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Contributions to Mineralogy and Petrology

Geochemistry and origin of basaltic lavas from Marquesas Archipelago, French Polynesia

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Abstract. The Marquesas Archipelago, a volcanic chain in French Polynesia (south-central Pacific Ocean), is predominantly composed of alkalic, transitional and tholeiitic basalts. The variation trends in these intraplate basaltic rocks imply that the magmas were derived from different upper mantle sources. Model calculations using the total inverse method show that the peridotite source of most Marquesas basalts was enriched in incompatible elements compared to a primordial mantle and had higher than chondritic ratios of several elements such as La/Yb, Ti/V and P/Ce. A metasomatic enrichment event is suggested by the sequence of element enrichment in the source relative to the primordial mantle (Ba > Nb > La > Ce > Sr > Sm > Eu > Zr > Hf > Ti > Y > Yb). On the other hand, some lavas including tholeiites of Ua Pou and alkalic basalts of Hiva

and McDougall 1974) range from 3.85 m.y. at Nuku Hiva to 1.35 m.y. at Fatu Hiva indicating a decrease of age in a SE direction and a rate of migration of volcanic activity of 9.9 cm/year. Furthermore, in two islands (Nuku Hiva and Hiva Oa) for which both age determinations and whole-rock analyses are available, the degree of undersaturation of the basalts increases with the decreasing age of the volcanic rocks.

The petrography and chemical mineralogy have been described for several islands of the Archipelago (Bishop and Woolley 1973; Maury 1976; Brousse and Guille 1975, 1978; Brousse et al. 1978). The dominant rock type is olivine basalt with subordinate and variable amounts of differentiated rocks including trachybasalt, trachyte and phonolite (e.g. Ua Pou island).

In this study, the analyzed samples have basaltic composition with either porphyritic or hyalophilic and subaphyric textures. The phenocryst phases are olivine (Fo 86-77) containing inclusions of

