Trace element evidence
for the origin of ocean island basalts:
an example from the Austral Islands (French Polynesia)

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Abstract. The Austral Islands, a volcanic chain in the South-Central Pacific Ocean (French Polynesia) are composed mainly of alkali basalts and basanites with subordinate amounts of olivine tholeiites and strongly undersaturated rocks (phonolite foidites and phonolite tephrites). The basaltic rocks have geochemical features typical of oceanic island suites. The distribution of incompatible trace elements indicate that the lavas were derived from a heterogeneous mantle source. The chondrite-normalized patterns of the incompatible elements in basaltic rocks of the Austral Islands are complementary to those of island arc tholeiites. As supported by isotope data, the observed trace element heterogeneities of the source are probably due to mixing of the upper mantle with subducted oceanic crust from which island arc tholeiitic magma was previously extracted.

Introduction

According to Hofmann and White (1980, 1982), Chase (1981) and Ringwood (1982, 1986), some within-plate basalts (WPB) including ocean island basalts (OIB) may have been generated by the melting of a large megalith formed by the accumulation of subducted oceanic lithosphere (basaltic crust and harzburgite) in the mantle for 0.5–2.0 b.y. Such a model postulates a connection between the petrogenesis of WPB and island arc basalts (IAB). The worldwide isotopic similarity between IAB and OIB supports such a genetic relationship (Morris and Hart 1983; White and Patchett 1984). The distribution of trace elements in OIB from the Austral Islands, French Polynesia, presented in this study, provides further evidence for the close relationship between the two types of basalts.

Geological setting

The Austral Islands are located in the South Central Pacific Ocean (Fig. 1) where they form the south-eastern part of Austral-Cook Islands chain. The Austral Islands stretch over more than 1500 km in a ESE-WNW direction, from about 29° S and 140° W to about 22° S and 155° W, subparallel to the Society and Tuamotu Islands chains. They are composed of seven main islands and several seamounts, guyots and shoals. With the exception of the currently active submarine volcano, MacDonald, discovered in 1967 (Norris and Johnson 1969), all the islands are extinct volcanoes rising from
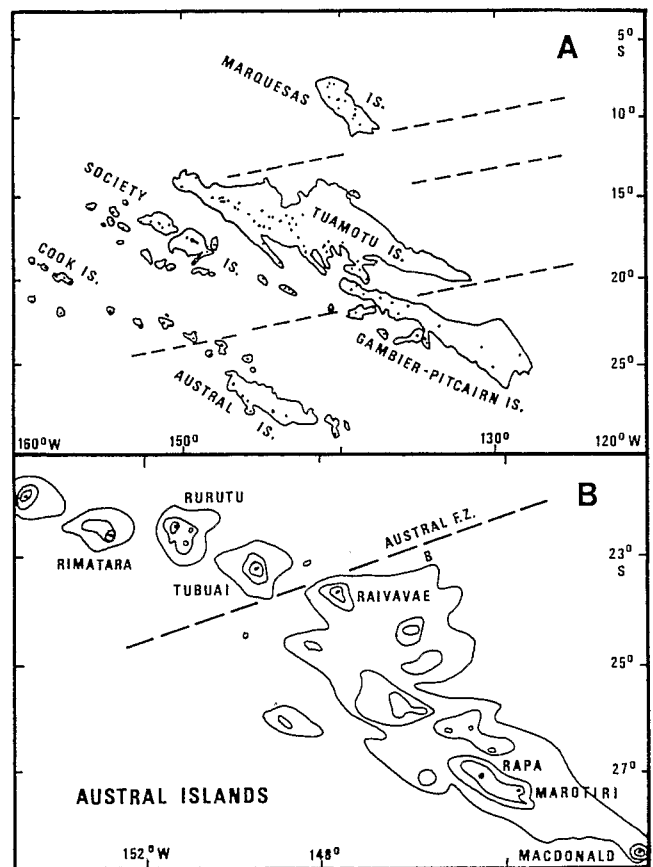
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Fig. 1 A, B. Maps of the Austral Islands (after Duncan and McDougall 1976) showing their location with respect to other archipelagos in the South Central Pacific Ocean (A) and distribution of the islands within the chain (B). *Dashed lines* represent the fracture zones. The contour lines are 4000 m isobaths on Map A and isobaths of 4000, 2000 and 1000 m on Map B

a sea-floor of Paleocene age (Pitman et al. 1974) at a depth of more than 4000 m. A fracture zone running from ENE to WSW crosses the chain between the islands of Raivavae and Tubuai (Mammerickx et al. 1975). The K/Ar dating of the Austral Islands (Krummenacher and Noetzlin 1966; Dalrymple et al. 1975; Duncan and McDougall 1976; Mottay 1976; Barsczus 1980; Bellon et al. 1980; Matsuda et al. 1984; Turner and Jarrard 1982) show an overall age progression (Duncan and Clague 1985) from the MacDonald seamount located at the southeastern end of the chain

Table 1. Representative major and trace element compositions of basalts from Austral Islands

	MacDonald					Marotiri		
	MCD-202 6984 TH	MCD-064 6970 TH	MCD-201 6983 AB	MCD-079 6974 BSN	MCD-110 6980 BSN	MRT-004 6991 AB	MRT-203 6996 BSN	MRT-001 6988 BSN
SiO_2	47.12	46.81	45.86	42.60	42.77	42.60	41.45	43.75
Al_2O_3	13.53	15.16	10.95	10.54	13.38	10.37	10.10	18.17
Fe_2O_3	11.67	12.08	11.70	13.20	13.70	12.71	12.63	11.43
MnO	0.16	0.16	0.15	0.17	0.17	0.16	0.18	0.16
MgO	8.00	4.75	13.18	13.74	9.83	16.16	12.92	3.50
CaO	12.65	10.53	11.90	11.23	10.43	10.55	12.40	9.91
Na_2O	2.31	3.07	2.16	3.60	3.54	1.82	2.26	4.88
K_2O	0.47	0.43	0.47	0.90	1.36	0.81	0.75	1.98
TiO_2	2.33	2.52	2.59	3.69	3.84	2.56	3.06	2.97
P_2O_5	0.35	0.26	0.31	0.50	0.69	0.55	1.25	0.90
L.O.I.	0.56	3.82	0.64	0.04	0.04	1.98	2.31	1.66
Total	99.15	99.59	99.91	100.21	99.75	100.27	99.30	99.31
[Mg]	0.61	0.46	0.72	0.70	0.62	0.74	0.69	0.41
Ne_{nor}	–	–	1.9	15.5	12.6	4.9	7.8	17.1
Hy_{nor}	2.8	6.7	–	–	–	–	–	–
Li (ppm)	9	4	8	6	7	6	9	8
Rb	10	9	6	16	30	20	5	39
Sr	411	341	368	575	757	600	545	1215
Ba	155	114	151	284	381	492	242	642
Sc	34	24	35	28	22	23	30	5
V	271	238	237	297	289	240	251	96
Cr	268	160	770	765	350	650	825	9
Co	123	45	63	70	56	89	99	60
Ni	73	102	304	362	173	497	356	32
Cu	82	69	109	70	37	65	76	108
Zn	110	118	110	128	139	100	117	115
Y	27	26	21	23	27	21	19	31
Zr	178	136	150	228	299	152	191	239
Nb	31	21	27	44	63	43	42	76
La	23.0	14.0	18.9	31.2	45.9	25.4	27.2	49.4
Ce	47.9	31.4	41.3	68.3	97.2	55.0	61.3	105.7
Nd	27.1	18.8	22.4	35.7	47.8	27.0	30.5	51.8
Sm	6.51	5.03	5.51	7.67	9.65	5.99	6.22	9.72
Eu	2.10	1.72	1.78	2.36	2.90	1.98	1.97	3.25
Tb	0.98	0.93	0.82	0.98	1.31	0.91	0.83	1.40
Yb	1.72	1.83	1.39	1.29	1.62	1.36	1.28	2.18
Lu	0.27	0.29	0.23	0.20	0.25	0.20	0.19	0.29
Hf	4.5	3.6	4.0	5.5	6.9	3.4	4.4	4.3
Th	2.5	1.4	1.9	3.3	5.2	3.2	3.2	5.8

