oceanic lavas during alteration, and it is generally believed that the added seawater component can be removed by HCl leaching (e.g. [16,17,23]). Thus, it is surprising that $^{87}\text{Sr}/^{86}\text{Sr}$ of three out of six leached and unleached sample pairs of Nauru tholeiites are statistically identical at the 95% confidence level (critical value = 0.000028). One sample (462A-41-4, 86-90) gives higher, instead of lower, $^{87}\text{Sr}/^{86}\text{Sr}$ in the leached than the unleached aliquot. Leached and unleached $^{87}\text{Sr}/^{86}\text{Sr}$ of another Nauru basalt

analyzed by Fujii et al. [12] also give similar results. Most important, $^{87}\text{Sr}/^{86}\text{Sr}$ of one of the analyzed leachates (462A-108-2, 12-16) and mineral separates [4,13] are identical within errors to their unleached counterpart. In addition, the $^{87}\text{Sr}/^{86}\text{Sr}$ of two preserved Nauru basaltic glasses are both 0.70367 [16] and this value is identical to the mean unleached $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.70368, $N = 11$ (c.f., 0.70369, $N = 16$ of [12]).

Leaching reduced Sr concentrations by ~ 5 to 45% and the Rb concentrations of samples 462A-94-4, 69-75 and 462A-108-2, 12-16 by $\sim 65\%$. However, the leached and unleached *initial* $^{87}\text{Sr}/^{86}\text{Sr}$ at $T = 110$ Ma [16] of these two samples are identical within errors using their respective leached-unleached Rb and Sr concentrations. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ of a Nauru leached-preserved glass pair are also identical using their respective Rb and Sr concentrations [16]. Based on these results, the original Sr isotopic composition of Nauru tholeiites apparently was only slightly altered by seawater.

The $^{143}\text{Nd}/^{144}\text{Nd}$ of leached aliquots are statistically higher than unleached splits in nine out of ten leached-unleached sample pairs that were analyzed at the 95% confidence level (critical value = 0.000032). The leached $^{143}\text{Nd}/^{144}\text{Nd}$ of the pair that agree within uncertainty (462A-41-4, 86-90) is also higher than that of the unleached split. Although the maximum difference between the leached-unleached pairs is only five times the analytical error, the more radiogenic Nd isotopic composition of leached splits most probably is real because the leached $^{143}\text{Nd}/^{144}\text{Nd}$ of a preserved Nauru glass also is slightly above the unleached glass ratio reported by Mahoney [16]. Mahoney's data also show that all leached $^{143}\text{Nd}/^{144}\text{Nd}$ are higher than unleached ratios of samples from nearby Pacific Plateaus, a few of them showing significant differences. Similarly, Cheng et al. [23] showed that the Nd isotopic composition of leached splits are significantly more radiogenic than that of unleached aliquots in some samples from the Louisville seamount chain.

Figure 4 summarizes the response of the Sm-Nd isotope systematics to the HCl-leaching procedure. Leaching reduced Sm and Nd concentrations by 25–55% to 35–75%, respectively, systematically increasing the $^{147}\text{Sm}/^{144}\text{Nd}$. Sm and Nd that were stripped by leaching are present in the leachates

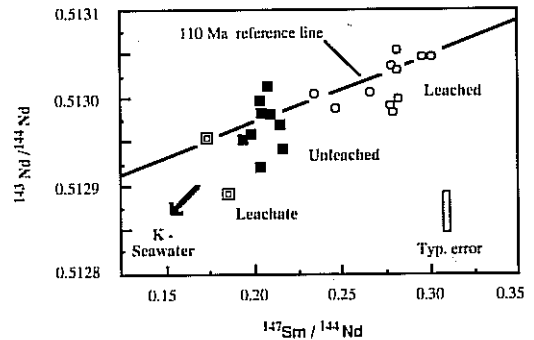


Fig. 4. $^{143}\text{Nd}/^{144}\text{Nd}$ against $^{147}\text{Sm}/^{144}\text{Nd}$ of leached and unleached aliquots plus two leachates for Nauru tholeiites. Arrow points to the direction of the composition of Cretaceous seawater [24]. Note that data generally align with the 110 Ma isochron.

(e.g., samples 462A-56-1 and 462A-108-2) although $^{143}\text{Nd}/^{144}\text{Nd}$ of leachates are similar within errors to the unleached samples. Lines that connect leached and unleached (plus two leachates) values (not shown in the figure) give rough isochron "ages" ranging from 85 to 170 Ma with large errors.

In summary, leaching results suggest that the radiogenic isotopic composition of the igneous complex generally was unaffected by seawater alteration. Apparently, the fairly rapid extrusion of Nauru complex followed immediately by sedimentation (see discussion below) limited the contact between rocks and seawater. As a result, the transformation of basaltic glasses and unstable minerals such as olivine and some pyroxenes into secondary clays and perhaps, more importantly, into secondary carbonate and phosphate phases occurred under a low water/rock ratio environment. In other words, secondary alteration occurred more or less in a closed system with respect to seawater. Thus, the addition of seawater Sr to the rock during alteration was only slight. It is important to note that Batiza et al. [3] arrived at a similar conclusion because the average $\delta^{18}\text{O}$ value of Nauru tholeiites at $\sim 7.2\text{‰}$ is lower than the average value of altered submarine lavas of comparable age.