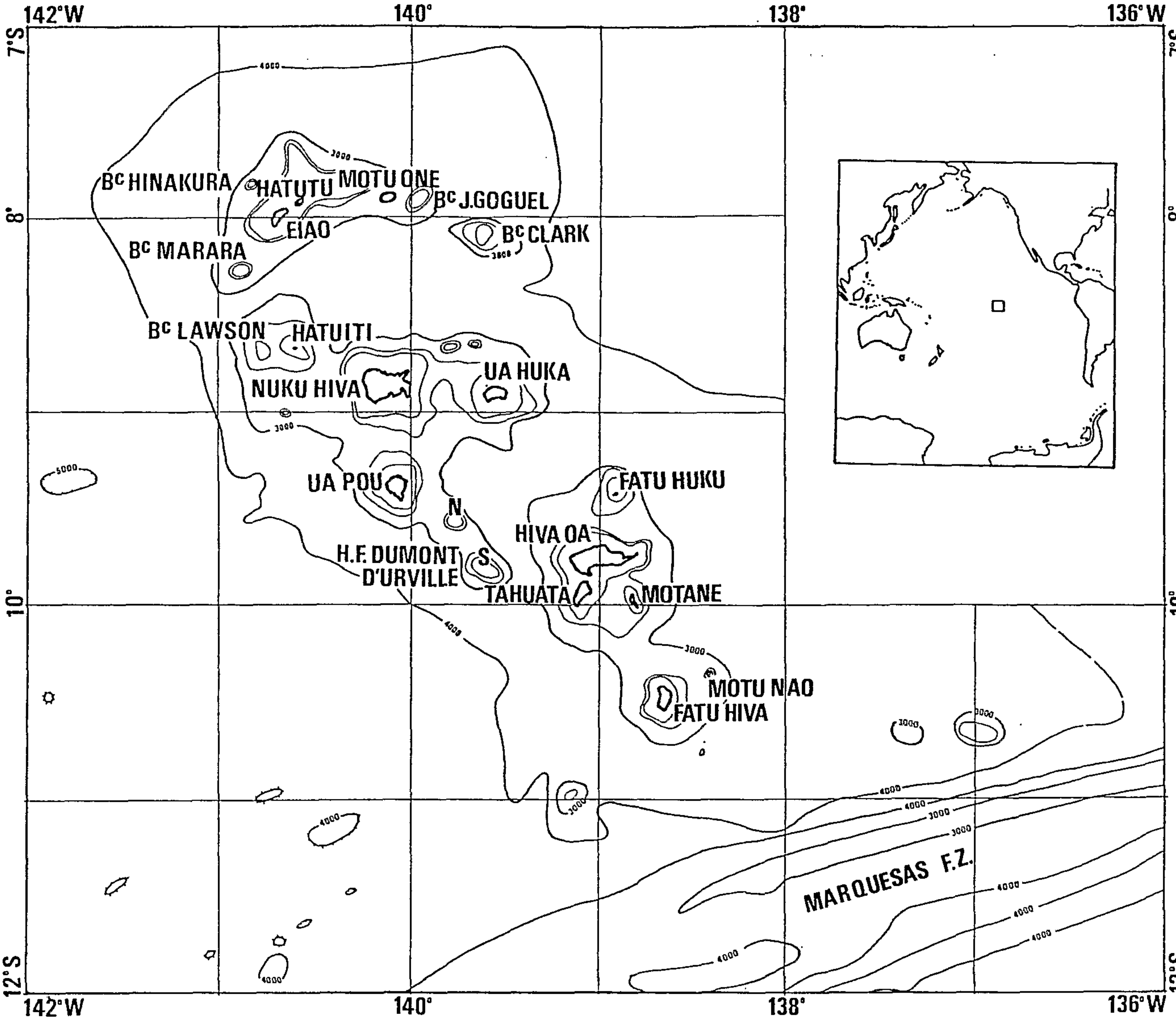


Fig. 1. Map of the Marquesas Archipelago. Contour lines drawn at 1,000 m intervals show simplified bathymetry (after CEBCO Map 297, Centre National Exploitation des Oceans, Paris, 1973). Square on insert map shows location of Marquesas islands in the Pacific Ocean

Using the classification of Feigenson et al. (1983), the tholeiites can be subdivided on the (Na_2O+K_2O) vs. SiO_2

Transition trace elements

Table 1. Representative major and trace element compositions of basalts from Marquesas Archipelago

