

## Contrasting old and young volcanism in Rurutu Island, Austral chain

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### Abstract

We present new geochemical data (major and trace element, and Sr, Nd and Pb isotopic compositions) for volcanic rocks from Rurutu Island in Polynesia. The rocks are divided into two age groups: 13–10.8 Ma old basalts derived from the plume that is now active beneath the Macdonald seamount, and 1.8–1.1 Ma old volcanics that were produced during a younger volcanic event. Marked chemical differences exist between the two generations of lavas. Typical HIMU isotopic compositions are found in the old lavas but not in the young lavas, and unusual trace element fractionations (Ce/Pb, Zr/Hf and Ti/Eu) are restricted to the young lavas.

These results are interpreted in a model in which the composition of the Quaternary lavas results from the interaction between magmas from an ascending young plume and the oceanic lithosphere under the island. The contaminating component in the lithosphere is thought to be a residual carbonatite liquid from the first volcanic episode. This contaminant has isotopic compositions similar to those of the first volcanic event but very high trace-element concentrations characterized by significant negative Ti and Pb anomalies. This model raises questions about the use of isotopic and trace element data from islands located downstream from another plume to understand the general composition and origin of the source of plume volcanism. However, it does not put into question the existence of extreme isotopic compositions (HIMU, EM I and EM II) in the mantle sources of oceanic island basalts. © 1997 Elsevier Science B.V.

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### 1. Introduction

The chemical composition of intra-plate volcanic rocks results from the superposition of various effects during their genesis: initial source composition,

entrainment of surrounding asthenosphere as the plume rises through the mantle, fractionation between melt and residual minerals, assimilation of lithospheric mantle and crust on the way to the surface, and crystal fractionation before eruption. A growing number of authors consider that the lithosphere plays a major role in the final composition of the lavas (e.g., Woodhead, 1992; Dupuy et al., 1993)

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by contributing significantly to the trace element and the isotopic composition of the volcanics. In mature continental environments, the picture is far from simple because both lithospheric mantle and crust are old and have distinctive isotopic signatures. In contrast, in oceanic plates, both lithospheric mantle and crust are relatively young, and the trace element and isotopic composition of the oceanic crust is relatively well constrained. The strong enrichment of incompatible elements in continental crust and in some mantle xenoliths is absent and the chemical and isotopic composition of oceanic lithosphere should be more moderate. Despite these constraints, direct information on the composition of the lithospheric mantle in oceanic areas is sparse. This lack of information has allowed the development of models in which the composition of various types of oceanic basalts is attributed to derivation from or interaction with the oceanic lithosphere (Dupuy et al., 1993).

In this paper, we attempt to constrain the composition of the oceanic lithospheric mantle using a comparison of old and young volcanics erupted at a single island (Rurutu) in Polynesia. The two volcanic episodes can be related to two different collinear plume traces whose isotopic characteristics are well constrained and different. Comparison of the characteristics of the two groups of lavas with those from the other islands on the same plume trace can therefore provide strong constraints on (1) the degree of interaction of the first plume with the lithosphere below the island and (2) the amount of remobilization of the lithosphere by melts from the second plume.

## 2. Geological setting

Neogene and Quaternary volcanism occurs in Polynesia at various locations. There are four quasi-parallel island chains (the Marquesas, Pitcairn–Gambier, Society and Austral–Cook chains) and in each of these, the age progression is generally consistent with motion of the Pacific plate towards the northwest over stationary hotspots (Duncan and McDougall, 1976). A slightly more complicated picture is observed in the most southerly Austral–Cook chain where volcanic activity can be separated into three

linear traces (Fig. 1). Most of the island chain appears to result from volcanism traced back to about 20 Ma on the island of Mangaia, and with a regular age progression down to the present time in the Macdonald seamount. This trend is shown in Fig. 1b as the ‘Tubuai trend’. However, two other almost linear traces of volcanism have been recognized and distinguished along the chain by Diraison (1991) on the basis of their ages (Fig. 1b): one, which we call the ‘Atiu trend’, would have its present activity some 1100 km west-northwest of Macdonald and the other (the ‘Rarotonga trend’) over 2000 km to the west-northwest.

Rurutu Island has a unique position because it is the only island where volcanics resulting of both the ‘Tubuai’ and the ‘Atiu’ linear trends are superimposed in the volcanic record. Old lavas are 13 to 10.8 Ma old while younger lavas are about 1.8 to 1.1 Ma (Dalrymple et al., 1975; Duncan and McDougall, 1976; Turner and Jarrard, 1982; Matsuda et al., 1984; Diraison, 1991) and they are separated by a 100-m-thick uplifted coral reef (Maury et al., 1997). The old volcanic activity corresponds to the general age progression along the Australs Island chain (the Tubuai trend in Fig. 1b). Fig. 1b shows that this older volcanism belongs to the plume trace that started at the island of Mangaia at 20 Ma and is presently active at the Macdonald seamount. The figure also shows that the  $\approx 12$  Ma volcanic activity in Rurutu should have the same general source as the  $\approx 10$  Ma volcanism on Tubuai (Vidal et al., 1984; Chauvel et al., 1992). Younger volcanic activity occurred 1.8 to 1.1 Ma ago. This second pulse of magmatism appears to be related to the volcanic activity dated at about 7 Ma on Aitutaki and Atiu and around 5 Ma on Mauke Island (the Atiu trend in Fig. 1b) and is also consistent with the movement of the Pacific oceanic plate. This younger volcanism should therefore be compared to the volcanic products of these two islands and not to that of Tubuai and Mangaia islands.

Old volcanics consist predominantly of alkali basalts with minor associated hawaiites, although one tholeiitic basalt has been sampled and its composition is reported here. Younger volcanics are mainly basanites with minor associated tephritic hawaiites. No severely fractionated liquids such as trachytes and phonolites were observed. The oldest lavas were

submarine, as shown by the presence of pillow lavas and hyaloclastic breccias, but they were covered later by subaerial flows. The main volcanism was followed by uplift, which brought the coral reef to 100 m above sea level, and then by the eruption of the young volcanics. These field observations are summarized in a geological map (Maury et al., 1997).

Previous studies of the Rurutu volcanics focussed on the geochemistry of mantle sources. These include work by Vidal et al. (1984), Palacz and Saunders (1986), Dupuy et al. (1988), Nakamura and Tatsumoto (1988) and Dupuy et al. (1989). However, no detailed petrological and geochemical work has been done on volcanics from this island.

### 3. Analytical techniques and results

Major and trace element concentrations as well as isotopic compositions were obtained on a selection of samples from both the old and young volcanics. Samples analyzed in this study were collected at different times by different people (see Tables 1 and 2). Major and trace element data for samples with numbers starting with RRT have already been published in Dupuy et al. (1988, 1989). The chemical data for all other samples are new, as are all the isotope data.

Major element compositions were measured by XRF at the University of Rennes or by ICP–AES at

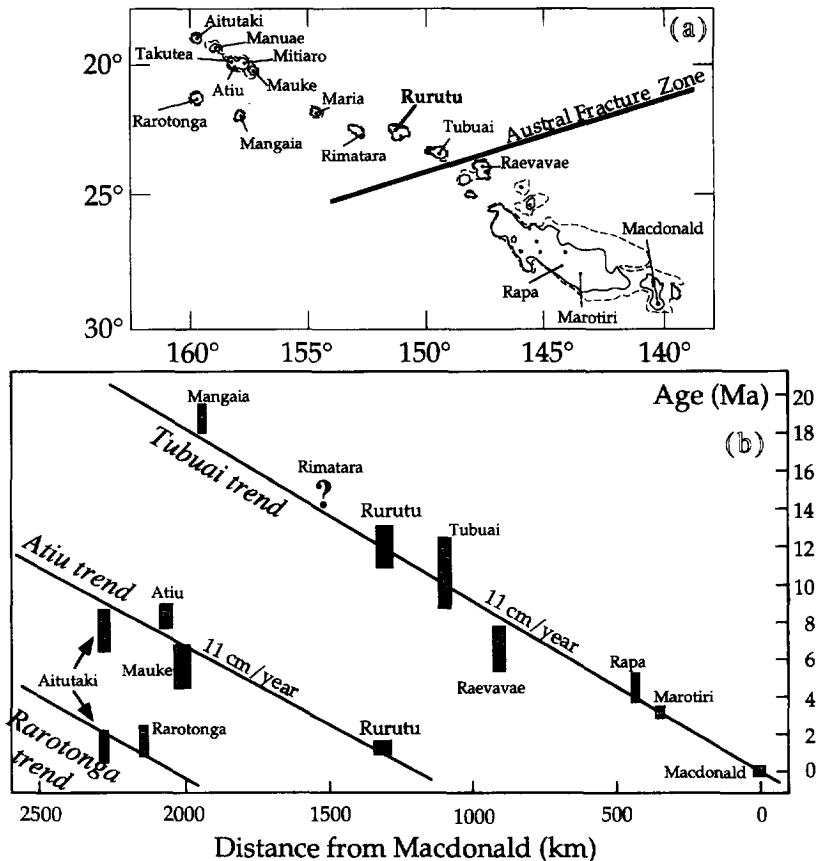


Fig. 1. (a) General map of the Austral alignment in the South Pacific showing the location of the various islands along the chain. (b) diagram of age vs. distance to the Macdonald seamount showing that the ages of the various islands require the presence of more than one plume conduit. The first plume trace is called the Tubuai trend and the second the Atiu trend. The third plume trace (Rarotonga trend) is too weak to be clearly identified. The diagram is modified from Diraison (1991) and based on data from Dalrymple et al. (1975), Duncan and McDougall (1976), Turner and Jarrard (1982), Matsuda et al. (1984), Diraison (1991), Maury et al. (1994) and Maury et al. (1997).