In contrast to Sr, the majority of which is contained in the relatively alteration resistant plagioclase, a large proportion of Sm (25–55%) and Nd (35–75%) are in the mesostasis phases, or most probably were transferred into the secondary

carbonate and phosphate phases (e.g. [24]). It follows that primary phases, particularly the clinopyroxene, have dramatically reduced Sm and Nd contents and these phases contain relatively higher Sm (parent) than Nd (daughter) concentrations. Since both altered mesostasis and the REE-bearing secondary phases are soluble in HCl, the leaching residues/leached aliquots naturally would give a lightly elevated $^{143}\text{Nd}/^{144}\text{Nd}$ (Table 1; Fig. 4). The observation that the tie-lines connecting the Sm-Nd data for the leached-unleached pairs give "ages" in the general range of the complex suggests the leaching, in essence, is providing something of a "mineral separation" through selective dissolution of certain phases formed close to the

eruption age of these rocks. This, coupled with the fact that (1) bulk REE concentrations of unleached samples produce nice and consistent patterns (Fig. 3; see also [4,14,15]), (2) leached and unleached initial $^{143}\text{Nd}/^{144}\text{Nd}$ in five out of nine pairs are statistically identical, and (3) the maximum difference between leached and unleached initial $^{143}\text{Nd}/^{144}\text{Nd}$ is less than three times analytical error compared to five times the error for the measured ratios, strongly support the argument.

Based on the results, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ for the Nauru complex used in Figs. 5, 6 and 7 are determined using unleached values. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Nauru igneous com-

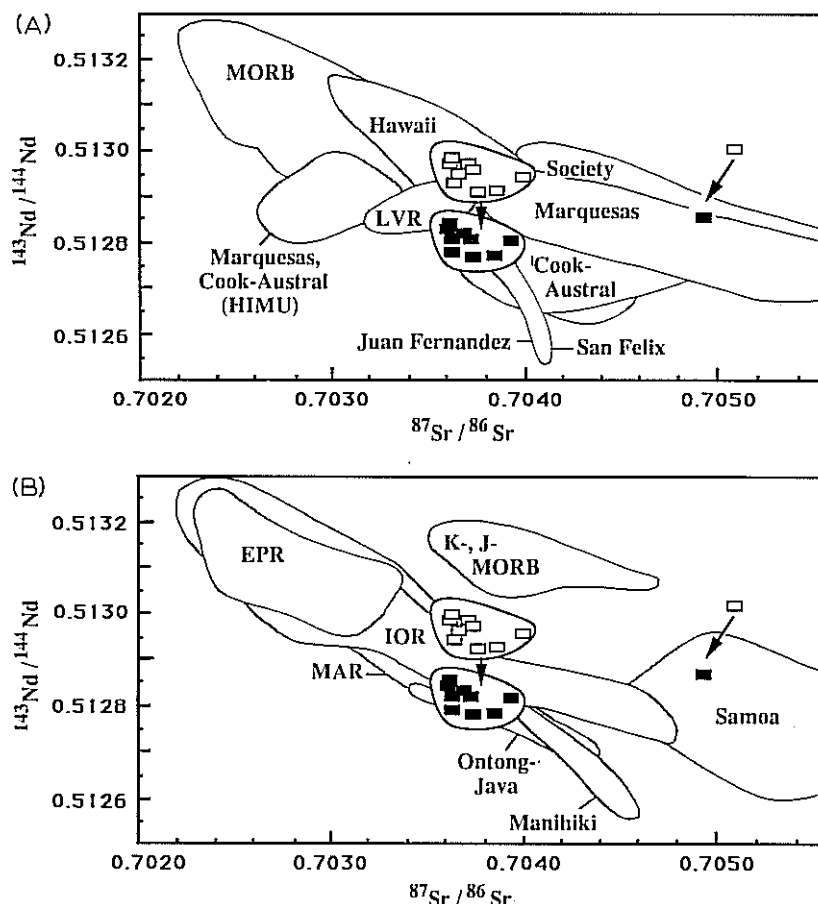


Fig. 5. Initial, unleached Sr and Nd isotopic data at $T=110$ m.y. for Nauru tholeiites. For clarity, fields for central Pacific islands and island chains, San Felix and Juan Fernandez island group, and mid-ocean ridges are shown for reference in (A) whereas fields for Samoa, Ontong-Java and Manihiki Plateaus, altered Cretaceous and Jurassic MORB from the Atlantic, and MORB from the Mid-Atlantic Ridge, Indian Ocean Ridges, and East Pacific Rise are shown for reference in (B). LVR is for Louisville Ridge. Sources of data are from the literature and the complete list of references is available from the principal author upon request.