TH = tholeiites; AB = alkali basalts; BSN = basanites; PT = phonolitic tephrites, PF = phonolitic foidites. $[Mg] = (Mg/Mg + Fe^{2+})$ with Fe^{3+}/Fe^{2+} assumed to 0.15. Ne_{nor} = normative nepheline. Hy_{nor} = normative hypersthene. W-1: $La = 10.7$, $Ce = 22.8$, $Nd = 14.8$, $Sm = 3.29$, $Eu = 1.06$, $Tb = 0.60$, $Yb = 2.05$, $Lu = 0.34$

to Rimatara located to the northwest. The latter island has a minimum age in excess of 21 m.y. (Turner and Jarrard 1982). On the basis of these ages, a hotspot origin for these islands was proposed (Dalrymple et al. 1975; Duncan and McDougall 1976). However, this age progression is far from regular especially at Rurutu where several groups of ages (1.1–1.9, 8.4 and 11.7–12.2 m.y.) have been obtained (Duncan and McDougall 1976) and at Tubuai where volcanic activity appears to span several millions of years (Bellon et al. 1980). At least two hotspots, aligned with the direction of the Pacific plate movement, would be required in order to explain the observed jumps in ages in these islands. The age pattern can also be explained by the activities of randomly distributed immature mantle plumes in that region (Barsczus 1980; Keating et al. 1982). If different plumes tap different mantle reservoirs, rocks with varying isotopic and geochemical features which are not in accordance with the general age progression predicted by the hotspot theory may be observed in the same island or among different islands.

Petrography and mineralogy

Descriptions of the petrography and mineralogy for most of the islands have been prevously given by Lacroix (1927, 1928), Smith and Chubb (1927), Jeremine (1959), Aubert de la Rue (1959), Mottay (1976), Maury et al. (1978), Brousse and Maury (1980) and Berger (1985). In general, the rocks closely resemble volcanic suites from Tahiti and Hawaii. The dominant rock type is olivine basalts associated with subordinate and variable amounts of differentiated rocks such as phonolites and trachytes particularly in Tubuai, Raivavae and Rapa. Coarse-grained rocks have also been described from the MacDonald seamount (Brousse and Richer des Forges 1980) and Rapa (Chubb, 1927).

Rapa				
RA-07	RPA-031	RPA-071	RPA-014	RA-24
3654	7263	7266	7260	3657
TH	AB	AB	AB	BSN
45.20	44.10	44.20	43.90	44.23
12.50	11.00	11.78	12.23	14.43
12.63	12.74	13.02	12.65	13.83
0.15	0.15	0.16	0.16	0.15
11.15	14.65	12.66	11.59	7.22
8.83	10.24	9.47	10.00	8.12
2.24	1.85	2.06	2.41	3.56
1.10	0.87	1.10	1.18	1.97
3.46	2.88	3.22	3.37	4.18
0.76	0.48	0.62	0.71	0.97
2.53	0.96	1.00	1.48	1.76
100.55	99.92	99.29	99.68	100.42
0.66	0.72	0.69	0.67	0.54
–	1.8	0.6	3.4	6.5
7.2	–	–	–	–
4	7	7	8	11
25	22	24	28	38
765	548	757	743	1070
315	242	330	349	500
19	24	20	21	14
223	212	214	206	226
346	576	384	340	168
77	71	64	64	61
266	285	250	217	128
44	58	56	65	50
134	110	119	122	162
22	21	23	25	26
270	202	253	279	397
49	39	48	55	74
37.2	26.4	34.0	38.2	56.3
85.5	60.2	76.3	89.6	129.3
42.3	31.3	39.9	47.1	64.5
8.18	6.33	7.56	8.59	11.51
2.66	2.03	2.47	2.84	3.68
1.17	0.90	1.01	1.23	1.49
1.35	1.20	1.26	1.43	1.31
0.19	0.18	0.17	0.22	0.18
6.2	4.4	5.3	6.2	9.00
4.3	3.1	3.8	4.6	7.0

Olivine basalts have either subaphyric, hyalophilic or porphyritic textures with phenocrysts of olivine (Fo 75–88) and clinopyroxene which has frequent oscillatory or sector zoning and highly variable core compositions (diopside – salite – augite). Phenocrysts of plagioclase (labradorite) occur in some tholeiites from Raivavae and MacDonald.

The groundmass of the basalts contains olivine, clinopyroxene, Fe – Ti oxides, plagioclase, phlogopite and some glassy interstitial patches. At Tubuai, some basic rocks lack plagioclase but are characterized by the presence of phenocrysts of salitic pyroxene, sodic sanidine and nepheline as well as xenocrysts of olivine (Brousse and Maury 1980). In some clinopyroxenes, the core of augitic composition is embedded in a green mantle rich in Na which in turn is rimmed by a pink Ti-rich zone. Such a complex zoning is typical of strongly undersaturated rocks and suggests mixing between differentiated magma and a venue of fresh primitive magma within a magmatic chamber (Duda and Schmincke 1985). Their groundmass consists of anorthositic plagioclase, noseane-sodalite feldspathoid and phlogopite in addition to the phases present as phenocrysts. The strongly undersaturated rocks correspond to murite described by Lacroix (1927). These rocks contain abundant xenoliths mainly of lherzolites (Berger 1981) and apatite-rich pyroxenites. Other strongly undersaturated rocks from Tubuai contain only phenocrysts of salitic pyroxene embedded in a groundmass of microcrysts of olivine, Fe – Ti oxide and abundant interstitial potassic analcime (Brousse and Maury 1980). Most samples have aphyric textures with the exception of TBA-120 which contains phenocrysts of olivine and pyroxene.

Analytical methods

From a suite of more than 300 samples collected between 1978 and 1981, about 130 were selected on the basis of freshness and analyzed for major elements and Li, Rb, Sr, V, Cr, Co, Ni, Cu and Zn by atomic absorption. From this set, 68 were further analyzed for Y, Zr, Nb and Ba by X-ray fluorescence and for rare earth elements (REE), Sc, Hf and Th by instrumental neutron activation. The precision and accuracy of the trace element analyses have been discussed elsewhere (Dostal et al. 1986). In general, the precision of the trace element data is better than 5%. Thirty-one selected analyses are reported in Table 1. The complete set of data can be obtained on request from the authors.