Table 1  
Major element composition of the old Rurutu lavas

Sample:	RRT-32 <sup>a</sup>	RRT-037 <sup>a</sup>	74-386 <sup>b</sup>	74-390 <sup>b</sup>	74-396 <sup>b</sup>	117G <sup>c</sup>	RR 01 <sup>d</sup>	RR 03 <sup>d</sup>	RR 11 <sup>d</sup>	RR 16 <sup>d</sup>	RR 67 <sup>d</sup>
Age (Ma):	14.2	11.3	8.4	12	12			12.42		12.11	
Type:	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Hawaite			Tholeiite
SiO <sub>2</sub>	45.29	44.62	44.01	43.93	44.29	45.43	44.40	45.80	43.00	46.70	47.20
TiO <sub>2</sub>	2.79	2.82	2.80	3.17	2.91	2.69	3.13	3.40	2.67	3.38	2.50
Al <sub>2</sub> O <sub>3</sub>	15.77	13.75	14.45	15.15	14.77	14.58	13.07	16.50	13.40	16.60	13.80
Fe <sub>2</sub> O <sub>3</sub>	13.95	12.87	2.39	2.42	2.23	13.64	14.12	13.65	11.30	13.88	12.58
FeO			11.94	12.08	11.13						
MnO	0.18	0.18	0.25	0.26	0.24	0.22	0.20	0.19	0.15	0.22	0.14
MgO	6.02	7.40	7.24	6.29	7.89	6.67	7.40	4.80	5.55	4.70	6.92
CaO	11.32	13.05	12.64	11.68	10.72	12.66	12.85	7.95	12.30	7.95	11.10
Na <sub>2</sub> O	2.34	2.80	2.39	3.04	2.88	2.14	2.32	3.75	1.88	4.22	2.44
K <sub>2</sub> O	0.29	0.55	0.75	0.73	1.03	0.39	0.47	0.99	0.55	0.93	0.38
P <sub>2</sub> O <sub>5</sub>	0.33	0.37	0.34	0.44	0.54	0.32	0.42	0.53	0.35	0.52	0.25
LOI	1.20	0.76	1.58	1.35	1.06	0.84	1.42	2.17	9.51	0.46	2.87
Total	99.48	99.17	100.78	100.54	99.69	99.54	99.80	98.83	100.66	99.56	100.18
Mg#	50.1	57.3	51.9	48.0	55.7	53.3	55.0	45.0	53.4	44.1	56.2

<sup>a</sup> Published by Dupuy et al., 1988, 1989.

<sup>b</sup> Published by Duncan and McDougall, 1976.

<sup>c</sup> Analyzed in Rennes by XRF.

<sup>d</sup> Analyzed at the University of Brest by ICP–AES.

the University of Brest. Trace element data were obtained using three techniques: ICP–AES at the University of Brest, ICP–MS at the University of

Montpellier and isotopic dilution at the Max-Planck Institut für Chemie in Mainz and at the University of Rennes (see Tables 3 and 4). Analytical details for

Table 2  
Major element composition of the young Rurutu lavas

Sample:	RRT-15 <sup>a</sup>	RRT-60 <sup>a</sup>	74-388 <sup>b</sup>	74-392 <sup>b</sup>	74-393 <sup>c</sup>	74-394 <sup>b</sup>	120D <sup>c</sup>	122M <sup>d</sup>	RR 20b <sup>d</sup>	RR 27 <sup>d</sup>	RR 28 <sup>d</sup>	RR 30 <sup>d</sup>	RR 59 <sup>d</sup>
Age (Ma):	1.23	1.16	1.07	1.05	2.1	1.85							
Type:	Nephel.	Hawaite	Hawaite	Hawaite	Hawaite	Basanite	Hawaite	Basanite	Hawaite	Hawaite	Basanite	Hawaite	
SiO <sub>2</sub>	42.00	45.87	41.99	45.38	45.31	43.01	43.36	42.40	45.25	44.25	41.00	41.60	41.00
TiO <sub>2</sub>	4.10	3.40	4.52	3.53	3.63	3.55	3.36	3.90	3.10	3.40	3.92	4.15	4.10
Al <sub>2</sub> O <sub>3</sub>	14.60	14.84	14.75	15.26	15.24	12.70	14.74	13.05	15.00	14.30	13.10	14.50	14.42
Fe <sub>2</sub> O <sub>3</sub>	15.90	14.77	2.68	2.57	15.50	2.48	15.40	14.15	15.25	15.80	15.00	17.10	16.90
FeO			13.41	12.86		12.38							
MnO	0.19	0.20	0.27	0.29	0.23	0.27	0.23	0.21	0.23	0.23	0.21	0.22	0.23
MgO	6.93	5.50	7.64	5.93	5.35	10.33	6.17	8.30	4.34	4.95	8.60	6.05	6.35
CaO	8.34	7.34	8.54	7.38	7.48	9.80	8.66	10.10	7.65	8.00	12.00	7.90	8.55
Na <sub>2</sub> O	4.53	4.37	4.46	4.80	4.56	3.50	4.10	3.24	5.40	5.00	3.35	4.70	4.48
K <sub>2</sub> O	1.55	1.35	1.66	1.45	1.46	1.08	1.41	1.04	1.77	1.73	0.96	1.68	1.62
P <sub>2</sub> O <sub>5</sub>	0.83	0.91	0.92	0.90	0.82	0.67	1.32	0.80	1.47	1.20	1.08	1.20	1.22
LOI	0.15	0.70		0.58	–0.15	0.72	0.54	1.63	0.37	0.47	0.57	0.53	0.61
Total	99.12	99.25	100.84	100.93	99.43	100.49	99.29	98.82	99.83	99.33	99.79	99.63	99.48
Mg#	50.4	46.5	50.3	45.0	44.6	59.7	48.3	57.7	39.9	42.2	57.2	45.2	46.7

<sup>a</sup> Published by Dupuy et al., 1988, 1989.

<sup>b</sup> Published by Duncan and McDougall, 1976.

<sup>c</sup> Analyzed in Rennes by XRF.

<sup>d</sup> Analyzed at the University of Brest by ICP–AES.

the measurements have been reported elsewhere. Isotopic measurements for Sr, Nd and Pb were performed in Mainz and in Rennes following essentially the same techniques as White and Patchett (1984). Blanks were always lower than 500 pg for Sr, 100 pg for Nd and 500 pg for Pb and were negligible compared to the amount of Sr, Nd and Pb present in the samples. Values for the Sr, Nd and Pb standards are given in the footnote of Table 5.

### 3.1. Major elements

Both new and published major element data are listed in Tables 1 and 2. All samples are alkalic and most are alkali basalts and basanites. A few more evolved lavas (hawaiites) are also presented. Fig. 2 shows that young and old lavas can be distinguished on the basis of their  $\text{SiO}_2$  vs. alkalis relationship. Young lavas are systematically more enriched in

Table 3  
Trace element composition of the old Rurutu volcanics

Sample:	RRT-32 <sup>a</sup>	RRT-37 <sup>a</sup>	74-386 <sup>b</sup>	74-390 <sup>b</sup>	74-396 <sup>b</sup>	117G <sup>c</sup>	RR 01 <sup>d</sup>	RR 03 <sup>d</sup>	RR 11 <sup>e</sup>	RR 16 <sup>e</sup>	RR 67 <sup>e</sup>
Li	6	6									
Sc	25	37				35.3	34	13	34	12.1	29.5
V	356	339					330	140	340	130	300
Cr	80	328				139	245	5	90	2	325
Co	53	52				62	50	28	46	29.5	47
Ni	58	86				127	118	4	88	3	126
Cu	110	98	114	95	65						
Zn	124	99	107	121	101						
Cs							0.109	0.318			
Rb	6	14	15	17	21	5	8.94	14.8	11	12.5	4.5
Sr	505	475	456	556	620	860	460	776	435	755	353
Y	24	23	21	25	24		22.5	28.4	26	31	22
Zr	157	188	158	208	224	169	205	260	175	232	125
Nb	28	34	29	41	44		38	45	30	52	19
Ba	127	191				169	162	256	152	270	85
La	20.0	26.1	22.9	30.9	33.8	24.4	28.2	35.2	25	37.5	15.6
Ce	45.3	56.2	49.9	68.7	72.8	52.7	64.0	81.1	53	77	33
Pr							7.4	9.7			
Nd	23.89	28.89	26.43	34.53	33.98	27.74	32.5	41.0	31	41	19.5
Sm	5.51	6.23	5.84	7.33	7.01	6.10	6.52	8.66			
Eu	1.88	2.07	1.94	2.36	2.26	2.02	2.17	2.81	2.05	2.9	1.7
Gd	5.42	6.01	5.92	6.94	6.38	6.00	6.27	7.92			
Tb							0.96	1.19			
Dy	4.50	4.76	4.84	5.53	5.03	4.92	5.26	6.47	5	6.3	4.7
Ho							0.94	1.17			
Er	2.15	2.24	2.22	2.58	2.21	2.36	2.29	2.89	2.4	2.8	2.2
Tm							0.308	0.389			
Yb	1.68	1.73	1.71	1.96	1.74	1.92	1.89	2.36	1.85	2.35	1.65
Lu	0.232	0.259	0.231	0.282	0.230	0.253	0.268	0.344			
Hf	3.58	4.30				4.79	4.73	5.77			
Ta	1.61					2.50	2.57	2.68			
Pb	1.65	2.01	1.89	2.65	3.12	2.24	2.14	2.46			
Th	2.14	2.74	2.35	4.49	3.31	2.54	3.15	3.74			
U	0.60	0.77	0.70	1.02	1.00	0.72	0.87	1.01			