	EIAO			HATUTU					HIVA OA				
	Th			Th			Alk		Tr		Alk		
REF:	6567	6559	6558	6465	6458	6466	6456	6457	6575	6577	6589	6570	6574
SiO_2	44.75	47.90	47.90	45.88	48.47	46.68	45.08	46.48	45.79	46.18	43.33	43.45	45.61
Al_2O_3	10.70	12.40	12.80	9.05	12.58	13.00	10.45	12.00	9.71	11.44	10.57	10.73	14.25
Fe_2O_3	13.54	12.73	13.02	11.97	12.50	12.11	13.33	12.28	14.15	13.33	14.33	13.91	12.92
MnO	0.17	0.17	0.17	0.18	0.18	0.17	0.19	0.17	0.18	0.17	0.18	0.18	0.16
MgO	14.63	8.50	8.00	16.15	7.18	7.30	15.20	11.31	15.60	10.80	13.49	12.10	6.56
CaO	7.85	10.87	10.95	9.80	11.70	11.73	8.51	10.82	8.68	9.47	9.43	10.92	8.98
Na_2O	1.88	2.29	2.45	1.79	2.50	2.57	2.04	2.47	2.02	2.37	2.59	1.81	2.71
K_2O	0.73	0.67	0.76	0.85	0.76	0.71	1.10	1.04	1.00	1.23	0.76	1.31	1.92
TiO_2	2.65	2.98	3.00	2.40	3.09	3.25	2.78	3.03	2.70	3.28	3.59	3.35	3.68
P_2O_5	0.43	0.44	0.44	0.34	0.40	0.50	0.42	0.42	0.35	0.45	0.50	0.51	0.64
H_2O^+	1.80	0.02	0.23	0.92	0.33	0.67	0.07	0.02	0.02	0.60	0.21	0.83	1.22
H_2O^-	0.50	0.49	0.35	0.38	0.80	0.46	0.56	0.21	0.21	0.36	0.15	0.36	0.52
$\sum$	99.63	99.46	100.07	99.71	100.49	99.15	99.73	100.25	100.41	99.68	99.13	99.46	99.17
[Mg]	0.71	0.60	0.58	0.75	0.57	0.57	0.72	0.68	0.72	0.65	0.68	0.66	0.53
Ne							0.10	2.00			4.50	3.30	0.70
Hy	11.40	14.40	10.20	2.50	9.80	2.70			1.00	1.80			
Li (ppm)	6.00	5.00	5.00	5.00	5.00	5.00	6.00	6.00	7.00	4.00	6.00	7.00	8.00
Rb	18.00	11.00	16.00	21.00	10.00	10.00	28.00	26.00	22.00	14.00	12.00	38.00	49.00
Sr	353.00	420.00	420.00	335.00	423.00	527.00	455.00	518.00	399.00	577.00	594.00	595.00	737.00
Ba	163.00	163.00	167.00	184.00	206.00	208.00	342.00	298.00	232.00	384.00	369.00	393.00	440.00
Sc	19.00	26.00	28.00	28.00	31.00	28.00	20.00	25.00	23.00	21.00	21.00	27.00	
V	248.00	298.00	308.00	270.00	332.00	317.00	268.00	297.00	247.00	271.00	315.00	330.00	295.00
Cr	630.00	403.00	344.00	1,225.00	271.00	283.00	825.00	570.00	705.00	464.00	600.00	760.00	184.00
Co	69.00	55.00	47.00	67.00	49.00	47.00	81.00	63.00	71.00	57.00	62.00	61.00	43.00
Ni	460.00	223.00	172.00	545.00	114.00	114.00	610.00	326.00	520.00	326.00	405.00	380.00	166.00
Cu	44.00	71.00	70.00	50.00	63.00	66.00	65.00	62.00	38.00	48.00	48.00	51.00	66.00
Zn	119.00	118.00	110.00	98.00	109.00	110.00	120.00	108.00	121.00	127.00	120.00	118.00	133.00
La	19.50	19.60	20.20	20.50	21.60	23.80	28.40	25.30	20.50	32.50	32.90	35.50	
Ce	40.80	44.30	49.40	47.90	50.70	57.70	63.50	57.20	45.00	67.80	64.80	72.60	
Nd	24.90	26.70	29.00	24.60	30.10	36.60	33.40	31.80	26.50	37.30	38.60	40.40	
Sm	6.77	7.13	7.34	5.98	7.51	8.57	6.98	7.48	6.55	8.79	8.60	8.64	
Eu	1.95	2.26	2.49	1.81	2.40	2.73	2.17		1.93	2.50	2.30	2.51	
Tb	0.82	1.01	1.07	0.86	1.01	1.23	0.84	1.07	0.83	1.01	0.88	0.98	
Yb	1.88	2.23	2.26	1.63	2.26	2.50	1.66	1.79	1.67	2.01	1.76	1.87	
Lu	0.28	0.32	0.33	0.24	0.32	0.36	0.24	0.25	0.24	0.29	0.25	0.26	
Y	27.00	30.00	33.00	25.00	30.00	36.00	26.00	30.00	25.00	31.00	28.00	28.00	
Hf	4.32	4.76	5.38	3.96	5.05	5.82	4.72	4.92	4.57	5.94	5.48	5.73	
Zr	213.00	216.00	221.00	173.00	211.00	249.00	215.00	214.00	194.00	274.00	265.00	253.00	
Nb	21.00	21.00	21.00	22.00	23.00	25.00	30.00	27.00	20.00	32.00	34.00	34.00	
Th	2.22	2.33	2.52	2.07	2.98	2.57	4.30	3.33	2.25	3.46	3.46	4.80	

Th – tholeiites, Tr – transitional basalts, Alk – alkalic basalts, BJG – Banc Jean Goguel sea-mount; [Mg]=(Mg/(Mg+Fe^{2+}) with Fe^{3+}/Fe^{2+} assumed to be 0.15), Ne – normative nepheline, Hy – normative hypersthene

Ti/V ratio remains constant in all basaltic types (Ti/V ~ 60) except in tholeiites of Ua Pou (Ti/V ~ 70) and alkalic basalts of Banc Jean Goguel sea-mount (Ti/V ~ 50). Zn is within the range of the Honolulu volcanics (Clague and Frey 1982). Cu remains constant in alkalic and transitional basalts up to [Mg] ~ 0.5 then tends to decrease. On the other hand, Cu increases with differentiation in the tholeiites to higher but more variable contents.

Incompatible trace elements

All samples display an enrichment of light REE (LREE) and fractionation of heavy REE (HREE) (Fig. 2). The La/Yb ratio increases from 9 in tholeiites to 29 in alkalic basalts. The transitional basalts have REE patterns similar to the alkalic basalts. The increase of the La/Yb ratio and the enrichment of LREE are positively correlated with the degree of undersaturation.