Geochemistry

Major elements

According to normative compositions, the predominant rock types on all of the islands are alkali basalts (AB) and
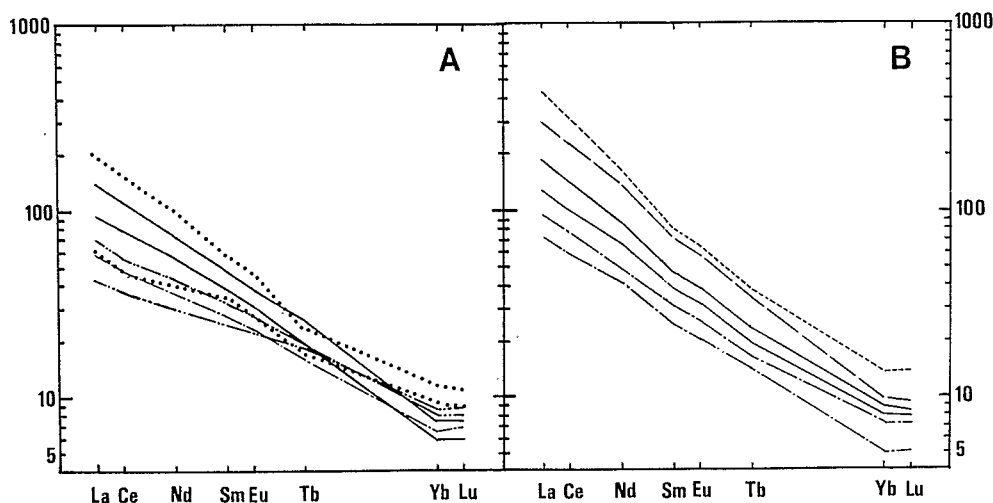

Fig. 2A, B. Chondrite-normalized REE abundances in the lavas from MacDonald (A) and Tubuai (B). Olivine tholeiites – *dashed double dotted line;* alkali basalts – *dashed dotted line;* basanites – *solid line;* phonolitic tephrites – *long dashed line;* phonolitic foidites – *short dashed line;* range of lavas from Marquesas Islands (Liotard et al. 1986) – *dotted lines*

Table 1 (continued)

	Raivavae			Tubuai				
	RVV-124 7276 TH	RVV-130 7277 TH	RVV-139 7279 AB	TBA-001 7280 AB	TBA-036 7288 AB	TBA-102 7290 BSN	TBA-023 7286 BSN	TBA-120 7301 PT
SiO_2	47.37	47.37	44.86	42.72	44.30	43.12	41.94	40.46
Al_2O_3	11.30	11.57	10.27	7.08	9.80	10.30	11.12	12.00
Fe_2O_3	12.64	12.10	13.44	13.48	13.18	13.88	14.60	16.28
MnO	0.14	0.14	0.16	0.18	0.18	0.20	0.19	0.23
MgO	14.04	12.52	15.73	19.27	13.81	11.77	11.25	8.82
CaO	8.10	9.13	9.98	12.16	11.73	13.06	11.80	11.73
Na_2O	2.39	2.34	2.20	0.65	1.51	2.07	2.60	4.45
K_2O	0.63	0.66	0.65	0.18	0.70	0.50	0.80	1.16
TiO_2	1.96	2.16	2.13	1.88	2.22	2.58	2.86	3.14
P_2O_5	0.32	0.36	0.37	0.26	0.41	0.47	0.59	0.94
L.O.I.	1.19	1.22	0.42	2.12	1.57	1.40	1.68	0.13
Total	100.08	99.57	100.21	99.98	99.41	99.35	99.43	99.34
[Mg]	0.71	0.70	0.73	0.76	0.70	0.65	0.63	0.55
Ne_{nor}	–	–	3.2	0.5	1.0	6.1	9.6	20.9
Hy_{nor}	11.0	10.6	–	–	–	–	–	–
Li (ppm)	5	5	5	5	6	7	10	13
Rb	10	13	18	5	18	17	18	43
Sr	321	395	478	272	462	538	683	1040
Ba	145	193	249	153	226	298	419	643
Sc	21	25	24	42	34	37	28	20
V	206	224	234	262	249	276	257	239
Cr	604	564	758	1281	973	594	350	211
Co	69	59	75	87	70	65	64	59
Ni	367	284	437	409	280	204	198	134
Cu	74	77	81	89	115	140	106	105
Zn	114	109	121	96	100	118	131	166
Y	21	21	21	18	23	25	30	35
Zr	137	150	156	117	169	195	259	389
Nb	28	34	46	32	47	57	82	126
La	18.7	21.9	30.4	22.9	30.5	40.5	58.7	94.0
Ce	39.6	48.3	65.5	49.1	64.5	83.7	118.8	190.1
Nd	19.7	25.6	29.9	25.4	30.0	40.8	53.0	84.8
Sm	4.65	5.34	5.85	4.81	6.04	7.49	9.12	13.94
Eu	1.56	1.81	1.85	1.54	1.92	2.37	2.91	4.31
Tb	0.73	0.86	0.86	0.71	0.82	0.98	1.15	1.78
Yb	1.13	1.17	1.26	1.07	1.54	1.72	1.91	2.10
Lu	0.16	0.18	0.18	0.17	0.24	0.26	0.28	0.31
Hf	3.2	3.4	3.5	3.2	3.9	4.6	5.9	8.3
Tb	2.3	2.6	3.7	3.0	3.9	5.2	8.5	13.0

basanites (BSN) (normative nepheline > 5%). Olivine tholeiites (OT) are less frequent and have been reported only from MacDonald and Raivavae islands (Barsczus and Liotard 1985a, b). The strongly undersaturated rocks (normative nepheline 19%–30%) which occur only on Tubuai, have the highest contents of Na and K. According to the classification of Streckeisen (1967), the strongly undersaturated rocks containing nepheline phenocrysts correspond to phonolite foidites (PF) whereas the nepheline phenocryst-free samples are phonolite tephrites (PT). The rocks with modal nepheline have higher contents of Na, K and P.

Compared to the Marquesas Islands rocks (Liotard et al. 1986), the lavas from the Austral Islands are generally lower in SiO_2 and have a higher proportion of undersaturated rocks. The contents of Na, K, P and Ti are similar in equivalent rocks of both chains except for tephrites and foidites from Tubuai which show high contents of Na, K and P and low contents of Ti. However, the Na_2O/K_2O ratio is significantly higher in samples from the Austral Islands ranging from 5.2 in OT to 2.9 in BSN compared to 3.0 to 1.8 for equivalent samples from the Marquesas Islands.

Incompatible trace elements

The chondrite-normalized REE patterns of all analyzed samples from the Austral Islands show an enrichment of light REE (LREE) and fractionation of heavy REE (HREE) (Fig. 2) with La/Yb between 9 in OT and 48 in PT. On Tubuai, the REE content increases with increasing silica-undersaturation but the slope of the REE patterns remains the same. On the other hand, at MacDonald seamount, this increase is limited to the LREE resulting in steeper slope of the REE pattern.