<sup>a</sup> Published by Dupuy et al. (1988) except for REE, Pb, Th and U measured by isotopic dilution in Rennes.

<sup>b</sup> Published by Duncan and McDougall (1976) with the same REE, Pb, Th and U exceptions.

<sup>c</sup> Measured by ICP–AES at the University of Brest with the same exceptions.

<sup>d</sup> Measured by ICP–AES at the University of Brest and by ICP–MS at the University of Montpellier.

<sup>e</sup> Measured by ICP–AES at the University of Brest.

Table 4  
Trace element composition of the young Rurutu volcanics

Sample:	RRT-15 <sup>a</sup>	RRT-60 <sup>a</sup>	74-388 <sup>b</sup>	74-392 <sup>b</sup>	74-393 <sup>b</sup>	74-394 <sup>b</sup>	120D <sup>c</sup>	122M <sup>c</sup>	RR 20b <sup>d</sup>	RR 27 <sup>e</sup>	RR 28 <sup>c</sup>	RR 30 <sup>c</sup>	RR 59 <sup>e</sup>
Li	10	11					12	10					
Sc							18.6	27.6	10	11.8	26.0	13.7	13.5
V							156	242	125	145	330	215	215
Cr							74	308	23	3	175	11	11
Co							40	53	30	31	53	47	47
Ni							78	157	10	10	145	44	41
Cu			65	23	24	67	52	92					
Zn			108	111	135	102	144	113					
Cs									0.44				
Rb	32	27	33	29	29	18	31	19	38.29	41	20	39	37
Sr	950	1115	945	1070	1200	795	1115	770	1288	1160	785	1000	1060
Y	35	38	33	35	36	33			38.9	47	38	41	40
Zr	369	371	346	352	360	250	409	298	465	435	285	425	410
Nb	86	80	75	76	78	53			84.4	99	65	98	98
Ba	423	406					440	290	465	450	270	400	395
La	60.1	62.9	58.7	63.6	64.5	113.1	80.4	50.6	89.6	84	58	75	75
Ce	125.3	131.1	122.1	133.1	134.7	231.3	170.4	109.1	194	165	115	150	154
Pr									21.8				
Nd	61.41	62.40	60.05	62.94	63.58	98.02	84.89	54.64	87.6	86	68	78	77
Sm	12.01	11.86	11.75	12.13	12.02	16.72	16.11	11.08	15.1				
Eu	3.69	3.77	3.68	3.73	3.83	4.92	4.95	3.32	4.6	4.40	3.65	4.00	4.05
Gd	10.54	10.13	10.18	10.72	10.53	13.44	13.73	9.77	12.5				
Tb									1.76				
Dy	7.53	7.70	7.37	7.74	7.84	8.80	9.61	7.29	9.11	8.8	7.4	7.9	7.9
Ho									1.61				
Er	3.35	3.51	3.24	3.63	3.56	3.52	4.30	3.04	3.8	4.0	3.0	3.6	3.7
Tm									0.508				
Yb	2.59	2.77	2.50	2.82	2.85	2.59	3.23	2.28	3.087	3.05	2.45	2.75	2.70
Lu	0.349	0.393	0.340	0.399	0.400	0.343	0.456	0.320	0.46				
Hf	7.55	7.29					8.62		9.22				
Ta	5.80	5.20					6.35	4.53	5.40				
Pb	2.63	3.50	3.53	3.92	3.54	6.41	3.95	2.88					
Th	6.03	6.70	5.37	5.83	7.10	8.93	7.54	5.42	9.10				
U	1.63	1.83	1.67	1.84	1.89	2.61	2.07	1.36	2.42				

<sup>a</sup> Published by Dupuy et al. (1988) except for REE, Pb, Th and U measured by isotopic dilution in Rennes.

<sup>b</sup> Published by Duncan and McDougall (1976) with the same REE, Pb, Th and U exceptions.

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<sup>d</sup> Measured by ICP–AES at the University of Brest and by ICP–MS at the University of Montpellier.

<sup>e</sup> Measured by ICP–AES at the University of Brest.

alkalis and more depleted in silica than the old ones. Young lavas also display higher TiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub> and lower CaO contents at a given Mg# than the older volcanics. On the other hand, the ranges of Mg#, MgO and Al<sub>2</sub>O<sub>3</sub> in both groups are similar.

### 3.2. Trace elements

Concentrations of transition elements are comparable in both groups, with the exception of Sc for which the young lavas generally display lower con-

centrations at a given Mg#. Concentrations of incompatible elements are systematically higher in young volcanics (e.g., Th 5–9 ppm versus 2–4 ppm). This overall difference is largest (about 100%) for the highly incompatible elements (Rb, Ba, Th, Nb, . . .) and only about 50% for less incompatible elements such as Y and Yb. Consequently, ratios of elements such as La/Yb display systematic differences: the young lavas have La/Yb ratios of about 22 to 30 while the older volcanics have ratios rang-

Table 5  
Isotopic compositions of Rurutu lavas

Sample	$^{87}\text{Sr}/^{86}\text{Sr}$	( $\pm 2\sigma_m$ )	$^{143}\text{Nd}/^{144}\text{Nd}$	( $\pm 2\sigma_m$ )	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
<i>Old volcanics</i>							
RRT-32	0.702864	$\pm 10$	0.512869	$\pm 9$	21.06	15.77	40.28
RRT-37	0.702852	$\pm 14$	0.512871	$\pm 8$	20.92	15.76	40.19
RRT-37 duplicate	0.702779	$\pm 12$	0.512897	$\pm 9$			
74-386	0.702987	$\pm 12$	0.512895	$\pm 10$	21.01	15.75	40.21
74-390	0.702780	$\pm 10$	0.512852	$\pm 24$	21.09	15.75	40.26
74-396	0.702762	$\pm 9$	0.512869	$\pm 11$	21.42	15.78	40.45
117G	0.702761	$\pm 11$	0.512895	$\pm 10$	20.71	15.74	39.98
RR 01	0.702857	$\pm 9$	0.512877	$\pm 5$	21.08	15.78	40.32
RR 03	0.702857	$\pm 7$	0.512884	$\pm 5$	20.98	15.75	40.19
RR 11	0.703003	$\pm 11$	0.512894	$\pm 5$	20.82	15.73	40.04
RR 16	0.702948	$\pm 10$	0.512900	$\pm 5$	20.97	15.74	40.17
RR 67	0.702807	$\pm 8$	0.512906	$\pm 8$	20.88	15.71	40.04
<i>Young volcanics</i>							
RRT-15	0.703388	$\pm 9$	0.512909	$\pm 14$	20.35	15.69	39.82
RRT-60	0.703244	$\pm 9$	0.512901	$\pm 10$	20.31	15.66	39.72
74-388	0.703369	$\pm 9$	0.512892	$\pm 4$	20.35	15.68	39.79
74-392	0.703298	$\pm 10$	0.512938	$\pm 8$	20.33	15.67	39.79
74-393	0.703454	$\pm 11$	0.512914	$\pm 15$	20.45	15.70	39.90
74-394	0.703296	$\pm 12$	0.512780	$\pm 10$	19.11	15.52	39.17
120D	0.703259	$\pm 9$	0.512918	$\pm 10$	20.27	15.66	39.71
122M	0.703277	$\pm 9$	0.512905	$\pm 12$	20.22	15.68	39.70
RR 05	0.703300	$\pm 9$	0.512897	$\pm 5$	20.29	15.67	39.76
RR 20b	0.703205	$\pm 8$	0.512946	$\pm 5$	20.28	15.67	39.76
RR 27	0.703252	$\pm 8$	0.512882	$\pm 5$	20.31	15.67	39.77
RR 28	0.703343	$\pm 9$	0.512908	$\pm 5$	20.34	15.67	39.75
RR 30	0.703309	$\pm 9$	0.512913	$\pm 4$	20.35	15.68	39.80
RR 59	0.703303	$\pm 9$	0.512918	$\pm 6$	20.35	15.68	39.82

Because samples were run in different conditions on separate instruments, all data have been homogenized by normalizing to reference values for standards:  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710250$  for NBS 987,  $^{143}\text{Nd}/^{144}\text{Nd} = 0.511850$  for La Jolla, and Pb ratios of 16.9373, 15.4925 and 36.7054 for NBS 981; the reproducibility of measurements for La Jolla and NBS 987 was always better than  $2 \times 10^{-5}$ . All samples were run in duplicate for Pb isotopes and averages of the two runs are reported in the table after a fractionation correction of typically 0.0014 pmu as determined by repeated runs of the standard.

ing between 10 and 20. However, ratios of the most incompatible elements differ in the opposite direction with, for example, Ba/Nb at about 4.5 for the young lavas compared with a range from 4 to 8 for the older rocks. The most puzzling differences between old and young lavas relate to ratios of elements with similar compatibilities such as Ce/Pb and Zr/Hf. Young lavas have Ce/Pb ratios of 34 to 48 and Zr/Hf of about 48 while old volcanics display ranges of 24 to 28 and 35 to 44.