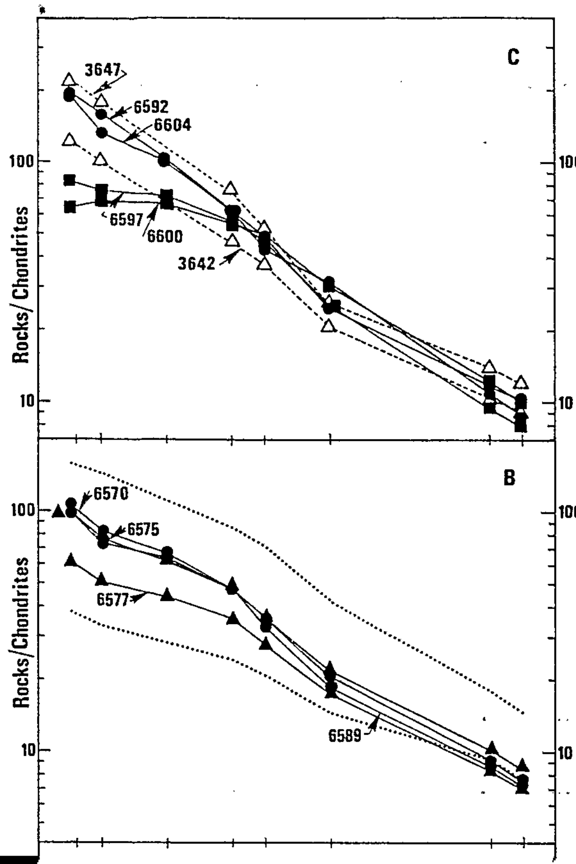
Incompatible elements including REE, P and Ti vary according to degree of differentiation, magmatic type and, for a given magmatic type, according to island. These variations are accompanied by a strong interelement correlation. The incompatible trace elements also correlate with several major elements (Fig. 3). The simultaneous increase of P and Ce (Table 1) with differentiation suggests that the fractionation of these two elements is not controlled by accesso-

