

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 Oa, were probably derived from relatively depleted upper mantle. In some islands such as Hatutu, the different types of basalts were generated from sources with rather similar compositions. The residual phases of the Marquesas magmas included garnet. The sources of these magmas were similar in trace element chemistry to the oceanic mantle below Hawaii.

Introduction

Mid-ocean ridge basalts (MORB) have been extensively studied during the last fifteen years but relatively little modern trace element data are available on oceanic island basalts (OIB). Since OIB are considered to be generated at greater depths, their study complements that of MORB.

This paper presents some data on the trace element distribution in volcanic rocks of the main islands of the Marquesas Archipelago, a volcanic island chain in French Polynesia, and provides constraints for their mantle source.

Geological and petrographic notes

The Marquesas Archipelago, located in the south-central Pacific Ocean consists of 12 islands and several sea-mounts which are the tops of large subterranean volcanoes rising more than 4,000 m from the Paleocene oceanic crust (Fig. 1). Their arrangement is approximately parallel to other volcanic archipelagoes of the eastern Pacific and is perpendicular to the East Pacific rise.

With the exception of Eiao island, which has been dated at 6.3 to 5.3 m.y. (Brousse and Bellon 1974), the K/Ar ages (Duncan

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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 Cr-spinel, and clinopyroxene with frequent oscillatory sector zoning. The composition of clinopyroxene is highly variable (diopside, augite and salite) but is compositionally distinct among the three basaltic types (tholeiitic, transitional and alkalic) similar to clinopyroxenes of Hawaii (Fodor and Keil 1975). In addition to olivine and clinopyroxene, the groundmass contains mainly Fe-Ti oxides, glass and occasionally plagioclase. In some samples, patches of devitrified glass have been transformed to chlorite while in other rocks, alkali feldspar and/or phlogopite appear as interstitial phases.

Analytic methods

Seventy-nine samples were analyzed for major elements and Li, Rb, Sr, Ba, V, Cr, Co, Ni, Cu and Zn by atomic absorption. Twenty-six samples were then selected from this suite for the determination of additional trace elements. Rare earth elements (REE), Sc, Hf and Th were determined by instrumental neutron activation and Y, Zr and Nb by X-ray fluorescence. The precision and accuracy of the trace element data were given by Dostal et al. (1983).

Geochemistry

Major elements

According to the normative composition (assuming $Fe^{3+}/Fe^{2+} = 0.15$), the rocks (Table 1) range from basanites (Ne > 5%) to olivine tholeiite, and in Ua Pou island to quartz normative basalts (Q ~ 1%). Although some samples have high content of H₂O, most rocks are without any mineralogical features of alteration. The positive correlation between mobile and immobile incompatible elements suggests that the rocks retained their primary magmatic distribution of elements.