### 3.3. Isotopes

Sr, Nd and Pb isotopes show systematic and significant differences between the old and the young

lavas. Old lavas display Sr, Nd and Pb isotopic compositions similar to those of the neighbouring island Tubuai which has been shown to have a HIMU (high  $^{206}\text{Pb}/^{204}\text{Pb}$ ) composition (Vidal et al., 1984; Chauvel et al., 1992):  $^{87}\text{Sr}/^{86}\text{Sr}$  vary between 0.70275 and 0.70300,  $^{143}\text{Nd}/^{144}\text{Nd}$  between 0.51285 and 0.51290 and  $^{206}\text{Pb}/^{204}\text{Pb}$  between 20.7 and 21.4. In contrast, the young volcanics display less extreme compositions:  $^{87}\text{Sr}/^{86}\text{Sr}$  between 0.7032 and 0.7035,  $^{143}\text{Nd}/^{144}\text{Nd}$  between 0.51288 and 0.51295 and  $^{206}\text{Pb}/^{204}\text{Pb}$  between 20.2 and 20.5 (with the exception of sample 74-394 which has a Nd isotopic composition of 0.51278 and a  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio of 19.2). Values obtained for the young lavas are intermediate between the old HIMU

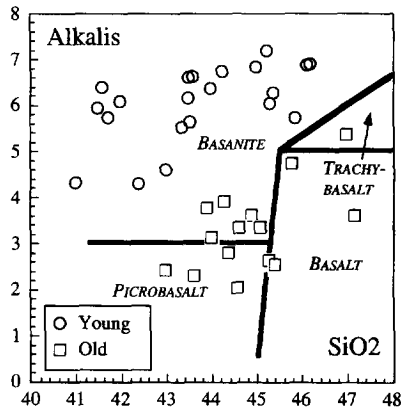


Fig. 2.  $\text{SiO}_2$  vs.  $\text{Na}_2\text{O} + \text{K}_2\text{O}$ . Data from Tables 1 and 2 and from Dupuy et al. (1988), Nakamura and Tatsumoto (1988). The field boundaries have been drawn according to Le Maitre et al. (1989).

islands and the more recent islands which have more subdued values. Isotopic ratios measured for sample 74-394 are very unusual in the Austral chain. We do not have any reasonable explanation for the values found for this sample, which was collected as a cobble included in the coral reef and has been dated at 1.85 Ma. This sample will be ignored in the following discussion.

#### 4. Discussion

In this section we make a comparison between (a) the old and the young volcanism on Rurutu, and (b) the Rurutu volcanism and that of the other islands in the Austral chain. Using the trends seen in Fig. 1 (age vs. distance to Macdonald), we first consider the changes in source compositions and melting conditions within each alignment. We then compare the two volcanic events in Rurutu in order to investigate how the source and melting conditions changed during the 10 Ma gap of volcanic activity. In particular, we concentrate on the possible role and contribution of the local oceanic lithosphere to magmatism.

##### 4.1. How do the two volcanic episodes relate to the Austral plume activity?

Continuous volcanic activity has been described and reported along the Austral chain between Man-

gaia at the northwest end and Macdonald seamount, the present site of the plume. Fig. 1b shows an age compilation of Diraison (1991) which clearly demonstrates that the various volcanoes did not form along a simple plume track but instead are aligned along three separate traces: the 'Tubuai trend', the 'Atiu trend' and the 'Rarotonga trend' as discussed earlier and shown in Fig. 1b. Diraison (1991) interpreted these traces as resulting from melting in three separate plumes. Alternatively, the age versus geographical position relationship of the Austral islands could be viewed as resulting from a single but wide plume that would pierce the oceanic crust in different locations at the same time. In this interpretation there would be only one plume trace but its expression on the surface of the oceanic plate could be compared to that of a 'shower' with distances in the order of 1200 km between the different volcanic islands formed by the same ascending plume. Both interpretations (three different plumes or a single wide plume) have their intrinsic difficulties: in the case of three plumes, it is difficult to imagine how their three sources could have been tapped in the mantle, to ascend independently to the base of the lithosphere; in the case of a single wide plume, the processes responsible for the splitting of the conduit to give rise to volcanic activities as far apart as 1200 km are difficult to imagine. These questions are important but beyond the scope of this paper and therefore they will not be considered in any more detail here. The only important aspect that is relevant to this paper is that data show that volcanism occurred at different localities at the same time in the Austral chain. We will therefore consider that the model presented by Diraison (1991) is valid in the framework of the interpretation of chemical data. The old volcanism in Rurutu should therefore be compared to that of the other islands of the 'Tubuai trend' (Mangaia, Rimatara, Tubuai, Raevavae, Rapa, Marotiri and Macdonald); the young volcanism on Rurutu should have had a source comparable to that of the islands on the 'Atiu trend' (the old Aitutaki lavas, Atiu and Mauke); and the third, less well expressed, plume trace (the 'Rarotonga trend') seems to be related to the recent Aitutaki volcanism as well as to that of Rarotonga. Trace element and isotopic variations among the various islands should therefore be considered in this framework, in order to better



understand the variations and the changes in source composition.

#### 4.1.1. The 'Tubuai trend': characteristics of the old volcanism

In this section we compare the chemical characteristics of the old Rurutu volcanism with that of volcanics on the other islands that made up the 'Tubuai trend'. Figs. 3 and 4 present compilations of isotopic data. They demonstrate clearly that significant isotopic heterogeneities exist along the island

chain. No systematic isotopic variation can be correlated directly to the age of the volcanism. The only general rule is that typical HIMU compositions (high  $^{206}\text{Pb}/^{204}\text{Pb}$  and low  $^{87}\text{Sr}/^{86}\text{Sr}$ ) are observed only in the oldest part of the chain (Mangaia, Rimatara, Rurutu and Tubuai) (Vidal et al., 1984; Palacz and Saunders, 1986; Nakamura and Tatsumoto, 1988; Chauvel et al., 1992). The younger islands and seamounts (Rapa, Marotiri and Macdonald) have isotopic compositions that plot in the middle of the general OIB fields (Hémond et al., 1994). The geographic limit between the two isotopically different groups is not clear. It could be the Austral fracture zone, but the absence of published data for Raivavae (located on the eastern side of the fracture zone) prevents us from drawing further conclusions on the position at which the composition changes from distinctly HIMU to more subdued compositions. The significant jump in isotopic composition between the old and the more recent islands in the chain could also be related to a change in the plume source composition about 8 Ma ago.

Old Rurutu volcanics (12 Ma) have very similar isotopic compositions to those of volcanics from Mangaia, Rimatara and Tubuai (10–20 Ma), suggesting that the characteristic HIMU composition of the plume source was essentially identical for about 10 Ma. However, some of the trace element signature of the old Rurutu lavas are different from those of the nearby Tubuai Island. In particular, the elevated Ce/Pb ratios of Tubuai volcanics are not found in Rurutu, suggesting that this might not be a ubiquitous feature of the source of HIMU volcanism.