FATU HUKU			UA POU				NUKU HIVA					BJG	
Tr			Th		Alk		Tr			Alk		Alk	
6446	6449	6450	6597	6600	6604	6592	3642	3643	3647	3644	3645	6471	6507
46.54	47.75	47.95	45.12	47.84	41.37	44.03	45.79	47.03	50.19	48.40	44.25	41.89	40.41
9.59	12.01	12.93	10.76	12.91	13.26	15.07	14.00	15.54	17.00	15.55	15.53	11.37	11.60
13.34	12.12	11.88	13.93	12.82	13.95	12.28	12.02	10.94	9.76	10.37	12.15	13.56	13.53
0.18	0.17	0.16	0.17	0.15	0.18	0.19	0.17	0.18	0.12	0.16	0.27	0.17	0.20
14.70	9.38	6.77	12.78	7.20	8.21	5.47	6.92	6.45	2.80	5.43	4.35	13.90	13.50
9.16	9.00	8.79	8.72	11.40	10.15	9.22	9.43	8.37	7.50	8.47	8.65	11.00	11.75
2.00	2.36	2.94	2.27	2.30	3.20	3.53	2.60	3.17	4.18	3.22	2.78	1.79	1.43
1.04	1.37	1.77	0.63	0.22	0.59	0.98	1.71	1.78	2.07	2.59	1.95	0.68	0.35
2.71	2.98	3.17	4.10	3.66	3.81	3.56	3.23	2.45	2.76	2.59	2.80	2.73	2.97
0.39	0.57	0.55	0.57	0.46	0.81	0.91	0.55	0.76	0.90	0.71	0.67	0.68	0.88
0.13	1.23	1.39	0.87	0.56	2.78	2.67	3.00	2.74	1.65	3.05	6.54	1.35	1.52
0.37	1.33	1.09	0.40	0.45	0.86	1.17	0.64	0.89	0.71	0.49	0.47	0.94	1.43
100.15	100.27	99.39	100.32	99.97	99.17	99.08	100.06	100.30	99.64	101.03	100.41	100.06	99.57
0.71	0.63	0.56	0.67	0.56	0.56	0.49	0.56	0.56	0.39	0.54	0.43	0.70	0.69
					7.00	3.10	0.10	0.10		1.30	0.90	4.20	2.90
4.70	14.00	6.00	8.50	17.90					4.40				
6.00	8.00	8.00	6.00	5.00	8.00	9.00	7.00	8.00	4.00	7.00	5.00	11.00	27.00
26.00	24.00	41.00	15.00	3.00	84.00	40.00	43.00	87.00	28.00	85.00	54.00	11.00	6.00
416.00	506.00	577.00	548.00	434.00	910.00	972.00	587.00	814.00	867.00	1,021.00	697.00	1,180.00	1,890.00
259.00	342.00	386.00	131.00	33.00	721.00	802.00	435.00	650.00	745.00	660.00	595.00	256.00	344.00
24.00	22.00	19.00	22.00	32.00	18.00	14.00	20.00	18.00	19.00	17.00	24.00	28.00	28.00
275.00	273.00	300.00	293.00	335.00	324.00	272.00	304.00	258.00	211.00	188.00	250.00	314.00	354.00
900.00	450.00	210.00	740.00	455.00	210.00	76.00	189.00	230.00	113.00	158.00	171.00	685.00	630.00
78.00	60.00	49.00	65.00	40.00	47.00	31.00	49.00	43.00	38.00	40.00	44.00	69.00	69.00
455.00	281.00	177.00	550.00	151.00	112.00	42.00	129.00	113.00	97.00	106.00	97.00	372.00	352.00
52.00	57.00	67.00	78.00	71.00	46.00	22.00	64.00	45.00	37.00	50.00	40.00	61.00	58.00
117.00	115.00	118.00	116.00	106.00	121.00	115.00	122.00	126.00	134.00	136.00	158.00	106.00	106.00
21.40	28.90	33.60	27.20	21.20	63.30	65.00	40.50	54.80	74.20	54.20	43.40	28.90	31.40
51.40	66.30	77.00	67.30	60.70	117.20	132.70	87.10	119.10	156.80	118.50	96.20	66.00	71.60
28.20	34.70	40.50	43.30	40.30	60.70	61.50	43.90					39.3	38.6
6.55	8.35	9.21	10.31	10.02	11.47	11.31	8.43	9.68	13.50	9.30	8.39	7.69	8.18
2.01	2.51	2.86	3.26	3.45	3.00	3.38	2.61	3.00	3.70	2.79	2.58	2.26	2.49
0.88	1.03	1.23	1.21	1.43	1.00	1.15	0.96	1.10	1.20	1.00	0.90	0.91	1.01
1.67	2.25	2.40	1.88	2.48	2.20	2.40	2.07	2.28	2.79	2.20	2.08	2.01	1.98
0.25	0.32	0.35	0.27	0.34	0.30	0.35	0.31	0.30	0.40	0.30	0.30	0.30	0.30
25.00	32.00	34.00	31.00	35.00	33.00	35.00	30.00	31.00	34.00	33.00	30.00	27.00	29.00
4.48	6.28	7.19	7.38	7.42	6.36	6.82	6.40	7.30	7.69	6.40		5.05	5.28
194.00	274.00	315.00	330.00	289.00	316.00	310.00	274.00	307.00	344.00	354.00	281.00	224.00	255.00
23.00	30.00	35.00	32.00	25.00	62.00	69.00	46.00	60.00	64.00	61.00	51.00	27.00	35.00
2.08	3.57	4.38	2.36	2.03	7.65	8.89	6.28	9.00	12.10	9.68	7.19	3.82	4.07

ry minerals such as apatite (c.f. Sun et al. 1979). The K/Ba ratio (Fig. 3) is nearly constant in the rocks of most islands (K/Ba=29–34) with the exception of the Ua Pou basalts in which this ratio is lower. Compared to equivalent rocks, the tholeiites of Ua Pou are depleted in Rb and Ba but enriched in Zr and Hf while the alkalic basalts of Nuku-Hiva are in general higher in Rb, Sr, Ba and Th. This suggests that the rocks of different islands were derived from sources of variable composition. Such heterogeneities of the upper mantle are well established from isotope geochemistry (O'Nions et al. 1979; Allegre et al. 1980) and documented for the mantle beneath French Polynesia by Vidal et al. (1984). Further evidence of upper mantle heterogeneities beneath the Marquesas Archipelago is provided by variations in the ratios of elements with a bulk partition coefficient (D)$\leqq$1 (e.g. Th/La, Nb/La); these ratios are generally considered to be insensitive to mineral fractionation.