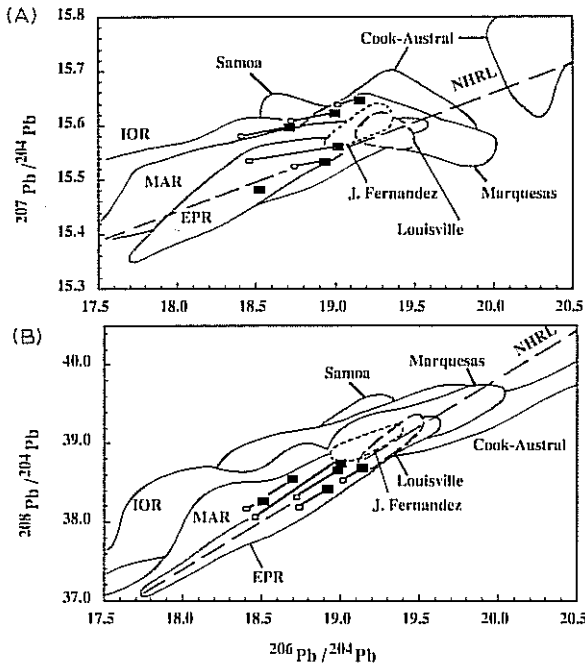


Fig. 6. (A) $^{207}\text{Pb}/^{204}\text{Pb}$ against $^{206}\text{Pb}/^{204}\text{Pb}$ and (B) $^{208}\text{Pb}/^{204}\text{Pb}$ against $^{206}\text{Pb}/^{204}\text{Pb}$ for Nauru tholeiites. Squares are measured values and open circles are minimum initial values at $T=110$ m.y. based on reported U and Th concentrations of Nauru tholeiites [4–6] and Pb concentration by isotope dilution (Table 3). Also shown are fields for lavas that overlap with the Nauru tholeiites in Fig. 5, except for Hawaiian lavas which have less radiogenic Pb than Nauru. Fields for Louisville Ridge and Juan Fernandez-San Felix group are enclosed by dotted and dashed lines, respectively. Sources of data are as in Fig. 5.

plex at $T=110$ Ma [16] range from 0.70356 to 0.70388, except for sample 462A-41-4, 86-90 which has initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.70487, whereas initial $^{143}\text{Nd}/^{144}\text{Nd}$ range from 0.51278 to 0.51287.

4.2. REE geochemistry

The range and pattern of chondrite-normalized REE concentrations of Nauru tholeiites are similar to those of typical normal MORB (Fig. 3). In particular, average $\text{La}/\text{Sm}_{\text{ch}}$, the light to middle REE ratio normalized to chondritic values, of the tholeiites is ~ 0.65 which is within the 0.70 limit defined for normal MORB (e.g. [25]). Moreover, Nauru $\text{La}/\text{Sm}_{\text{ch}}$, similar to those of normal MORB, are fairly constant around the mean $\text{La}/\text{Sm}_{\text{ch}}$. $\text{La}/\text{Sm}_{\text{ch}}$ of Cretaceous MORB from the Atlantic, for example, range from only 0.38 to 0.50 [26]. In contrast, $\text{La}/\text{Sm}_{\text{ch}}$ of hotspot lavas and MORB erupted near hotspots or plume

MORB are variable and generally > 1.00 [25,27, 28]. MORB produced by mixing plume and normal MORB mantle sources (transitional MORB) also have variable $\text{La}/\text{Sm}_{\text{ch}}$ but are > 0.70 .

Schilling and co-workers (e.g. [25,27]) suggested that normal MORB are from a fairly homogeneous depleted upper mantle source that is free from hotspot influence. If this is the case, then REE data suggest that the Nauru tholeiites are normal MORB from such a homogeneous mantle source. However, recent geochemical and isotopic investigations of MORB erupted from isolated seamounts near the ridge axis (e.g. [29,30]) showed that the depleted upper mantle is heterogeneous on a varying scale. Moreover, other investigators (e.g. [31,32]) showed that MORB are only homogeneous in incompatible element (e.g., Ba/TiO_2 , La/Sm , etc.) and Sr, Nd and Pb isotope ratios within a given ridge segment; inter-segment variations can be significant. Hence, the mantle source of the Nauru tholeiites could be quite heteroge-

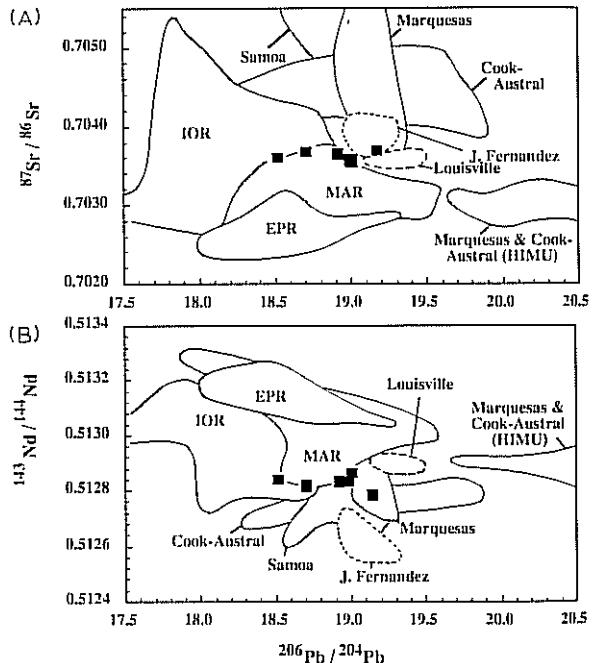


Fig. 7. (A) Initial $^{87}\text{Sr}/^{86}\text{Sr}$ against measured $^{206}\text{Pb}/^{204}\text{Pb}$ and (B) initial $^{143}\text{Nd}/^{144}\text{Nd}$ against measured $^{206}\text{Pb}/^{204}\text{Pb}$ for Nauru tholeiites. Note that fields for Marquesas and the Cook-Austral islands are divided into two fields for clarity — one having lower $^{206}\text{Pb}/^{204}\text{Pb}$ and the other having the higher $^{206}\text{Pb}/^{204}\text{Pb}$ (also called the HIMU group (e.g. [37])). Symbols and sources of data are as in Fig. 5. Discussion is in the text.

neous also but the processes of mixing and melting of the various source components, followed by crystal fractionation and mixing of lavas [4–6], were able to homogenize the trace element compositions.