Like the LREE, the other incompatible elements (IE) increase with degree of undersaturation, reaching the high-

Tubuai			Rurutu				Rimatara		
TBA-017 7285 PT	TBA-035 7287 PF	TBA-107 7294 PF	RRT-130 7329 AB	RRT-042 7319 BSN	RRT-037 7317 BSN	RRT-013 7309 BSN	RMT-003 7330 AB	RMT-012 7334 BSN	RMT-008 7332 BSN
42.13	41.54	41.35	43.65	45.09	44.62	43.55	44.80	41.92	45.10
14.49	12.25	12.54	10.20	13.78	13.75	14.36	11.50	14.20	13.35
14.60	15.30	15.70	13.60	12.75	12.87	14.70	13.30	17.06	14.64
0.21	0.26	0.27	0.18	0.18	0.18	0.20	0.17	0.23	0.18
5.41	8.19	7.65	12.42	7.33	7.40	7.03	11.80	6.10	5.14
11.10	9.23	9.43	12.00	12.95	13.05	8.77	10.45	7.60	12.10
4.72	6.10	6.22	1.70	2.78	2.80	4.33	2.08	4.70	2.28
1.42	1.51	1.62	0.60	0.55	0.55	1.30	1.70	1.62	2.53
3.20	2.83	2.88	2.74	2.78	2.82	3.31	3.23	4.00	3.04
0.89	1.05	0.94	0.42	0.37	0.37	1.20	0.54	1.25	0.49
1.40	0.78	0.93	1.59	0.83	0.76	0.27	0.10	0.47	0.21
99.57	99.04	99.53	99.10	99.39	99.17	99.02	99.67	99.15	99.06
0.45	0.55	0.52	0.67	0.56	0.56	0.52	0.67	0.45	0.44
19.5	27.8	29.4$^+$	1.9	5.2	6.1	10.8	3.8	13.8	6.9
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13	21	21	9	6	6	9	7	12	7
52	62	59	17	13	14	29	32	40	28
968	1460	1525	443	472	475	1098	701	1059	468
620	884	905	225	182	191	442	423	472	203
15	16	16	42	37	37	15	24	14	34
233	169	165	280	345	339	196	275	198	335
9	168	136	681	338	328	121	423	13	29
44	47	47	68	51	52	57	63	51	56
51	112	98	219	88	86	93	260	31	61
108	70	75	161	94	98	70	68	75	83
159	183	178	137	100	99	142	133	168	104
38	46	45	25	25	23	42	28	42	29
361	504	515	208	183	188	383	301	439	222
126	189	189	45	36	34	84	44	101	44
89.1	137.7	144.6	33.6	26.2	26.2	68.9	37.4	77.9	33.0
177.2	263.4	275.1	71.6	56.9	56.4	149.2	84.0	163.4	73.0
74.8	100.5	103.9	34.7	29.8	29.8	73.8	43.5	77.8	36.7
12.37	15.48	16.09	7.32	6.28	6.28	14.29	9.58	14.28	7.90
3.83	4.82	5.04	2.31	2.13	2.09	4.39	2.96	4.35	2.55
1.59	1.85	1.96	0.87	0.81	0.80	1.48	1.07	1.48	0.97
2.59	2.88	3.11	1.69	1.64	1.71	2.73	1.70	2.88	2.18
0.39	0.45	0.47	0.28	0.26	0.27	0.39	0.24	0.42	0.34
7.6	9.1	9.7	4.7	4.3	4.3	7.6	6.5	8.8	5.2
13.1	22.5	23.3	3.8	2.9	2.9	6.9	4.5	8.2	3.6

est values in PT of Tubuai. On some of the islands (Raivavae, MacDonald), this increase is accompanied by constant IE ratios (e.g. Th/La, Nb/La) suggesting that AB and BSN are derived from the same source rocks by variable degrees of partial melting. On other islands (Marotiri, Rimatara), these ratios differ in various rock types and imply derivation from different sources. Such a variability of source composition may also be found on a single island and for a single rock type. For example, BSN from Tubuai with equivalent [Mg] ratios (Mg/Mg + Fe^{2+} with Fe^{3+}/Fe^{2+} = 0.15) have variable contents of IE associated with different values of their corresponding ratios (e.g. K/Ba = 13 to 22, Th/La = 0.13 to 0.17). However, the largest variations are encountered among the islands. On rectangular plots such as Sr—Ce, P-Ce and Nb—Zr (Fig. 3) the samples display a positive correlation and Tubuai is clearly distinct from the other islands because of its relative enrichment of Nb and depletion of P and Sr. Also on this island, the P$_2$O$_5$/Ce ratio

decreases from 58 in alkali basalts to 38 in the most undersaturated rocks suggesting an increase of residual apatite with the decrease of the degree of partial melting as suggested for the Hawaiian nephelinite (Clague and Frey 1982). Other differences among basaltic rocks from the various islands appear when the ratios of the most incompatible elements are considered: the Nb/La and Th/La ratios are higher while Ba/La is generally lower on Rapa, Tubuai and Raivavae islands. In fact, the Ba/La and Ba/Nb ratios are the only ratios which decrease geographically from MacDonald and Marotiri islands in the southeast to Rimatara in the northwest.

In addition to their REE patterns, the Austral Islands basalts have contents of several other incompatible elements similar to those of the Marquesas Islands and other OIB (Liotard et al. 1986). This is also apparent in Fig. 3 which depicts Ce vs P$_2$O$_5$. In spite of the large variations, the basalts from the Austral Islands plot in the field for OIB
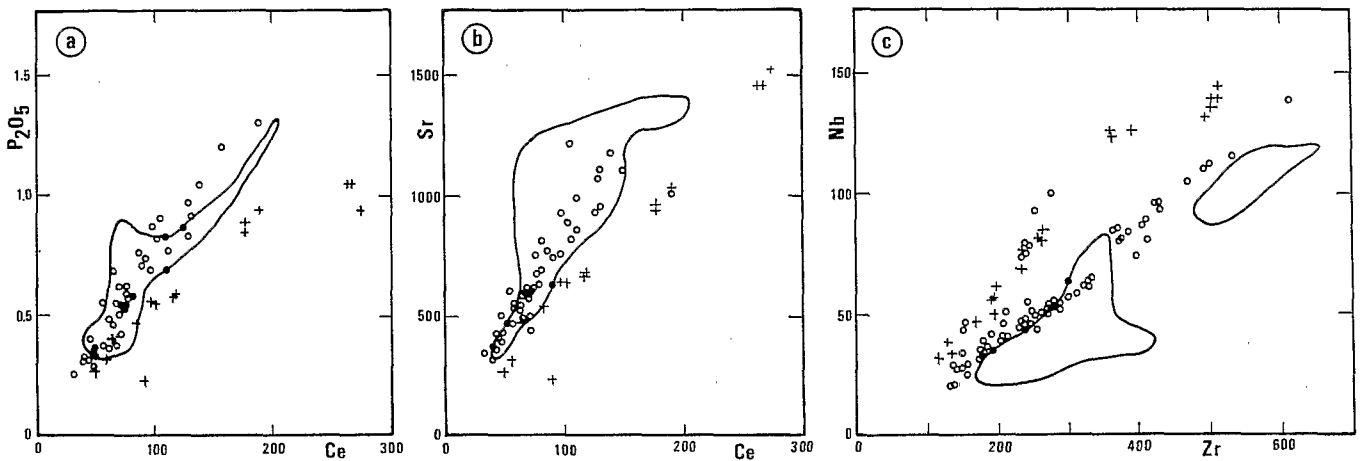
Fig. 3A–C. Variations of P_2O_5 vs Ce, Sr vs Ce and Nb vs Zr in lavas from the Austral Islands. Tubuai – *crosses;* other Austral Islands – *open circles. Solid line* delineates the field of Marquesas Islands rocks (Liotard et al. 1986). Ce, Sr, Zr and Nb concentrations are in ppm; P_2O_5 is in %
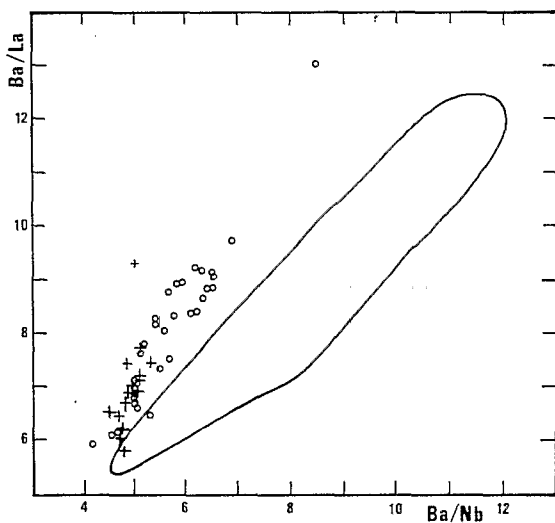