The Th/La ratio (Fig. 4 and Table 2) ranges between 0.085 and 0.18. Transitional and alkalic basalts from Nuku-Hiva have the highest ratios while the lowest are found in tholeiites of Ua Pou and alkalic basalts of Fatu Huku. Such variations cannot be explained by variable degrees of partial melting from a homogeneous source. The variations of other ratios (Table 2) support this observation.

The variability in composition of the studied basalts is as large as that reported for the Hawaiian basalts (Clague and Frey 1982; Roden et al. 1984; Feigenson et al. 1983; Feigenson 1984), but on average the Marquesasian basalts



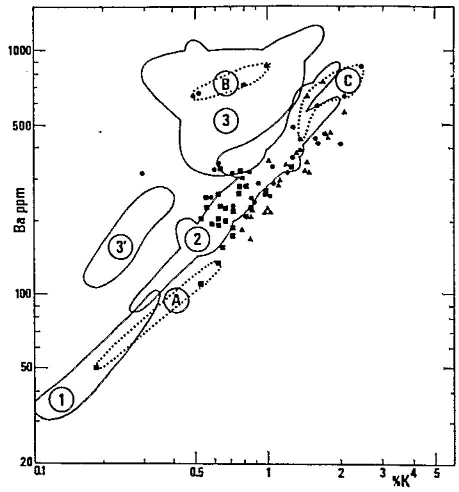


Fig. 3. Ba vs K diagram for the Marquesas samples (*full squares:* tholeiites; *full triangles:* transitional basalts, *full circles:* alkalic basalts). Fields delineated by *solid lines* are: 1 – tholeiites, 2 – alkalic basalts and 3 – post-erosional basalts from various Hawaiian islands (Frey and Clague 1983). Fields outlined by dotted lines are: A – tholeiites from Ua Pou, B – alkalic basalts from Ua Pou and C – alkali and transitional basalts from Nuku Hiva (present study)

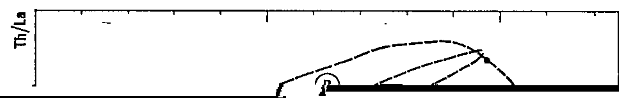


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Table 2. Average element ratios in basalts from the Marquesas Archipelago

	EIAO	HATUTU		HIVA OA		FATU HUKU	UA POU		NUKU HIVA		BJG
	Th	Th	Alk	Tr	Alk	Tr	Th	Alk	Tr	Alk	Alk
n	3	3	2	2	2	3	2	2	2	1	2
Th/La	0.119	0.116	0.141	0.107	0.119	0.120	0.092	0.120	0.160	0.181	0.130
Nb/La	1.06	1.06	1.06	0.98	0.99	1.05	1.18	0.98	1.12	1.13	1.02
Ti/Zr	80	83	82	77	80	70	75	72	59	44	71
Sr/Ce	8.9	8.1	8.1	8.7	8.7	7.7	7.6	7.8	6.7	8.6	–
Zr/Hf	45	43	44	44	46	44	42	50	43	55	46
Ba/La	8.3	9.1	11.9	11.5	11.1	11.8	3.1	11.4	–	–	9.8
Ti/V	61	57	61	69	64	62	74	71	61	83	51
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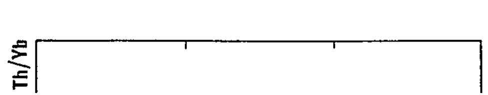
n – number of samples, Th – tholeiites, Alk – alkalic basalts, Tr – transitional basalts, BJG – Banc Jean Goguel



link between the two magmatic types. Similarly, the data in Table 2 may suggest that transitional and alkalic basalts

Table 3. Calculations of source composition of the Marquesas basalts by the total inverse method