#### 4.1.2. The 'Atiu trend': characteristics of the young volcanism

The young Rurutu lavas have isotopic compositions significantly different from those of the other islands (Aitutaki, Atiu and Mauke) on the Atiu trend (Figs. 3 and 4). As seen in Fig. 1b, the age and position of these islands is consistent with them having formed from the same plume. Sr and Pb isotopes are less radiogenic in Rurutu lavas while Nd isotopic ratios are higher. In both Figs. 3 and 4, young Rurutu lavas plot at a position intermediate between that of the other three islands formed by the same plume (Aitutaki, Atiu and Mauke) and the old islands formed by the Tubuai plume. If, as seems to

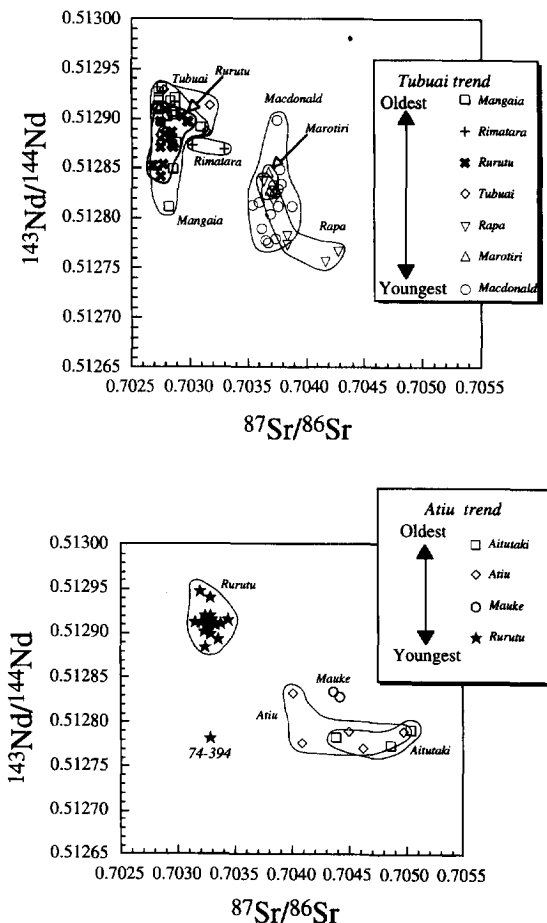


Fig. 3.  $^{143}\text{Nd}/^{144}\text{Nd}$  vs.  $^{87}\text{Sr}/^{86}\text{Sr}$  diagrams showing in the upper part the range of isotopic compositions measured on volcanic islands related to the Tubuai trend, and in the lower part the isotopic range in the Atiu trend. Data from Vidal et al. (1984), Palacz and Saunders (1986), Nakamura and Tatsumoto (1988), McDonough and Chauvel (1991), Chauvel et al. (1992), Woodhead (1996) and this work. The Nd isotopic composition of sample 74-394 is not understood.

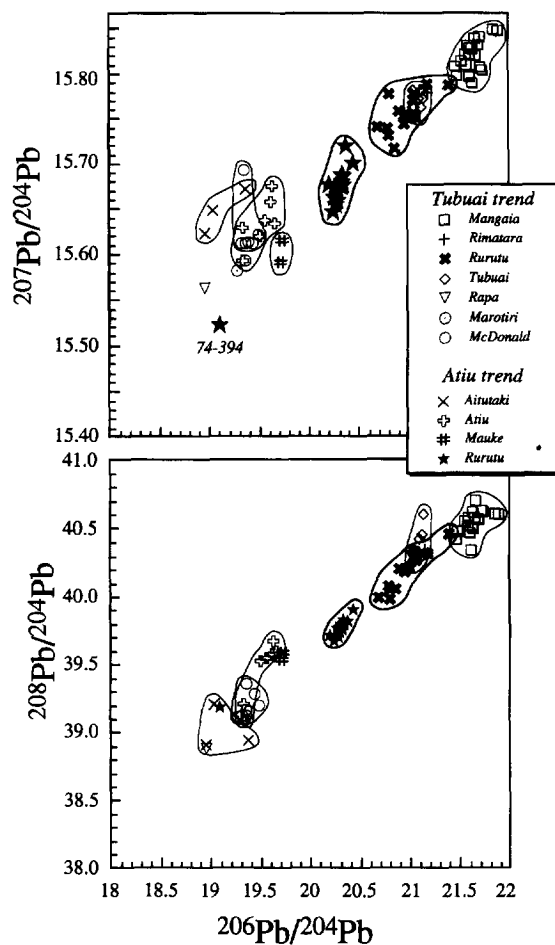


Fig. 4.  $^{206}\text{Pb}/^{204}\text{Pb}$  vs.  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  vs.  $^{208}\text{Pb}/^{204}\text{Pb}$  for both the Tubuai and the Atiu trends. The legend applies to both diagrams. Data from Vidal et al. (1984), Palacz and Saunders (1986), Nakamura and Tatsumoto (1988), McDonough and Chauvel (1991), Chauvel et al. (1992), Woodhead (1996) and this work. Note again the very different isotopic composition of sample 74-394.

be the case of the Tubuai trend from Mangaia to Tubuai, the composition of the plume source did not change through time, the young Rurutu lavas require

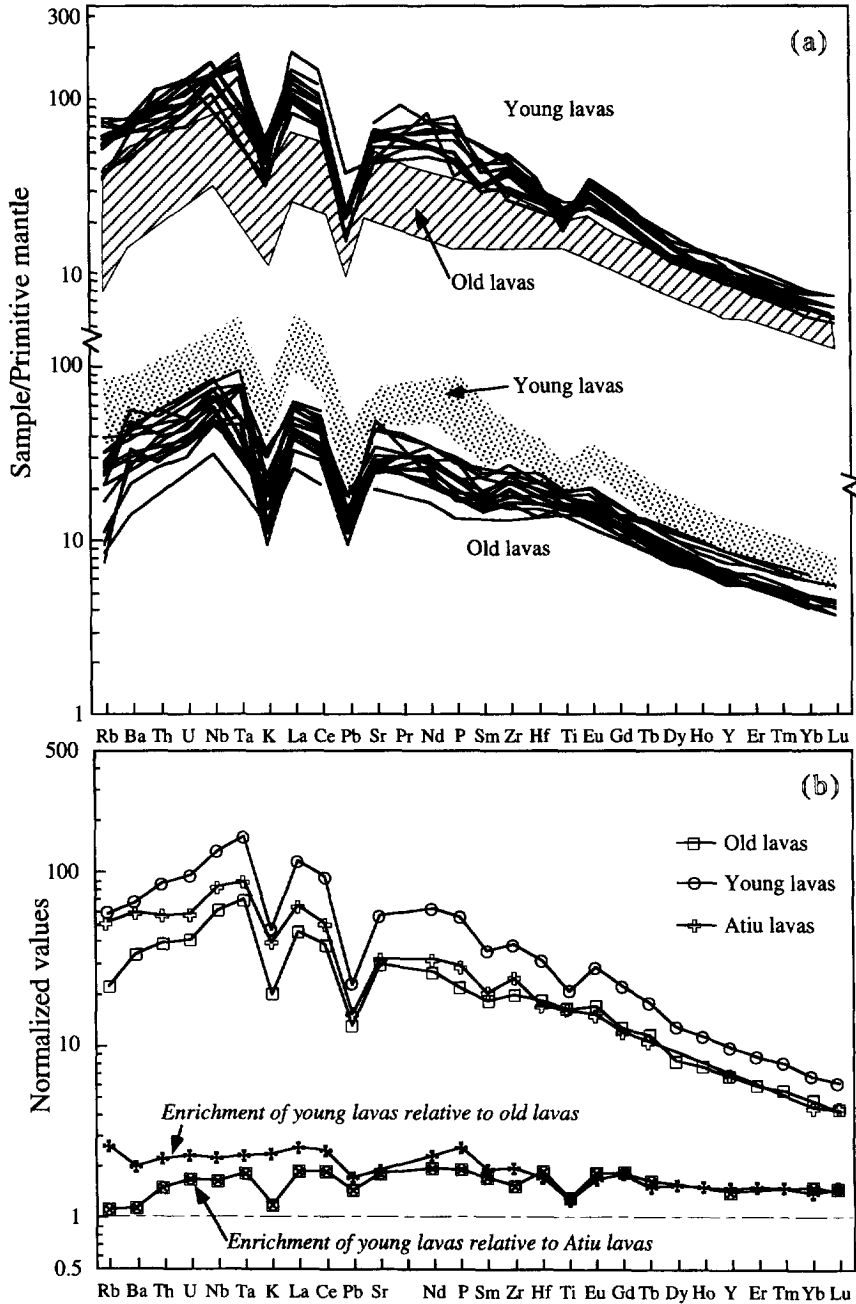
that a mixing event responsible for their unique isotopic characteristics occurred during their formation. The contaminant which changed the isotopic

Fig. 5. (a) Mantle normalized diagrams for both old and recent volcanics in Rurutu showing the systematic enrichment of young lavas compared to old volcanics and the deep K anomalies present in all samples. Data are normalized to the primitive mantle of Hofmann (1988) and include data from the literature (Palacz and Saunders, 1986; Dupuy et al., 1988; Nakamura and Tatsumoto, 1988; Dupuy et al., 1989). (b) Trace element patterns presenting (1) the average values of the young and old Rurutu lavas, as well as that of Atiu volcanics, and (2) the average composition of young lavas normalized to that of the old lavas and to that of Atiu lavas. Averages are reported instead of fractionation-corrected values because the range of Mg# in the lavas is relatively limited, and the errors associated to the correction are too large to provide a reliable estimate of the composition of the primary liquid. The figure clearly shows that trace element concentrations in the young lavas are twice those of the old lavas. It also highlights the negative Ba, Pb, Hf and Ti anomalies and the positive Rb, and P anomalies. Relative to the Atiu volcanics, the young Rurutu lavas are about 1.5 times richer and display negative Rb, Ba, K, Pb, Zr and Ti anomalies.

compositions can be constrained to have had radiogenic Pb isotopic composition and low  $^{87}\text{Sr}/^{86}\text{Sr}$ , like those of the old Rurutu lavas.