4.3. Sr, Nd and Pb isotope geochemistry

Figure 5 shows Nauru Sr and Nd isotopic composition compared to the fields defined by modern MORB, Cretaceous (K)- and Jurassic (J)-MORB from the Atlantic, and lavas from ocean islands and plateaus in the central Pacific. Nauru tholeiites have slightly lower $^{143}\text{Nd}/^{144}\text{Nd}$ and higher $^{87}\text{Sr}/^{86}\text{Sr}$ than MORB from the EPR. Compared to the MORB from the Mid-Atlantic Ridge (MAR), Nauru tholeiites overlap with those from the Oceanographer Fracture Zone [20] and most probably with a few MORB near the Azores that have $^{87}\text{Sr}/^{86}\text{Sr}$ as high as 0.70349 [33] but these data are not included in the plot because their $^{143}\text{Nd}/^{144}\text{Nd}$ are not available. The Nauru tholeiites also approach the Sr and Nd isotopic compositions of south Atlantic MORB based on preliminary data ($^{87}\text{Sr}/^{86}\text{Sr}$ up to 0.70347 and $^{143}\text{Nd}/^{144}\text{Nd}$ as low as 0.51301) of Cole et al. [34] and our MORB data for young isolated seamounts near the Mid-Atlantic Ridge at about 26°S [30]. A few MORB from the Indian Ocean ridges (IOR) overlap with Nauru tholeiites in $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ (e.g. [35,36]). It is difficult to compare K- and J-MORB [26,37] with Nauru tholeiites because Sr isotopic composition of these MORB clearly were altered by seawater. Nevertheless, the altered MORB overlap significantly in Nd isotopic composition with modern, normal MORB, but not with Nauru tholeiites. Nauru tholeiites also are isotopically identical to some of the hotspot lavas of the Louisville Ridge, Hawaii, Marquesas, Cook-Austral, Juan Fernandez and Pacific Plateaus.

Figure 6 shows Pb isotopic compositions of Nauru tholeiites relative to the fields of modern MORB and lavas from south central Pacific hotspots. Measured $^{206}\text{Pb}/^{204}\text{Pb}$ overlap with those of radiogenic MORB and of south central Pacific hotspots. However, their estimated minimum initial Pb isotopic compositions calculated at ~110 Ma, based on previously reported U and Th concentrations [4,5,15] and measured Pb contents of the samples, generally plot more inside

the MORB fields than the hotspot fields. It is also worth noting that most of the initial $^{207}\text{Pb}/^{204}\text{Pb}$ against $^{206}\text{Pb}/^{204}\text{Pb}$ isotopic compositions of Nauru tholeiites are above the northern hemisphere regression line proposed by Hart [38].

Nauru tholeiites can be further separated from modern Pacific MORB in Figure 7, which shows plots of measured $^{206}\text{Pb}/^{204}\text{Pb}$ against initial $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ of Nauru tholeiites. Sr, Nd and Pb isotopic compositions of Nauru tholeiites are outside the field of the Pacific MORB but the overlap with some of the Indian and Atlantic MORB is retained. Nauru tholeiites still overlap with some of the lavas from south central Pacific hotspots in these plots but their overlap can be minimized if the initial Pb isotopic values were used.

In general, Nauru tholeiites overlap isotopically with hotspot lavas and MORB that have some of the characteristics of the Dupal isotope signature [38,39]. The origin of this isotope signature is still the subject of intense scrutiny, nevertheless, it appears that the locations of the maximum signal of the isotope anomaly and the locations of the minimum *P*-wave velocity structure of the lower mantle are correlated (e.g. [38,39]). The Dupal anomaly maxima and *P*-wave minima are located in the south central Pacific Ocean and in the Indian-south Atlantic Ocean, with the latter extending over to the north Atlantic Ocean [39,40]. We believe that the correlation of the Dupal anomaly maximum and the *P*-wave velocity minimum in the south central Pacific plays an important role in creating the anomalous isotopic character of Nauru tholeiites and thus the following discussion will revolve around this general idea.

5. Discussion and conclusion

Some investigators have suggested that Nauru igneous activity and the Ontong–Java hotspot volcanism are related [3,16]. The suggested relationship is based on the fact that (1) the Ontong–Java Plateau forms the western boundary of and is known to be tectonically attached to the Nauru igneous complex, (2) the Sr and Nd isotopic ratios of two Nauru basalt glasses are identical to Ontong–Java lavas, and (3) lavas from the plateau and the Nauru Basin at Site 462 apparently were

extruded contemporaneously at ~ 110 Ma [16]. New Sr and Nd isotopic data support the suggestion that the Ontong–Java Plateau and Nauru are similar isotopically, but the same relationship may hold true between Nauru and the ~ 110 Ma Manihiki Plateau [16], which lies farther to the southeast (Fig. 1). That is, the horizontal trend of $^{147}\text{Sm}/^{144}\text{Nd}$ against $^{143}\text{Nd}/^{144}\text{Nd}$ of Nauru tholeiites intersects the steeper trends of lavas from both Ontong–Java and Manihiki (Fig. 8) suggesting that the Nauru tholeiites were not influenced by the Ontong–Java hotspot alone, but also by the Manihiki hotspot. Moreover, if Nauru tholeiites were MORB influenced by hotspots, then these have to be unique. First, the $\text{La}/\text{Sm}_{\text{ch}}$ of Nauru tholeiites are lower and definitely less variable than the $\text{La}/\text{Sm}_{\text{ch}}$ of typical transitional-MORB and second, the mixing event that produced the Nauru geochemical and isotopic signature must have been fairly efficient since the same source persisted for at least 50 Ma, presumably even after the hotspots already were far away from the general vicinity of the basin.