	Starting model 'a priori' parameters		Inverse model adjusted parameters	
	D_r	C_0	C_0	H
Ba	0.027 (0.008)	20 (6)	19 (11)	22
Nb	0.048 (0.014)	2.4 (0.7)	2.4 (0.4)	3.00
La	0.040 (0.010)	2.0 (0.6)	2.2 (0.3)	2.23
Ce	0.046 (0.014)	4.9 (1.4)	5.1 (0.6)	5.05
Sr	0.066 (0.019)	47 (14)	48 (6)	55
Sm	0.073 (0.02)	0.84 (0.25)	0.85 (0.11)	
Eu	0.106 (0.031)	0.31 (0.09)	0.32 (0.04)	
Zr	0.12 (0.03)	34 (10)	34 (4)	
Hf	0.12 (0.03)	0.78 (0.22)	0.77 (0.09)	
Ti	0.13 (0.04)	0.49 (0.14)	0.48 (0.06)	
Tb	0.17 (0.04)	0.18 (0.05)	0.19 (0.02)	
Yb	0.34 (0.07)	0.66 (0.15)	0.65 (0.07)	
		F%	F%	
Tholeiite			8.1 (1.0)	
Transitional basalt		10±5%	6.5 (0.08)	
Alkali basalt			5.2 (0.06)	

Values in brackets coresspond to standard deviation; C_0 – concentration in the original source, D_r – bulk partition coefficient for residuum, F – degree of partial melting, H – estimates of the source for the Honolulu volcanics (Roden et al. 1984). Note that the adjusted parameters are better constrained than 'a priori' parameters

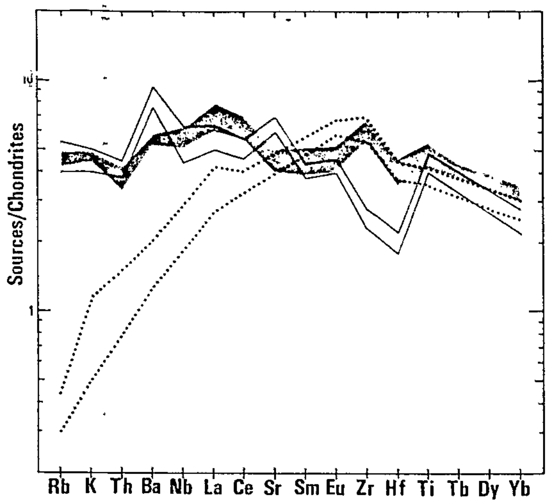


Fig. 6. Chondrite-normalized (Sun et al. 1979) source rock composition for basalts of the Marquesas Islands (*shaded field*). All element contents (except K and Rb) have been calculated by the inverse method. The C_0 for K and Rb were evaluated by using the F value reported in Table 3 and assuming D_r (residual bulk partition coefficient) = 0.04. Following the same procedure, the source compositions of alkalic basalts from Oahu (*field delineated by continuous lines*) and of tholeiites from Kohala volcano (*dotted lines*) were calculated. For Oahu, two alkalic-basalts (samples 31 and 34) and two basanites (25 and 26) of Clague and Frey (1982) were used in the source composition calculation. For Kohala volcanics, three tholeiites (W-1, W-11 and W-19) of Feigenson et al. (1983) were used. In latter case, data for Th, La, Zr and Hf were taken from Leeman et al. (1980). Each field corresponds to an interval of variation represented by x+s.d

contents of ultramafic xenoliths. The value was used to calculate C_0^{Th} from which C_0 and D_r for other elements were ascertained. The results of the two methods differ by a factor of 2 to 3. In order to make allowance for uncer-

et al. (1983) for the Kohala volcanics. However, the available data (e.g. Table 2) indicate that not all the volcanics of the Marquesas Archipelago are derived from a common source. For example, the tholeiites and alkalic basalts from sources for both chains were similarly heterogeneous and were both affected by similar enrichment processes (mixing and/or metasomatism). The mixing process cannot be ascertained in the absence of isotopic data although the isotopic data of White (1985) suggest that the sources of Hawaiian and Marquesas basalts may be relatively distinct. Nevertheless the sequence of element enrichment in the source rocks relative to the primordial mantle (Ba > Nb > La > Ce > Sr > Sm > Eu > Zr > Hf > Ti > Y > Yb) resembles the sequence of enrichment attributed to metasomatism (e.g. Clague and Frey 1982). On the other hand, as in Hawaii (Feigenson et al. 1983), some basalts were probably derived from a relatively depleted source including both tholeiites of Ua Pou and alkalic basalts of Hiva Oa.

The near constant contents of Yb, Lu and Y among the various magmatic types is consistent with garnet as a residual phase. Although the high Ti/V ratio suggests melting of an amphibole-bearing source (Wass 1980), the calculated D value for Ti (~0.13) appears to exclude amphibole as a residual phase. The presence of apatite is negated by the P/Ce correlation. For a few alkalic basalts, phlogopite

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