4.1.3. A single plume with a changing composition

It can also be argued that the age vs. distance relationship seen in Fig. 1b could be interpreted in



terms of a single plume source whose isotopic composition changed about 8 Ma ago. In this interpretation, the various volcanic islands with the same age (Aitutaki and Atiu at 8 Ma, Rapa and Marotiri at about 5 Ma, and Rarotonga and the second volcanic event in Rurutu at about 1.5 Ma) had a common source and the plume led to the formation of islands as far apart as 1500 km. We would then have a situation in which the HIMU isotopic characteristics of the plume disappeared about 10 Ma ago to be replaced by a more subdued composition such as that of the islands of Atiu, Rapa and Macdonald. In this case, the composition of the young Rurutu volcanics still remains exceptional in the Austral chain because they are the only lavas with Pb isotopic compositions intermediate between the two main groups in Fig. 4. Here again, the young Rurutu basalts require a source different from that of the other volcanic islands with

the same age. This source, as highlighted above, could result of a mixing between the original plume composition and a component characterized by radiogenic Pb isotopic composition.

#### 4.2. Melting conditions and source composition for the young Rurutu volcanics

##### 4.2.1. Trace elements

Young volcanism in Rurutu is more alkaline (Fig. 2) and more enriched in highly incompatible elements than the older volcanism. This is clearly seen from the general spidergrams (Fig. 5a) and it is accentuated when the data from the old volcanics are used to normalize the trace element concentrations of the young volcanics (Fig. 5b). It also appears clearly when the La/Yb ratios of old and recent volcanics are compared at a given Mg# value (Fig. 6).

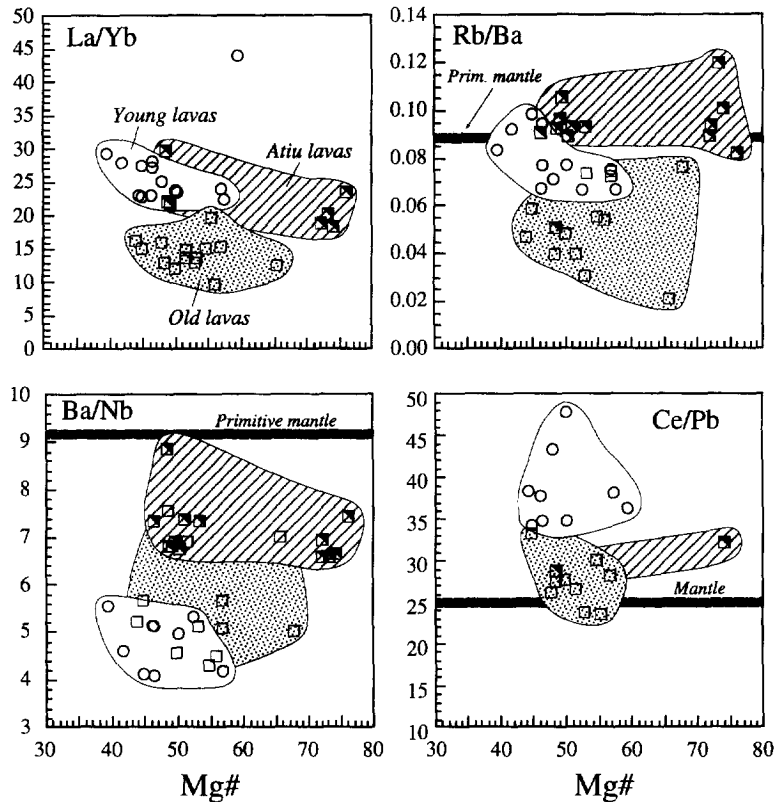


Fig. 6. Plots of several trace element ratios (La/Yb, Rb/Ba, Ba/Nb, Ce/Pb, P/Nd, Zr/Hf, Hf/Sm and Sm/Ti) as a function of Mg# showing the systematic difference between the Atiu volcanics, the old Rurutu volcanics and the young volcanics. Atiu volcanics are represented by half-filled squares, the old Rurutu volcanics are shown by white squares, while the young volcanics are represented by white circles. Data as reported in Tables 3 and 4 and from Palacz and Saunders (1986), Dupuy et al. (1988), Nakamura and Tatsumoto (1988) and Dupuy et al. (1989).

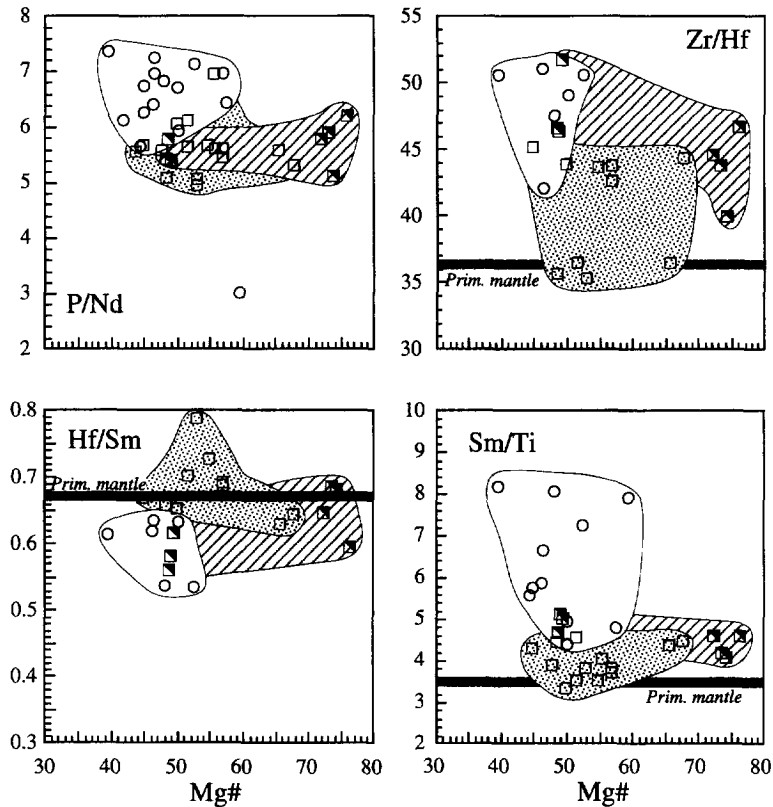


Fig. 6 (continued).

To a first approximation, this systematic difference could be attributed to a lower degree of melting during formation of the young lavas, as compared to the old volcanics. However, other systematic differences between old and young Rurutu volcanics cannot be explained by differences in the extent of melting. These include lower Ba/Nb and Hf/Sm ratios in the young volcanics, and higher Rb/Ba, Ce/Pb, P/Nd, Zr/Hf and Sm/Ti ratios (Fig. 6). All these ratios should not be significantly affected by changes in degree of melting because, in each pair, both elements are thought to be similarly incompatible during melting of usual mantle mineral assemblages. The systematic difference in all these ratios must therefore be attributed to differences in source composition. The combination of higher Rb/Ba and lower Ba/Nb ratios in the young volcanics suggests that their source was depleted in Ba and enriched in Rb compared to that of the older volcanics. The higher Sm/Ti, P/Nd and Ce/Pb ratios and the lower Hf/Sm in the young volcanics

constrains the relationship in the source region between REE and these other four trace elements, because each of them has an incompatibility similar to the associated REE. Ti, Hf and Pb appear depleted relative to the REE in the source of young volcanics while P is enriched. In summary, the source of the young volcanics is relatively enriched in Rb and P and depleted in Ba, Ti, Hf and Pb.

When compared to the Atiu volcanics (Dupuy et al., 1989) (the volcanics formed in the previous island in the same age vs. distance trend in Fig. 1b), the young Rurutu lavas also display systematic differences. Fig. 5b shows that the young Rurutu lavas have trace element contents generally about 1.5 to 2 times higher than Atiu with the exception of Ti, Pb, K, Rb and Ba. Fig. 6 also shows that, as in the case of the comparison with the old Rurutu lavas, the young Rurutu volcanics have ratios of similarly incompatible elements that are distinct from those of the Atiu basalts. In particular, Rb/Ba and Ba/Nb are significantly lower in the young Rurutu lavas

while their Ce/Pb, P/Nd and Sm/Ti ratios are much higher than those of the Atiu volcanics. This relationship suggests that the source of the young Rurutu lavas was depleted in Rb, Ba, Pb and Ti and enriched in P relative to that of the Atiu volcanics.