A variation of the model that relates Nauru Basin tholeiites to hotspot volcanism had been suggested by Fujii et al. [12]. They proposed that Nauru tholeiites were formed from a mantle plume that had been previously depleted of incompatible elements during the formation of oceanic islands. Studies of rejuvenated volcanism along hotspot traces, however, show that a mantle source that previously had formed oceanic islands is more likely to produce lavas that are more geochemically and isotopically variable than oceanic island lavas [41,42]. There are other proposed mechanisms to introduce ocean–island mantle materials

into MORB mantle source (e.g. [25,28,43,44]), but most of the erupted MORB in these scenarios are also transitional type with variable and/or time-dependent incompatible element and isotopic ratios. Thus, our new data suggest that the petrology of Nauru tholeiites may not be a direct result of any local hotspot influence.

As mentioned above, the alternative explanation for the origin of the Nauru tholeiites favored here is based on their MORB-like petrology and isotope signature which are distinct from those of the normal-type MORB. We suggest that the Nauru tholeiites are a Cretaceous analogue of some of the modern MORB from the IOR and the MAR which have a pattern of multi-component source heterogeneity dominated by the Dupal isotopic signature [39]. Although MORB with a Dupal type isotopic signature commonly has been associated with hotspots (e.g. [27,35]), recent studies have shown that this is not always the case [20,36,39]. For example, MORB erupted along the Southeast Indian Ridge to the west of the Australian–Antarctic Discordance and along the $25^{\circ}30'$ to $26^{\circ}30'S$ latitude of the MAR are far from hotspots but these lavas still have the Dupal isotope signature.

Shirey et al. [20] suggested that the Dupal signature of MORB from the northern Atlantic may be due to fragments of the subcontinental materials detached during the formation of the Atlantic Ocean. In the present case, we suggest that similar type of materials are continuously being embedded in the lithosphere and then subducted into the lower mantle; these together with other subducted materials [45] would later upwell, creating regional isotopic anomalies. Hotspots most probably are direct manifestations of the upwelling [39,40], but it also appears that the upwelling is manifested on a much broader scale. Specifically, part of the mantle beneath the south central Pacific has had the Dupal isotopic characteristics since at least the Cretaceous [46]. This region, termed as the Pacific superswell by McNutt and Fischer [47], or SOPITA by Smith et al. [46], is anomalously shallow for its age, is the locus of high igneous activity and has low values of elastic thickness. Interestingly, the Nauru Basin is anomalously shallow for its age [1] indicative of intense volcanic activity. Paleomagnetic [1,2] and hotspot track [46,48] evidence indicate that the basin may have

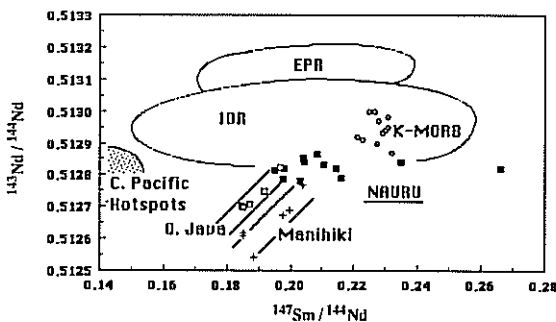


Fig. 8. $^{143}\text{Nd}/^{144}\text{Nd}$ against $^{147}\text{Sm}/^{144}\text{Nd}$ for unbleached Nauru tholeiites. Sources of data as in Fig. 5. Discussion is in the text.

been very close to the south central Pacific during its formation in the Cretaceous. Hence, the isotopic signature of the Nauru tholeiites is a part of the regional characteristic of the south central Pacific sub-oceanic mantle in the same way that the Dupal isotopic signature of modern MORB is a part of the regional signature of the lower mantle upwelling beneath the Indian and Atlantic oceans [39]. In contrast, MORB from the modern EPR generally do not have the Dupal isotopic signature because the rise is far from these upwellings in the lower mantle [39]. It is implicit in this model that other Cretaceous MORB formed near the south central Pacific most likely will show a similar isotopic signature. Our preliminary Pb, Sr, and Nd isotopic data for Cretaceous MORB-like tholeiites from the nearby East Mariana Basin recently drilled by the Ocean Drilling Program Leg 129 [49] are consistent with this notion.

In conclusion, the isotopic and trace element data presented here are inconsistent with, although do not necessarily disprove, the earlier proposed *off-ridge* mechanism for emplacement of the Nauru igneous complex. The fairly monotonous, light-element-depleted REE pattern of the ~ 640 m thick Nauru tholeiites, when combined with other geochemical and geologic arguments [1,2,4], strongly suggest that the bulk of the tholeiites were extruded along an ocean ridge system, as this is by far the most common oceanic setting where lavas with this type of REE concentration pattern can be generated for an extended period of time. The Sr, Nd and Pb isotopic ratios of Nauru tholeiites are similar to those of some modern MORB from the South Atlantic and Indian Ocean which are dominated by the Dupal isotope signature and, thus, the composition of the tholeiites is not entirely unique for MORB. Finally, petrographic, geochemical and isotopic (Sr and O) evidence also suggests relatively little rock-seawater interaction and this argues against the assumed rapid cooling of the complex.