Fig. 4A–D. Variations of Ba/La vs Ba/Nb ratios in lavas from the Austral Islands. Symbols are the same as in *Fig. 3*

from other oceanic islands. However, these rocks also display some distinct characteristics. Basalts from the Austral Islands have distinctly lower Ba/La, Ba/Nb (Fig. 4) and Rb/Ce as well as higher Nb/La and Nb/Zr ratios than many other OIB. Unlike the OIB from the Marquesas, the chondrite-normalized IE patterns of these rocks (Fig. 5) display a relative depletion of alkali (K, Rb) and alkali earth (Ba, Sr) elements compared to other IE. This depletion is particularly marked on Tubuai. The exceptions are some AB from Marotiri with $(Ba/La)_N > 1$ (N-chondrite-normalized) and from Rimatara with $(Ba/La)_N \sim 1$. The latter pattern with the high Ba/La ratio is common in basalts from the Marquesas Islands whereas the former Austral Islands pattern with $(Ba/La)_N < 1$, is rare in the Marquesas and is encountered only on the island of Ua Pou. Both archipelagos also differ in their isotopic data; compared to the Marquesas, the Austral Islands basalts have lower $^{87}Sr/^{86}Sr$ ratios for a given ε_{Nd} and, in the case of Tubuai, these values are close to those from St. Helena (Vidal et al. 1984).

Transition elements

While the variations in IE are mainly related to the magmatic type, the transition element contents vary mostly with the degree of differentiation. Ni, Cr and Co decrease while Zn and V increase toward the more differentiated rocks without showing any significant difference according to magmatic type, except in the case of the latter two elements. For a given [Mg] ratio, the contents of Zn and V of OT from MacDonald are lower than in coexisting BSN suggesting that both elements behave as IE during the partial melting process. In addition, OT from MacDonald show higher Cu/Zn and lower Ti/V ratios compared to the more undersaturated rocks. The Ti/V ratio displays large variations (45–105) which might be related to the geographical distribution of the islands; in AB and BSN, the lowest values are encountered in the northern islands (Rurutu, Tubuai, Raivavae). This distribution probably reflects the heterogeneity of their upper mantle sources.

The variation of Ni vs. MgO also shows different patterns according to island. For MacDonald and Raivavae islands (Fig. 6A) the suite displays a relatively sharp decrease of Ni with respect to MgO suggesting fractionation dominated by olivine and to a lesser extent by pyroxene. However, for Rapa and especially for Tubuai (Fig. 6B), these two elements show a trend roughly subparallel but quite different from that of a liquid produced by partial melting of the pristine upper mantle (Hart and Davis 1978). In these two islands, such a relationship between Ni and MgO indicates either different minerals involved in fractionation (probably clinopyroxene) or their derivation from the melting of different sources.

Discussion

The large variations of large-ion-lithophile elements (LILE) and the corresponding element ratios indicate that the lavas were derived from a heterogeneous mantle source; such a heterogeneity is common to oceanic island basalts particularly in French Polynesia (Duncan and Compston 1976; Vidal et al. 1984). Although the basalts from the Austral Islands display geochemical features similar to those of other OIB, they have some distinct trace element and
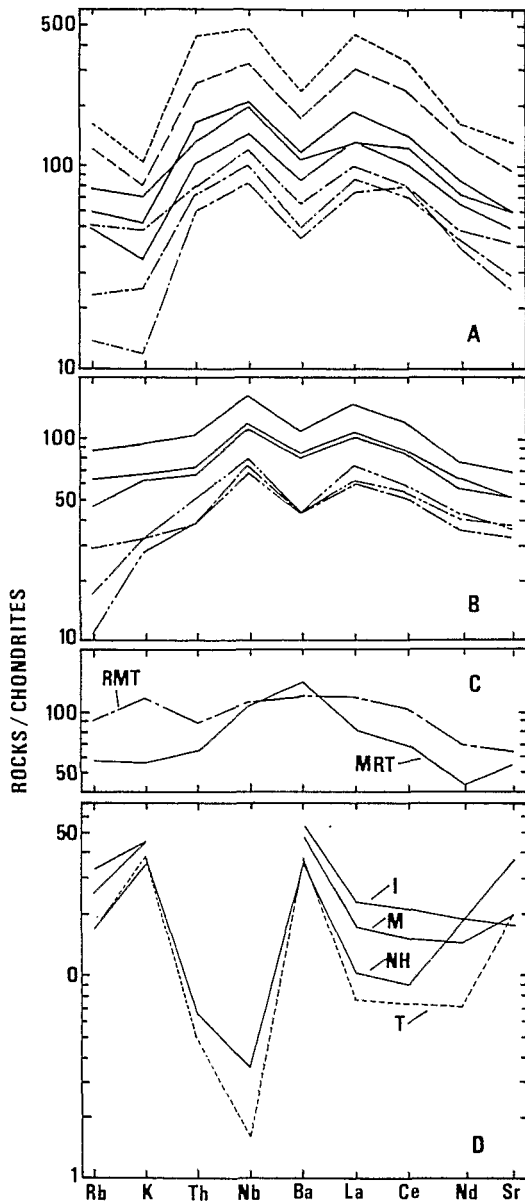
Fig. 5A–D. Chondrite-normalized abundances of highly incompatible elements in the basaltic rocks of the Austral Islands (A–C) and various island arcs (D). A – Tubuaí, B – MacDonald, C – Rimatara and Marotiri. The symbols are the same as in *Fig. 2.* *RMT* – Rimatara, *MRT* – Marotiri, *T* – Tonga (Ewart et al. 1973), *M* – Marianas (White and Patchett 1984), *I* – Izu (White and Patchett 1984), *NH* – New Hebrides (Dupuy et al. 1982)

two components, one of which should have Ba/La <6, Ba/Nb <4, to produce the data reported on Fig. 5.