Such characteristics are quite unusual and difficult to relate to the absence or overabundance of a particular mineral in the source. The presence of residual amphibole or phlogopite could account for the negative Ti anomaly seen in the young volcanics (Fig. 5b) as well as for the significant K anomaly displayed by both the old and the young lavas (Fig. 5), but it is inconsistent with the concomitant presence of a Rb positive anomaly in the young lavas compared to the old lavas. Green (1994) presented a compilation of partition coefficients ( $K_D$  values) between amphibole, phlogopite and silicate liquids that shows that both minerals would concentrate Ti, K and Rb in relatively similar proportions and would create negative anomalies for these three elements relative to the neighbour elements. We conclude, therefore, that fractionation of amphibole and phlogopite cannot explain the essential differences in trace elements that characterize the young Rurutu volcanics.

The trace element partition coefficients between orthopyroxene and silicate liquid (Kennedy et al., 1993) suggest that residual orthopyroxene might explain the Ti and Ba anomalies in the young lavas (Fig. 5b) and the excess of Nb compared to La in both old and young. However, this mineral should also create a negative Zr anomaly, which is not observed. In addition, the Opx/liquid  $K_D$  values (Kennedy et al., 1993) are generally too low to have any significant effect on liquid concentrations. Residual orthopyroxene does not seem to be a good candidate to explain the Rurutu chemical characteristics.

The positive P anomaly (Fig. 5b and Fig. 6) is even more difficult to explain by melting processes involving normal mantle minerals. It requires preferential digestion of apatite, an unreasonable proposition. Finally, no reasonable melting process can be suggested to account for the significant Pb depletion observed in the young Rurutu volcanics.

In summary, the trace element characteristics of the young Rurutu lavas cannot easily be accounted for by normal mantle melting. They require a differ-

ent process, most probably the contamination of basaltic liquid by a component whose main characteristics are a general enrichment in trace elements, particularly P, and a depletion in Ti, Hf, Pb and Ba. To fully understand and constrain the nature of this contaminant, we need to complement the trace element constraints with the isotopic data.

#### 4.2.2. Isotopes

The young volcanics have isotopic compositions that are displaced from the original plume composition, taken here as that of Atiu volcanics, towards a composition comparable to that of the older volcanics in the island. This change in isotopic compositions is significant because Pb isotopic ratios are closer to the old Rurutu lavas compositions than to the Atiu, Mauke and Aitutaki compositions. Any two-component mixing array is a straight line in the  $^{206}\text{Pb}/^{204}\text{Pb}$  vs.  $^{207}\text{Pb}/^{204}\text{Pb}$  diagram (Fig. 4) and the distance to the opposite end-member composition provides an immediate evaluation of the proportion of Pb coming from each component. In the present case, we calculate a contribution of about 40% of Pb from the plume and 60% from the other material. These proportions apply to Pb present in the mixture; the relative proportion of each end-member must then be adjusted depending on the Pb contents of both terms of the mixing array. Similarly, the Sr isotopic compositions of the young lavas are closer to that of the old Rurutu lavas than to the original plume composition as represented by the Atiu lavas in Fig. 3. The influence of the contaminant must therefore be major and could also dominate the trace element budget.

#### 4.3. What is the contaminant?

The simplest model would require a single contaminant that could explain both the isotopic and the trace element characteristics. We know that the only highly radiogenic Pb isotopic compositions in the area are found in the old volcanics, and it follows that the contaminant could be related to the early magmatic event. Although the old lavas themselves are an obvious candidate, the trace element characteristics of the young lavas cannot be explained in terms of digestion of the older rocks: in particular, the Ce/Pb ratios of the young lavas are higher than not only those of the old lavas, but also the Atiu

lavas and the ambient mantle (see Fig. 6). The contaminant involved in the genesis of the young lavas must therefore have an isotopic composition similar to that of the old volcanics but its trace element ratios must have been drastically different from what is usually observed in oceanic volcanics. The composition of the contaminant appears to have been characterized by unusual trace element fractionations such as Ba depletion relative to Rb and Nb, Pb depletion relative to Ce, P overabundance, high Zr/Hf and Sm/Ti and low Hf/Sm, features that can not be explained by melting of a normal mantle.

Carbonatites are known to have unusual trace element patterns (Nelson et al., 1988; Lehnert, 1989). They are extremely enriched in trace elements, particularly the REE, and they display systematic and large negative K and Ti anomalies and smaller negative Zr anomalies (see Fig. 7). Such features are qualitatively similar to the peculiar fractionation noticed in the young Rurutu lavas.

Carbonatites are known to intrude continental lithosphere. Data on peridotite xenoliths brought up by alkali basalts (O'Reilly et al., 1991; Yaxley et al., 1991; Rudnick et al., 1993) show that carbonatitic liquid can be pervasive in continental rift environments, and can dominate the trace element budget of samples from the lithospheric mantle. In particular, detailed trace element studies of mantle xenoliths demonstrate fractionation of HFSE and REE (e.g., Rudnick et al., 1993) with a general enrichment in REE relative to the HFSE and a marked negative Ti anomaly. It is commonly accepted that the differences between those peridotite nodules and normal peridotites result from the addition of a carbonatite component to the lithosphere from which the nodules originated. Such an interpretation is supported by experimental studies of element partitioning between carbonatitic and silicate liquids. A compilation of partition coefficients by Green (1994) shows that HFSE are fractionated from REE during the separation of carbonatitic and silicic liquids. However, a marked difference between the data from natural samples and the experimental data can be seen within the HFSE. While Ti always displays the largest anomaly in the natural samples, it would be predicted from published  $K_D$  values that Hf should be drastically more affected. It is not, however, the aim of this paper to discuss this issue. We will avoid the

problem by considering the data on natural samples as more representative of the composition of carbonatitic melts.

Although carbonatites are more common in continental areas, their presence has also been reported in oceanic environments (e.g., Cape Verde Islands; Silva et al., 1981) and their existence has been suspected under various oceanic islands (Schiano et al., 1992; Schiano et al., 1994; Wulff-Pedersen et al., 1996), particularly in the Austral chain (Hauri et al., 1993; Hémond et al., 1994). We suggest therefore that carbonatite might be responsible for the peculiar trace element pattern observed in the young Rurutu lavas.

Hauri et al. (1993) reported some detailed trace element and isotopic analyses of xenoliths collected in two islands, one Samoa, the other Tubuai in the Austral chain. They showed that the xenoliths were drastically affected by carbonate metasomatism that changed the trace element composition of both the whole-rock and the constituent mineral phases. Fig. 7 shows values calculated by Hauri et al. (1993) for a putative melt in equilibrium with clinopyroxene from one of the Tubuai xenoliths. This melt is

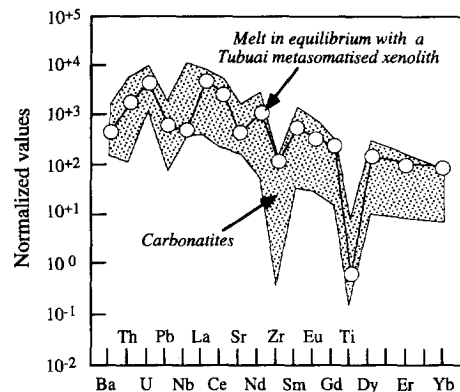


Fig. 7. Trace element patterns simplified from Hauri et al. (1993) showing the composition of a putative melt in equilibrium with a Tubuai xenolith as well as a field representing the composition of carbonatites. Following the representation of Hauri et al. (1993), concentrations are normalized to chondritic values of Anders and Grevesse (1989), except for Pb for which a value of 0.060 ppm was used. If the primitive mantle values of Hofmann (1988) had been used, the depth of the Pb negative anomaly would be about twice as big. Note that the Sr enrichment in carbonatites is not significantly different from that of LREE. Mixing of carbonatite with silicate liquid should therefore not produce a systematic Sr excess in the mixed magmas.

characterized by extreme enrichment in trace elements and a marked negative Ti anomaly. No samples with these characteristics are found in the eruption products on Tubuai, and Hauri et al. (1993) argued that this melt, with a trace element composition very similar to carbonatites, had not found its way to the surface. They also noted that the isotopic composition of the xenolith was similar to that of the Tubuai lavas, which suggests that the trace-element enrichment due to the carbonatitic metasomatism was a recent event related to the volcanic activity in Tubuai Island. We envisage a similar scenario under Rurutu Island. A carbonatitic component similar to that suggested by Hauri et al. (1993) could have invaded and polluted the lithosphere underneath the island during the first volcanic event. As in Tubuai, it would be characterized by an extreme enrichment in trace elements as shown in Fig. 7, a marked depletion in Ti and by Sr, Nd and Pb isotopic compositions similar to those of the first volcanic activity in Rurutu. This carbonatitic component would then have been digested by magmas rising through the lithosphere during the second volcanic event, and would thus have provided the peculiar characteristics of the young Rurutu lavas.