New borehole data in the complex or adjacent sea floor inside the basin and/or magnetic lineation data are certainly needed in order to fully understand the mechanism for emplacement of the Nauru igneous complex. Since such data are not available yet, we propose an alternative working hypothesis for the history of igneous activity in the basin that is more consistent with our new

results and other data already on hand. The earliest part of the history of Nauru Basin is the formation of the oceanic crust in the Early to Late Jurassic along the Pacific Plate boundary [1,9,10]. The proto-Nauru Basin was most probably near, or drifted near the anomalous south central Pacific region in the Early Cretaceous, perhaps between the two hotspots that were starting to form the Ontong-Java Plateau and the Marshall Gilbert Island chain. Either due to the vigorous volcanic activity in this region, or due to the presence of hotspots which in some cases seem to capture spreading ridges (e.g., Galapagos, Iceland, Easter), or a combination of both, a rift was formed in the northern part of the basin above and more or less subparallel to the M-series magnetic anomalies. In this case, the Nauru tholeiites are MORB coming from a mantle containing a Dupal isotopic component. However, rifting in the basin did not last very long because the Pacific plate was drifting NNW in the Cretaceous [46,48] and, hence, the Nauru Basin was separated from the high-volcanic-activity region. In addition, plate spreading in the Pacific shifted from the west to the presently observed configuration in the east at M-0 time [9,50]. Pacific MORB may have slowly changed its isotopic signature since then. Due to this plate reorganization, rift volcanism in Nauru was terminated and replaced by sill intrusion until ~ 75 Ma. Thus, the bulk of Nauru tholeiites were erupted from a ridge crest environment with overlying younger sills. It is important to note that Larson, Schlanger et al. [1] unanimously concluded that the conduit of Nauru igneous complex lavas must have been very close to DSDP Site 462 because of the well-preserved sill and flow structures of the volcanic rock units. Further, the nearby Ontong-Java Plateau most probably was formed by a hotspot near a spreading center [16]. Both of these suggestions are consistent with our model. The only major problem in this model of emplacement is that it assumes that the older M-series magnetic anomalies are compressed and/or rifted apart which is inconsistent with the interpretation of Cande et al. [10] who claimed that the M-26 to M-28 lineations were nicely preserved near Site 462. We speculate that the older continuation of the M-series lavas in the southern part of the Nauru Basin lies to the north of DSDP Site 462, near and beneath the northern extension of the

Marshall Gilbert Island chain. The presence of Middle Jurassic crust in the East Pigafetta Basin [49], which lies in the NNE part of the basin, is consistent with the proposed scenario.

A modern analogue of the tectonic scenario we propose here is perhaps the Panama Basin in eastern equatorial Pacific. In this area, the Galapagos Spreading Center appears to have been captured by the Galapagos hotspot for at least the last 25 Ma such that there is a more or less complete magnetic anomaly record on the accreted Cocos Plate in the north (roughly equivalent to the southern part of the Nauru basin), but older magnetic anomalies in the Nazca Plate in the south (roughly equivalent to the northern part of the basin) are now incomplete [51]. Alternatively, the Nauru Basin may represent Cretaceous analogue of the Easter microplate which is bounded by two spreading centers. If these two spreading centers would be abandoned, buried under a thick pile of sediments, rifted away from their former sites, and then would be drilled ~110 m.y. later based on the assumption that spreading was simply symmetric (e.g. [9,10]), then results would perhaps be as equally interesting as in the Nauru Basin.