In the Austral Islands as in other intraplate oceanic islands, isotopic and trace element data indicate a long-term depletion of the source and a subsequent IE enrichment. This complex genesis of OIB has been discussed by Ringwood (1982, 1986) who suggested a geochemical relationship between intraplate basaltic magma and magma erupted above a subduction zone. Such a relationship, already inferred from the isotopic data (Morris and Hart 1983; White and Patchett 1984) is supported by the distribution of trace elements (Fig. 5). The basalts of the Austral Islands and island arc tholeiites (IAT) display antipathic trace element patterns which are especially marked for K, Rb, Sr and Ba. This also applies to the high field strength (HFS) elements when considering ratios such as Nb/La or Hf/Lu (Table 2). These ratios are significantly higher in the Austral Islands basalts and lower in IAT than in MORB. Otherwise OIB and IAT have, as suggested by White and Patchett (1984), many IE ratios similar to MORB. The pattern in Fig. 5 indicates that the elements enriched in IAT are depleted from OIB source rocks and conversely, the elements lost from IAT are gained by OIB. Such discrepancies may be explained if it is assumed that the upper mantle source of the Austral Islands basalts have incorporated pieces of subducted lithosphere which had already undergone partial melting generating IAT at a previous stage. In addition, the Ni – MgO relationship strongly supports the presence of some basaltic components in the source of the Austral basalts.

The linear evolution with a smooth variation of Ni relative to MgO displayed by basalts from Tubuai and Rapa (Fig. 6B) could suggest a fractionation process dominated by clinopyroxene crystallization. Although some clinopyroxene cumulation is obvious from the thin section observation in the samples with MgO >12%, such a process cannot explain all the geochemical data. For example, in the AB with MgO ~11%, 80% of clinopyroxene fractionation would be required to generate the IE content of PF observed at Tubuai. This implies a strong depletion of Cr and Sc which is not found in these rocks. In addition, the rocks from Tubuai have variable Th/La ratios which correlate with the Ni/MgO ratios if the four samples with [Mg] values <0.55 are excluded (Fig. 7). Thus, such a correlation is probably the result of a mixing process.

The abundances of Ni also argue against the derivation of the basaltic rocks from the normal upper mantle. According to the partition coefficients of Hart and Davis (1978) for Ni in upper mantle phases, the partial melting of a primitive upper mantle containing 2000 ppm of Ni should produce a liquid in the range indicated by lines A and B of Figure 6. However, the lower Ni contents in the liquid probably require a source with lower Ni than that of the upper mantle. Such a depletion of Ni in the source can be obtained by mixing upper mantle rocks with a basaltic component of eclogitic composition. On Figure 6, line D corresponds to a liquid produced by partial melting of a mixed source composed of 20% garnet lherzolite and 80% basalt. However, this line remains slightly divergent from the trend displayed by the basalts from Tubuai and Rapa. The discrepancy may be accounted for by an increase of the basaltic component in the source from 80% for AB with higher Ni contents to 90% for PT and PF which have lower Ni contents. In fact, the petrogenetic process is prob-
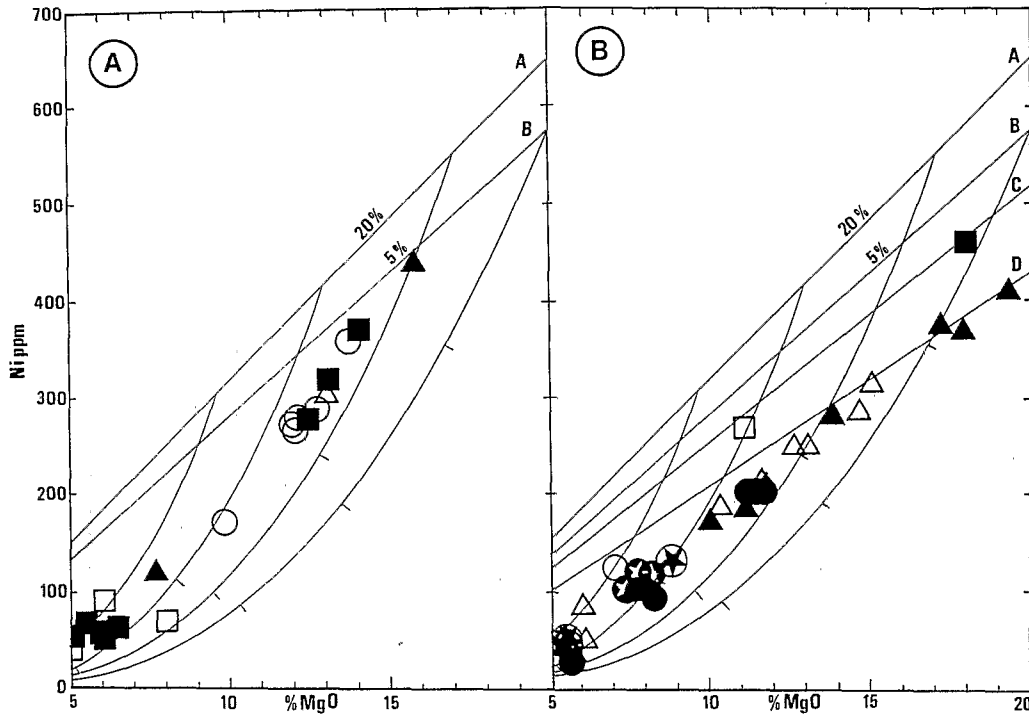
isotope characteristics. The trace element patterns (Fig. 5) with a relative depletion of K, Rb and Ba may partially reflect the influence of a K-rich phase, such as phlogopite, as a residue during partial melting or as a mineral phase during fractional crystallization. However, such fractionation does not account for most of the other geochemical features of the patterns such as the relative depletion of Sr and the low Sr/Ce and high Nb/La ratios. Furthermore, several ratios involving the most incompatible elements, when plotted against each other (e.g. Ba/La vs Ba/Nb), show a significant positive correlation (Fig. 4) despite some dispersion. These variations suggest that the heterogeneities of this source may be the result of mixing between at least

Fig. 6A, B. Variations of Ni vs MgO in samples from the Austral Islands. **A:** *Open symbols* – MacDonald; *solid symbols* – Raivavae; **B:** *Open symbols* – Rapa; *solid symbols* – Tubuai; *Squares:* olivine tholeiites; *triangles:* alkali basalts; *circles:* basanites; *solid star in open circles:* phonolitic tephrites; *open star in solid circles:* phonolitic foidites. Lines **A** and **B** represent liquids produced by batch partial melting (20 and 5% respectively) of an upper mantle. Lines C and D correspond to liquids produced by 5% of batch melting of a source composed of upper mantle and respectively 50% and 80% of a basaltic component (50% Cpx and 50% Grt with 100 ppm Ni). Parameters of melting:

	C_o^{Ni}	X^{OL}	X^{OPX}	X^{CPX}	X^{GT}	P^{OL}	P^{OPX}	P^{CPX}	P^{GT}
Lines A, B	2000	0.57	0.17	0.12	0.14	0.57	0.17	0.12	0.14
Line C	1050	0.28	0.08	0.32	0.32	0.05	0.10	0.45	0.40
Line D	480	0.11	0.03	0.43	0.43	0.05	0.10	0.45	0.40

X – weight fractions of a phase in the source; P – proportion of a phase in the melt; C – concentration in upper mantle source; Partition coefficients of Ni after Hart and Davis (1978) and Dupuy et al. (1980)

Table 2. Average ratios of incompatible elements in Austral Islands rocks and island arc tholeiites

		n	Ba/La	K/Th $\times 10^{-3}$	Sr/Ce	Nb/La	Hf/Lu	Ba/Rb	Th/La
Austral Islands									
Tubuai	AN	3	6.9	0.9	5.5	1.5	17	21	0.131
	BSN A	2	7.2	0.8	5.7	1.4	21	21	0.145
	BSN B	1	9.3	1.2	6.4	1.9	14	14	0.167
	PT	3	6.9	0.8	5.4	1.4	21	13	0.144
	PF	3	7.2	0.6	5.5	1.3	21	14	0.160
Rimatara	AB	1	11.3	3.1	8.3	1.2	27	13	0.120
	BSN	3	6.1	1.6	7.1	1.3	17	12	0.108
MacDonald	TH	2	7.9	2.1	10.2	1.5	13	25	0.101
	AB	1	8.0	2.0	8.9	1.4	18	25	0.103
	BSN	6	8.8	2.2	8.1	1.4	27	15	0.106
Island Arc Tholeiites									
New Hebrides		9	36	4.9	60	0.3	5	17	0.110

Abbreviations are the same as in *Table 1*; n = number of samples. The variations of these ratios in rocks from the other islands are within the range of Tubuai and MacDonald. The data for New Hebrides are from Dupuy et al. (1982)
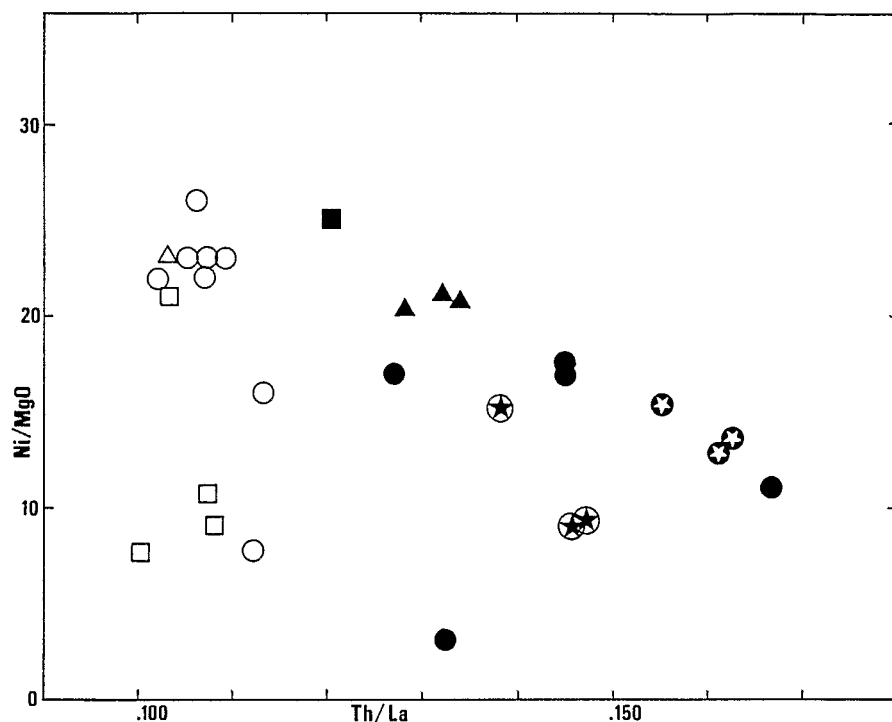
Fig. 7. Variations of Ni/MgO vs Th/La in rocks of the MacDonald (*open symbols*) and Tubuai islands (*full symbols*). The Tubuai basalts show a distinct negative correlation with the exception of three differentiated ([Mg] 0.5) samples which have low Ni/MgO ratios. The other islands including MacDonald do not show such a correlation

ably more complex. For example, a polybaric melting of the two component sources involving variable degrees of melting and variable proportions of fused minerals followed by mixing between the two end members may be also proposed.

Conclusion

The basalts of the Austral Islands possess geochemical characteristics of OIB including their high content of LILE and distinctly fractionated REE patterns. However, these rocks have some distinct geochemical traits displayed by their chondrite-normalized IE patterns with a relative enrichment of Nb and a relative depletion of K, Rb, Ba and Sr in most of the samples.

The large variations of LILE abundances and IE ratios not only among various rock types but even within a single rock-type from the same island suggest the existence of a heterogeneous upper mantle. In the Austral Islands the observed trace element heterogeneities of the upper mantle which corroborate the isotopic heterogeneities (Vidal et al. 1984) may be related to a megalithic source (Ringwood 1982) which contained variable amounts of a former oceanic crust strongly depleted in alkali and alkali-earth elements. According to such a model, subducted oceanic crust, residual after extraction of IAT, was incorporated into the upper mantle to form the megalith. However, the imprint of the characteristics of the former oceanic crust is highly variable depending on the degree of IAT extraction, residence time in the mantle, and the relative proportions of the oceanic crust and upper mantle in the megalith.

References

Aubert de la Rüe E (1959) Etude géologique et prospection minière de la Polynésie Française. Insp Gén Mines et Géol Paris:7–43

Barsczus HG (1980) Les Iles Australes (Polynésie Française) et la théorie des points chauds. Notes et Doc (Géophys) Centre ORSTOM de Papeete/Tahiti 80/27:1–15

Barsczus HG, Liotard JM (1985a) Géochimie des laves du volcan sous-marin MacDonald, Polynésie Française (Océan Pacifique Sud): coexistence de tholeiites à olivine, de basaltes alcalins et de basanites. CR Acad Sci Paris Sér II 300:915–918

Barsczus HG, Liotard JM (1985b) Contribution à la connaissance pétrographique et géochimique de l'île de Raivavae (Polynésie Française, Océan Pacifique Centre-Sud). CR Acad Sci Paris Sér II 301:1409–1412

Basaltic Volcanism Study Project (1981) Basaltic volcanism on the terrestrial planets. Pergamon Press, p 1296

Bellon H, Brousse R, Pantaloni A (1980) Age de l'île de Tubuai. L'alignement des Australes et des Cook. Cah Indo-Pacif 2:219–240

Berger ET (1981) Enclaves ultramafiques, mégacristaux et leurs basaltes hôtes en contexte océanique (Pacifique Sud) et continental (Massif Central). Thèse d'Etat Paris-Orsay, p 470

Berger ET (1985) Hétérogénéités pétrographiques du manteau sud-pacifique sous l'Archipel des Australes: mise en évidence et interprétation par l'étude des enclaves ultramafiques. Bull Soc Géol Fr 8:207–216