The young lavas, which in general have lower Ti/Eu ratios than both the old Rurutu lavas and the Atiu lavas, also have a high Ce/Pb ratio (Fig. 8). The elevated Ce/Pb ratio typical of the young Rurutu lavas could therefore result from the addition of a carbonatitic component to the silicate lava. Pb concentration data on metasomatized nodules are rare and cannot be used to evaluate whether the carbonatitic metasomatism would change the Ce/Pb ratio. However, the  $K_D$  values compiled by Green (1994) and the data obtained on natural carbonatites show that a carbonatitic liquid should have a higher Ce/Pb ratio than the associated silicate liquid. We therefore interpret the general anticorrelation of Ce/Pb, Nd/Pb and Ti/Eu ratios in Fig. 8 as resulting of mixing of silicate and carbonatitic components. This carbonatitic liquid ought to be related to the first (old) volcanic event in Rurutu because it is characterized by extremely radiogenic Pb isotopic compositions, and it has the following characteristics: high Ce/Pb, P/Nd and Sm/Ti ratios and low Ba/Nb ratio.

In summary, we suggest that when the second

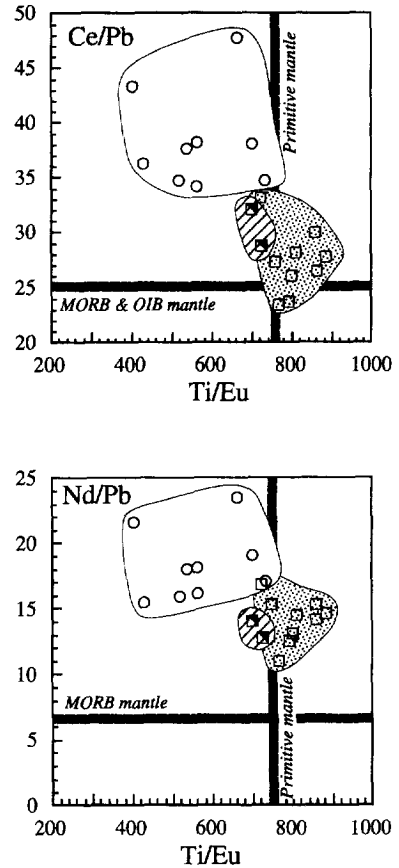


Fig. 8. Ce/Pb and Nd/Pb vs. Ti/Eu diagrams showing the negative correlation between the ratios and suggesting that the process responsible for the Ti depletion is also responsible for the Ce/Pb fractionation.

plume arrived under Rurutu Island about 2 Ma ago, the resultant magmas digested a carbonatitic component that had been left in the lithosphere by the first plume melting event at 12 Ma. Such a scenario can be roughly quantified for most trace elements if one constrains the amount of digested carbonatitic material using the Pb isotopic compositions and Ce/Pb ratios of Atiu volcanics and the compositions of both old and young volcanics in Rurutu. From the Pb isotopic compositions we calculate that about 60% of the total Pb in the young volcanics originates from the old carbonatitic component. Using a Ce/Pb ratio of 25 as characteristic of the plume material during both young and old volcanic events, we can calculate a Ce/Pb ratio of about 47 for the carbonatitic contaminant. This ratio is about double of what is



normally observed in mantle melts but is consistent with the REE enrichment usually observed in carbonatites. Extending this calculation to other trace elements, we calculate that the carbonatitic component contributes about 75% of the budget of the highly incompatible elements (Th, U, Nb, La, Sm, for example) in the young volcanics, but only 50% for more compatible elements such as Yb. Because absolute trace element concentrations in carbonatites are extremely variable (see Fig. 7), it is difficult to translate these proportions into percentages of carbonatitic liquid in the young lavas, but it would be in the order of 5–10%. The anomalies in ratios of similarly compatible elements (Rb/Ba, Ba/Nb, Ce/Pb, P/Nd, Zr/Hf, Sm/Ti and Hf/Sm) are also qualitatively supported by partition coefficients determined between carbonatitic and silicate liquids (see compilation by Green, 1994) and by recent data reported for fluid inclusions in mantle xenoliths (Rosenbaum et al., 1996). We cannot constrain more quantitatively the amount and the precise composition of the carbonatite digested by the young lavas because the range of isotopic variation ( $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$ , for example) is too limited in the young Rurutu lavas. The relative variation of trace-element ratios such as Ti/Eu and Ce/Pb in the young lavas is much larger than that of the isotopes and Ti/Eu vs.  $^{87}\text{Sr}/^{86}\text{Sr}$  relationships can not be used to constrain the mixing event.

#### 4.4. Constraints from Rurutu volcanics on mantle composition and heterogeneities

The interpretation that we propose above raises two important questions about the chemical character of the source of intraplate volcanism: (a) the HIMU component in the source of OIB might be less common than previously thought (Vidal et al., 1989; Chauvel et al., 1992), and (b) fractionation of trace elements such as Ce/Pb, Ti/Eu, Zr/Hf could be primarily due to the influence of carbonatitic liquids and not to long-term processes in the mantle. We now address these two issues.

Data on the young Rurutu volcanics suggest that their original plume source did not have the particularly radiogenic Pb isotopic composition that characterizes HIMU lavas, and that they acquired their final composition through contamination by a carbonatitic component produced during the first volcanic event.

If such a process is widespread, the composition of mantle plumes might be quite different from the picture we get from oceanic island volcanism. If plume melts commonly reach the base of the lithosphere without making it to the surface, carbonatitic liquids might invade the lithosphere and affect its composition. This component could easily be remobilized when another plume rises to the surface and could then change the chemical and isotopic signature of the resulting hybrid liquid.

Separation of carbonatitic liquids from their silicate counterpart has drastic effects on trace elements. If we want to constrain the general geochemical characteristics of present-day depleted mantle, and of plume sources, we have to avoid lavas that have undergone such a fractionation process. The young Rurutu volcanic event seems to be a good example of oceanic volcanism that provides little information about the ultimate origin and evolution of the plume source. If it is true, for example, that the elevated Ce/Pb ratios measured on the young volcanics are due to carbonatite/silicate fractionation that occurred in the lithosphere during the first volcanic pulse, then changes in Ce/Pb ratios tell us little about the long-term origin and evolution of the plume, in contrast to what was suggested by Chauvel et al. (1992) and Hémond et al. (1994).

In a broader context we can distinguish two types of oceanic islands: (a) those produced by plumes whose trace in the ocean follows that of an old plume, and (b) islands produced by a simple plume track on virgin oceanic lithosphere. The former may have chemical compositions that are not representative of their original mantle source, and the latter should provide more reliable information on the isotopic and chemical composition of the mantle. The most prominent example of the latter type is Hawaii, which has a moderate isotopic composition falling in the middle of the general ocean island basalt field. On the other hand, Tubuai Island, which is set on a relatively old oceanic plate ( $\approx 90$  Ma), could be suspected to have an underlying lithosphere polluted by a previous plume. Such a process might explain the extreme undersaturation of the basalts and their elevated Ce/Pb ratios. However, the 90 Ma is not sufficient to create the extreme Tubuai HIMU isotopic composition in the lithosphere. The radiogenic Pb isotopic composition of Tubuai must

therefore have its origin in the mantle plume. The same could be argued for Pitcairn Island and its typical EM I signature. St Helena, which has isotopic and trace element characteristics essentially similar to those of Tubuai, is set on very young oceanic lithosphere and it is difficult to argue that its source has been polluted by a preexisting plume.

In summary, the extreme isotopic composition that characterizes the HIMU signature of Tubuai and St Helena, as well as the EM I component seen in Pitcairn, cannot be produced within the limited time that elapsed between the creation of oceanic lithosphere and the eruption of oceanic basalts. These isotopic compositions cannot therefore be attributed to carbonatite invasion in the lithosphere through which the basalts erupted. Little doubt is left about the provenance of these isotopic compositions which must be in the plume source deep in the terrestrial mantle. However, questions can be raised about their chemical characteristics (particularly the elevated Ce/Pb ratio in the case of the HIMU lavas) which might not be totally inherited from the ultimate plume source and might have been affected by contamination in the lithosphere.

## 5. Conclusions

The most important conclusions of this study are the following.

(a) The young Rurutu lavas display systematic and unusual trace element fractionation (high Ce/Pb, P/Nd, Zr/Hf and Ti/Eu) associated with isotopic compositions different from those of other islands on the same plume trace. These features are best explained by contamination of plume melts by a carbonatitic component. Their isotopic compositions suggest that the contaminant was left in the lithosphere during the initial volcanic event that built the island.

(b) Pollution of the lithosphere by carbonatitic liquids might be a widespread phenomenon in oceanic areas. These liquids might be formed by immiscibility when magmas produced by rising plumes reach the lithosphere. They might not always find their way to the surface. If a subsequent plume pierces such a lithosphere, drastic effects might be observed on the chemical and isotopic composition of the erupted liquid. Element ratios such as Ti/Eu, P/Nd

and Ce/Pb can be highly fractionated by the digestion of this carbonatitic component by the basalts, and will provide little information about the deep source of the plume.

(c) The general isotopic variation that characterizes ocean island volcanism cannot be explained by systematic assimilation of lithosphere by the magmas. The lithosphere can contribute only two major types of characteristics: those acquired during formation at mid-ocean ridges, and those brought about by preceding plumes. In no case can extreme isotopic compositions such as HIMU and EM I have their origin in the lithosphere itself. Models of mantle structure, dynamics and evolution based on these end-member compositions are still robust.

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