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References

- 1 R.L. Larson, S.O. Schlanger et al., *Init. Rep. D.S.D.P. 61*, 885 pp., U.S. Gov. Print. Off., Washington, D.C., 1981.
- 2 R. Moberly, S.O. Schlanger et al., *Init. Rep. D.S.D.P. 89*, 678 pp., U.S. Gov. Print. Off., Washington, D.C., 1985.
- 3 R. Batiza, S. Shcheka, H. Tokuyama, K. Muehlenbachs, T. Vallier, F. Lee-Wong, K. Seifert, K. Windom, P. Book and N. Fujii, Summary and index to petrologic and geochemical studies of Leg 61 basalts, in: R. Larson, S. Schlanger et al., eds., *Init. Rep. D.S.D.P.*, pp. 829–839, U.S. Gov. Print. Off., Washington, D.C., 1981.
- 4 P.R. Castillo, R. Batiza and R. Stern, Petrology and geochemistry of Nauru Basin igneous complex: large-volume, off-ridge eruptions of MORB-like basalt during the Cretaceous, in: R. Moberly, S. Schlanger et al., eds., *Init. Rep. D.S.D.P.*, pp. 555–576, U.S. Gov. Print. Off., Washington, D.C., 1985.
- 5 P.A. Floyd, Petrology and geochemistry of oceanic intraplate sheet-flow basalts, Nauru Basin, Deep Sea Drilling Project, Leg 89, in: R. Moberly, S. Schlanger et al., *Init. Rep. D.S.D.P.*, pp. 471–497, U.S. Gov. Print. Off., Washington, D.C., 1985.
- 6 A.D. Saunders, Geochemistry of basalt from the Nauru Basin, Deep Sea Drilling Project Legs 61 and 89: implications for the origin of oceanic flood basalts, in: R. Moberly, S. Schlanger et al., eds., *Init. Rep. D.S.D.P.*, pp. 499–518, U.S. Gov. Print. Off., Washington, D.C., 1985.
- 7 H. Tokuyama and R. Batiza, Chemical composition of igneous rocks and origin of the sill and pillow basalt complex of Nauru basin, Southwest Pacific, in: R. Larson, S. Schlanger et al., eds., *Init. Rep. D.S.D.P.*, pp. 673–687, U.S. Gov. Print. Off., Washington, D.C., 1981.
- 8 S. Shcheka, Igneous rocks of Deep Sea Drilling Project Leg 61, in: R. Larson, S. Schlanger et al., eds., *Init. Rep. D.S.D.P.*, pp. 633–649, U.S. Gov. Print. Off., Washington, D.C., 1981.
- 9 R.L. Larson, Late Jurassic and Early Cretaceous evolution of the western Pacific Ocean, *Geomag. Geoelectr.* 28, 219–236, 1976.
- 10 S.C. Cande, R.L. Larson and J.L. La Brecque, Magnetic lineations in the Pacific Jurassic quiet zone, *Earth Planet. Sci. Lett.* 41, 434–440, 1978.
- 11 R.L. Larson and S.O. Schlanger, Cretaceous volcanism and Jurassic magnetic anomalies in the Nauru Basin, western Pacific Ocean, *Geology* 9, 480–484, 1981.
- 12 N. Fujii, K. Notsu and N. Onuma, Chemical composition and Sr isotopes of Deep Sea Drilling Project Leg 61 basalts, in: R. Larson, S. Schlanger et al., eds., *Init. Rep. D.S.D.P.*, pp. 697–700, U.S. Gov. Print. Off., Washington, D.C., 1981.
- 13 K. Notsu, N. Onuma and N. Fujii, Rb-Sr isotope systematics and Sr/Ca and Ba/Ca ratios of Nauru Basin basalts, Deep Sea Drilling Project leg 61, in: R. Moberly, S. Schlanger et al., eds., *Init. Rep. D.S.D.P.*, pp. 523–527, U.S. Gov. Print. Off., Washington, D.C., 1985.
- 14 R. Batiza, Trace element characteristics of Leg 61 basalts, in: R. Larson, S. Schlanger et al., eds., *Init. Rep. D.S.D.P.*, pp. 689–695, U.S. Gov. Print. Off., Washington, D.C., 1981.
- 15 K. Seifert, Geochemistry of Nauru Basin basalts from the lower portion of Hole 462A, Deep Sea Drilling Project Leg 61, in: R. Larson, S. Schlanger et al., eds., *Init. Rep. D.S.D.P.*, pp. 705–708, U.S. Gov. Print. Off., Washington, D.C., 1981.
- 16 J.J. Mahoney, An isotopic survey of Pacific oceanic plateaus: implications for their nature and origin, in: Seamounts, Islands and Atolls, B. Keating et al., eds., pp. 283–296, Am. Geophys. Union, Washington, D.C., 1987.
- 17 B.D. Taras and S. Hart, Geochemical evolution of the New England seamount chain: isotopic and trace element constraints, *Chem. Geol.* 64, 35–54, 1987.
- 18 R.W. Carlson, Isotopic constraints on Columbia River flood basalt genesis and the nature of the sub-continental mantle, *Geochim. Cosmochim. Acta* 48, 2357–2372, 1984.