Brousse R, Richer des Forges B (1980) Les laves alcalines et différenciées du volcan sousmarin MacDonald (Australes – Pacifique). CR Acad Sci Paris Sér D 290:1055–1057

Brousse R, Maury R (1980) Volcanisme et pétrologie de l'île de Tubuai dans les Iles Australes (Pacifique Sud) Cah Indo-Pacif 2:131–193

Chase CG (1981) Oceanic Island Pb: Two-Stage Histories and Mantle Evolution. Earth Planet Sci Lett 52:277–284

Chen CY, Frey FA (1983) Origin of Hawaiian tholeiites and alkalic basalt. Nature 302:785–789

Clague DA, Frey FA (1982) Petrology and trace element geochemistry of the Honolulu volcanics, Oahu: Implications for the oceanic mantle below Hawaii. J Petrol 23:447–504

Chubb LJ (1927) The geology of the Austral or Tubuai Islands (southern Pacific). Quart J Geol Soc London 83:291–316

Dalrymple GB, Jarrard RD. Clague DA (1975) K—Ar ages of some volcanic rocks from the Cook and Austral Islands. Geol Soc Am Bull 86:1463–1467

Dostal J, Dupuy C, Liotard JM (1982) Geochemistry and origin of basaltic lavas from Society Islands, French Polynesia (South Central Pacific Ocean) Bull Volcanol 45:51–62

Dostal J, Baragar WRA, Dupuy C (1986) Petrogenesis of the Nat-kusiak continental basalts, Victoria Island, Northwest Territories, Canada. Can J Earth Sci 23:622–632

Duda A, Schmincke HU (1985) Polybaric differentiation of alkali basaltic magmas: evidence from green-core clinopyroxenes (Eifel, FRG) Contrib Miner Petrol 91:340–353

Duncan RA, McDougall I (1976) Linear volcanism in French Polynesia. J Volcanol Geotherm Res 1:197–227

Duncan RA, Compston W (1976) Sr-isotope evidence for an old mantle source region for French Polynesian volcanism. Geology 4:728–732

Duncan RA, Clague DA (1985) Pacific plate motion recorded by linear volcanic chains. In: Nairn AE, Stehli FG, Uyeda S (eds) The Ocean Basins and Margins. Plenum Publ Corp, vol 7A, pp 89–121

Dupuy C, Dostal J, Liotard JM, Leyreloup A (1980) Partitioning of transition elements between clinopyroxene and garnet. Earth Planet Sci Lett 48:303–310

Dupuy C, Dostal J, Marcelot G, Bougault H, Joron JL, Treuil M (1982) Geochemistry of basalts from central and southern New Hebrides arc: implication for their source rock composition. Earth Planet Sci Lett 60:207–225

Ewart E, Bryan WB, Gill JB (1973) Mineralogy and geochemistry of the younger volcanic islands of Tonga, SW Pacific. J Petrol 14:429–465

Hart SR, Davis K (1978) Nickel partitioning between olivine and silicate melt. Earth Planet Sci Lett 40:203–219

Hofman AW, White WM (1980) The role of Subducted Oceanic Crust in Mantle Evolution. Carnegie Inst of Washington, Yearbook 79:477–483

Hofmann AW, White MW (1982) Mantle plumes from ancient oceanic crust. Earth Planet Sci Lett 57:421–436

Jeremine E (1959) Sur quelques laves de l'île de Raivavae. Bull Volcanol 21:117–125

Keating B, Naughton J, Epp D, Barsczus HG (1983) Tectonic history of the Austral – Tubuai and Southern Cook Islands. 18th Gen Ass IUGG, Hamburg, FRG, 1983, IUGG Interdisciplinary Symp Progr and Abstr, vol 1:276

Krummenacher D, Noetzlin J (1966) Ages isotopiques K—Ar de roches prélevées dans les possessions françaises du Pacifique. Bull Soc Géol Fr 8:173–175

Lacroix A (1927) La constitution lithologique des îles volcaniques de la Polynésie Australe. Mém Acad Sci Paris 59:1–82

Lacroix A (1928) Nouvelles observations sur les laves des îles Marquises et de l'île de Tubuai. CR Acad Sci Paris 187:365–369

Liotard JM, Barsczus HG, Dupuy C. Dostal J (1986) Geochemistry and origin of basaltic lavas from Marquesas Archipelago, French Polynesia. Conbrib Mineral Petrol 92:260–268

Mammerickx J, Anderson RN, Menard HW, Smith SM (1975) Morphology and tectonic evolution of the east central Pacific. Bull Geol Soc Am 86:111–118

Matsuda JI, Notsu K, Okano J, Yaskawa K, Chungue L (1984) Geochemical implications from Sr isotopes and K—Ar age determinations for the Cook-Austral Islands chain. Tectonophysics 104:145–154

Maury R, Andriambololona R, Dupuy C (1978) Evolution comparée de deux séries alcalines du Pacifique Central: rôle de la fugacité d'oxygène et de la pression d'eau. Bull Volcanol 41:1–22

Morris JD, Hart SR (1983) Isotopic and incompatible element constraints on the genesis of island arc volcanics from Cold Bay and Amak Islands, Aleutians and implications for mantle structure. Geochim Cosmochim Acta 47:2015–2030

Mottay G (1976) Contribution à l'étude géologique de la Polynésie Française, Archipel des Australes, Mehetia (Archipel de la Société). Thèse 3ème Cycle, Paris-Orsay, p 217

Norris RA, Johnson RH (1969) Submarine volcanic eruptions recently located in the Pacific by SOFAR hydrophones. J Geophys Res 64:650–654

Pitman WC, Larson RL, Herron EM (1974) The age of the ocean basins. Geol Soc Am Map Series MC-6

Ringwood AE (1982) Phase transformations and differentiation in subducted lithosphere: implications for mantle dynamics, basalt petrogenesis, and crustal evolution. J Geol 90:611–643

Ringwood AE (1986) Dynamics of subducted lithosphere and implications for basalt petrogenesis. Terra Cognita 6:67–77

Roden MF, Frey FA, Clague DA (1984) Geochemistry of tholeiitic and alkalic lavas from the Koolau Range, Oahu, Hawaii: Implications for Hawaiian volcanism. Earth Planet Sci Lett 69:141–158

Smith WC, Chubb LJ (1927) The petrography of the Austral or Tubuai Islands. Quart J Geol Soc London 83:317–341

Streckeisen A (1967) Classification and nomenclature of igneous rocks. N Jb Miner Abh 107:144–214

Sun SS, Nesbitt RW, Sharaskin AY (1979) Geochemical characteristics of mid-ocean ridge basalts. Earth Planet Sci Lett 44:119–138

Turner DL, Jarrard RD (1982) K—Ar dating of the Cook-Austral Island chain: A test of the hot-spot hypothesis. J Volcanol Geotherm Res 12:187–220

Vidal P, Chauvel C, Brousse R (1984) Large mantle heterogeneity beneath French Polynesia. Nature 307:536–538

White WM, Patchett JP (1984) Hf—Nd—Sr isotopes and incompatible element abundances in island arcs: implications for magma origin and crust-mantle evolution. Earth Planet Sci Lett 67:167–185