- 19 G. Manhes, J.F. Minster and C.J. Allègre, Comparative uranium-thorium-lead and rubidium-strontium study of the Saint Séverin amphoterite: consequences for early solar system chronology, *Earth Planet. Sci. Lett.* 39, 14–24, 1978.
- 20 S.B. Shirey, J.F. Bender and C.H. Langmuir, Three-component isotopic heterogeneity near the Oceanographer transform, Mid-Atlantic Ridge, *Nature* 325, 217–223, 1987.
- 21 E.L. Catanzaro, T.J. Murphy, W.R. Shields and E.L., Absolute isotopic abundance ratios of common, equal-Atom, and radiogenic lead isotopic standards, *J. Res. Nat. Bur. Stand. Sect. A* 72, 1968.
- 22 S.S. Sun, Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs, *Phil Trans. R. Soc. London* 297, 409–445, 1980.
- 23 Q. Cheng, K.-H. Park, J.D. Macdougall, A. Zindler, G.W. Lugmair, J. Hawkins, P. Lonsdale and H. Staudigel, Isotopic evidence for a hot spot origin of the Louisville seamount chain, in: *Seamounts, Islands and Atolls*, B. Keating et al., eds., pp. 283–296, Am. Geophys Union, Washington, D.C., 1987.
- 24 H.F. Shaw and G.J. Wasserburg, Sm-Nd carbonates and phosphates: implications for Nd isotopes in seawater and crustal ages, *Geochim. Cosmochim. Acta* 49, 503–518, 1986.
- 25 J.-G. Schilling, M. Zajac, R. Evans, T. Johnston, W. White, J. Devine and R. Kingsley, Petrologic and geochemical variations along the Mid-Atlantic Ridge from 29°N to 73°N, *Am. J. Sci.* 283, 510–586, 1983.
- 26 B.-M. Jahn, J. Bernard-Griffiths, R. Charlot, J. Cornichet and F. Vidal, Nd and Sr isotopic compositions and REE abundances of Cretaceous MORB (Holes 417D and 418A, Legs 51, 52 and 53), *Earth Planet. Sci. Lett.* 48, 171–184, 1980.
- 27 B.B. Hanan, R.H. Kingsley and J.-G. Schilling, Pb isotope evidence in the south Atlantic for migrating ridge-hotspot interactions, *Nature* 322, 137–144, 1986.
- 28 A.P. Le Roex, H. Dick, A. Erlank, A. Reid, F. Frey and S. Hart, Geochemistry, mineralogy and petrogenesis of lavas erupted along the Southwest Indian Ridge between the Bouvet triple junction and 11 degrees east, *J. Petrol.* 24, 267–318, 1983.
- 29 A. Zindler, H. Staudigel and R. Batiza, Isotope and trace element geochemistry of young Pacific seamounts: implications for the scale of upper mantle heterogeneity, *Earth Planet. Sci. Lett.* 70, 175–195, 1984.
- 30 P.R. Castillo and R. Batiza, Sr, Nd and Pb isotope constraints on near-ridge seamount production beneath the South Atlantic, *Nature* 342, 262–265, 1989.
- 31 C.H. Langmuir, J. Bender and R. Batiza, Petrologic and tectonic segmentation of the East Pacific Rise between 4°30′–14°30′N, *Nature* 322, 15–16, 1986.
- 32 P. Castillo, E. Klein, S. Shirey, J. Bender, C. Langmuir and R. Batiza, Relationship of Sr, Nd, and Pb isotopes of EPR and MAR basalt glasses to bathymetry and ridge segmentation, *Trans. Am. Geophys. Union* 69, 1477, 1988.
- 33 W.M. White and J.-G. Schilling, The nature and origin of geochemical variation in mid-Atlantic Ridge basalts from the central north Atlantic, *Geochim. Cosmochim. Acta* 42, 1501–1516, 1978.
- 34 M.W. Cole, B.B. Hanan, R. Kingsley and J.G. Schilling, Isotopic variations in South Atlantic MAR basalts: implications on mantle plume-migrating ridge dynamics, *Trans. Am. Geophys. Union* 66, 408, 1985.
- 35 B. Hamelin, B. Dupré and C.J. Allègre, Pb-Sr-Nd isotopic data of Indian Ocean ridges: new evidence of large-scale mapping of mantle heterogeneities, *Earth Planet. Sci. Lett.* 76, 288–298, 1986.
- 36 J.J. Mahoney, J.H. Natland, W.M. White, R. Poreda, S.H. Bloomer, R.L. Fisher and A.N. Baxter, Isotopic and geochemical provinces of the western Indian Ocean spreading centers, *Geophys. Res.* 94, 4033–4052, 1989.
- 37 D.C. Gerlach, R.A. Cliff, G.R. Davies, M. Norry and N. Hodgson, Magma sources of the Cap Verdes archipelago: isotopic and trace element constraints, *Geochim. Cosmochim. Acta* 52, 2979–2992, 1988.
- 38 S.R. Hart, A large-scale isotope anomaly in the southern hemisphere mantle, *Nature* 309, 753–757, 1984.
- 39 P.R. Castillo, The Dupal anomaly as a trace of the upwelling lower mantle, *Nature* 336, 667–670, 1988.
- 40 P.G. Silver, R.W. Carlson and P. Orson, Deep slabs, geochemical heterogeneity and the large-scale structure of mantle convection: an investigation of an enduring paradox, *Annu. Rev. Earth Planet. Sci.* 16, 477–541, 1988.
- 41 E. Wright and W.M. White, the origin of Samoa: new evidence from Sr, Nd and Pb isotopes, *Earth Planet. Sci. Lett.* 81, 151–162, 1986.
- 42 P.R. Castillo, R. Batiza, D. Vanko, E. Malavassi, J. Barquero and E. Fernandez, Anomalously young volcanoes on old hot spot traces: I. geology and petrology of Cocos Island, *Geol. Soc. Am. Bull.* 100, 1400–1414, 1988.
- 43 D. Epp, Possible perturbations to hotspot traces and implications for the origin and structure of the Line Islands, *J. Geophys. Res.* 89, 11273–11286, 1984.
- 44 J.G. Fitton and D. James, Basic volcanism associated with intraplate linear features, *Phil. Trans. R. Soc. London* 317, 253–266, 1986.
- 45 A.W. Hofmann and W.M. White, Mantle plumes from ancient oceanic crust, *Earth Planet. Sci. Lett.* 57, 421–436, 1982.
- 46 W.H.F. Smith, H. Staudigel, A.B. Watts and M.S. Pringle, The Magellan Seamounts: Early Cretaceous record of the south Pacific isotopic and thermal anomaly, *J. Geophys. Res.* 94, 10,501–10,523, 1989.
- 47 M.K. McNutt and K.M. Fischer, The south Pacific super-swelling, in: *Seamounts, Islands, and Atolls*, B.H. Keating, P. Fryer, R. Batiza and G.W. Boehlert, eds., pp. 25–34, Am. Geophys. Union, Washington, D.C., 1987.
- 48 L.J. Henderson, Pacific hot spot tracks, PhD. Thesis, Northwestern University, 1985 (?).
- 49 R.L. Larson, Y.P. Lancelot et al., Jurassic crust and sediments recovered from the Pacific plate, *Nature*, submitted, 1991.
- 50 M.L. Renkin and J.G. Sclater, Depth and Age in the North Pacific, *J. Geophys. Res.* 93, 2919–2935, 1988.
- 51 R.N. Hey, Tectonic evolution of the Cocos-Nazca spreading center, *Geol. Soc. Am. Bull.* 88, 1404–1420, 1977.
- 52 S.R. Hart and H. Staudigel, Ocean crust vein mineral deposition: Rb/Sr ages, U-Th-Pb geochemistry, and duration of circulation at DSDP sites 261, 462 and 516, *Geochim. Cosmochim. Acta* 50, 2751–2761, 1986.