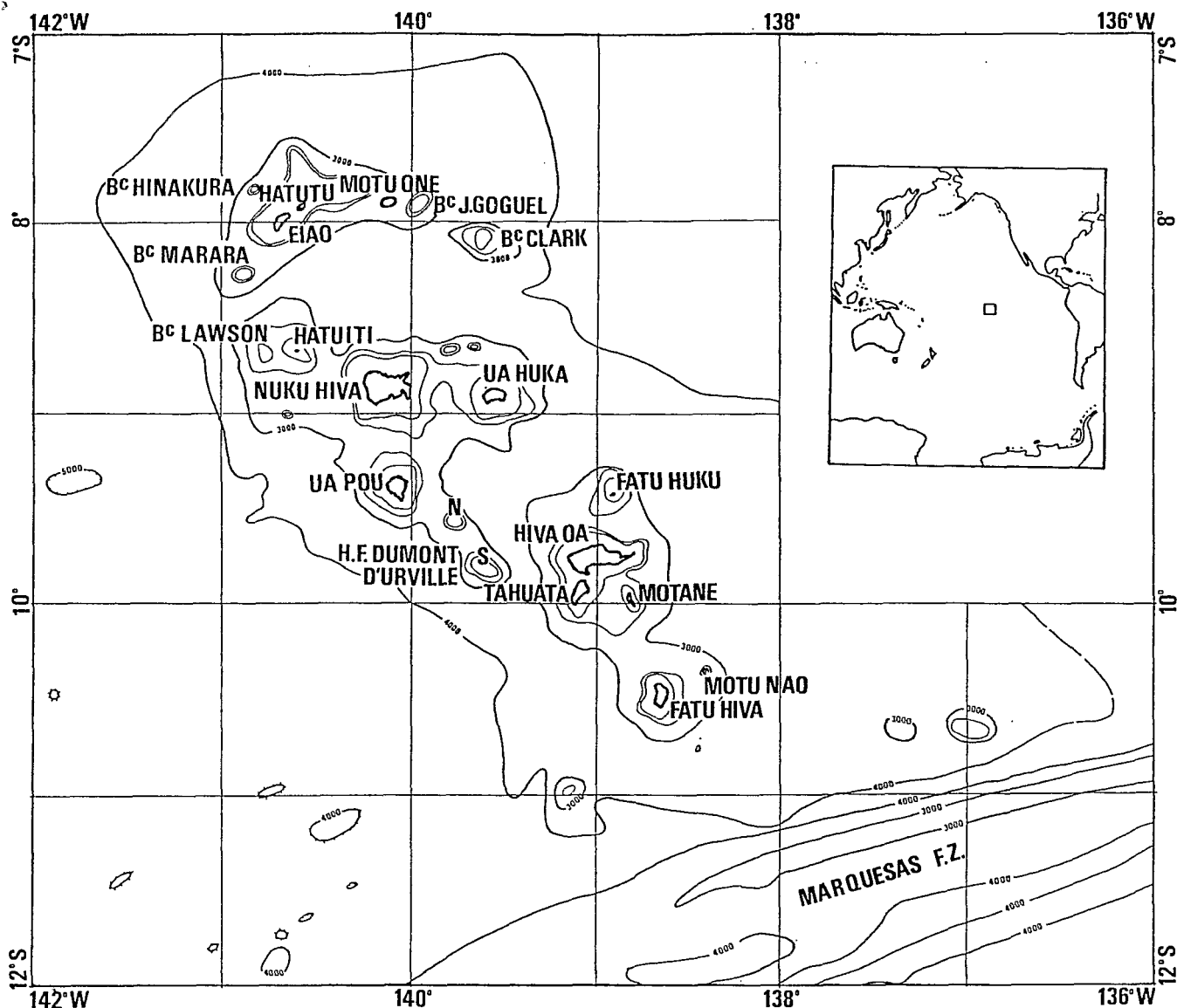


Fig. 1. Map of the Marquesas Archipelago. Contour lines drawn at 1,000 m intervals show simplified bathymetry (after CEBCO Map 297, Centre National Exploitation des Océans, Paris, 1973). Square on insert map shows location of Marquesas islands in the Pacific Ocean

Using the classification of Feigenson et al. (1983), the tholeiites can be subdivided on the $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ vs. SiO_2 diagram into two groups: a) tholeiitic basalts which lie in the tholeiitic field and b) transitional basalts which plot into the alkalic field. Tholeiites are mainly found in the northern islands (Eiao, Hatutu and Ua Pou) while transitional basalts predominate in the southern ones (Hiva Oa and Fatu Huku). The [Mg] ratio ($\text{Mg}/\text{Mg} + \text{Fe}^{2+}$ with $\text{Fe}^{3+}/\text{Fe}^{2+} = 0.15$) of the basalts ranges between 0.78 and 0.39 indicating that they have undergone variable degrees of low-pressure fractionation. A decrease of [Mg] up to 0.55 is accompanied by an increase of Al, Ca, Ti and P while Fe remains constant suggesting that the differentiation is dominated by olivine. The influence of clinopyroxene is indicated by the steeper increase of Al compared to that of Ca. In the latter stages of differentiation in the transitional and alkalic basalts, clinopyroxene fractionation predominates as implied by the steady decrease of Ca while Al continues to increase with differentiation.

Transition-trace elements

Ni and Co decrease with the decreasing [Mg] ratio, but for a given value of this parameter, the contents of these elements are not distinct for individual islands and magmatic types. Most samples have a $10^4 \times \text{Ni}/\text{Mg}$ ratio between 50 and 65 and may represent a near-primary magma derived from a mantle source with olivine Fo 87–90. For rocks with $[\text{Mg}] > 0.55$, the Cr/Ni ratio varies between 1.2 and 2.0 in transitional and alkalic basalts and is higher in tholeiites (Cr/Ni = 1.4 to 3.0). In rocks with $[\text{Mg}] < 0.55$, the Cr/Ni ratio decreases with differentiation in all three magmatic series indicating that Cr becomes more compatible than Ni and thus implying the influence of clinopyroxene and/or Cr-spinel.

V increases with differentiation in tholeiitic and transitional basalts from 240 to 380 ppm. It also increases in alkalic basalts from 260 to 400 ppm up to $[\text{Mg}] = 0.55$ then decreases, indicating some Fe-Ti oxide fractionation. The

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

REF:	EIAO			HATUTU			HIVA OA						
	Th			Th			Alk		Tr		Alk		
	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 ₂ O 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 ₂ O 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 ₂ O	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 ₂ O	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 ₂ O 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 ₂ O ⁺	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 ₂ O ⁻	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
Σ	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. B.J.G. – Banc Jean Goguel sea-mount; [Mg] = (Mg/(Mg + Fe²⁺)) with Fe³⁺/Fe²⁺ 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 vari-

ations in the ratios of elements with a bulk partition coefficient ($D \leq 1$) (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

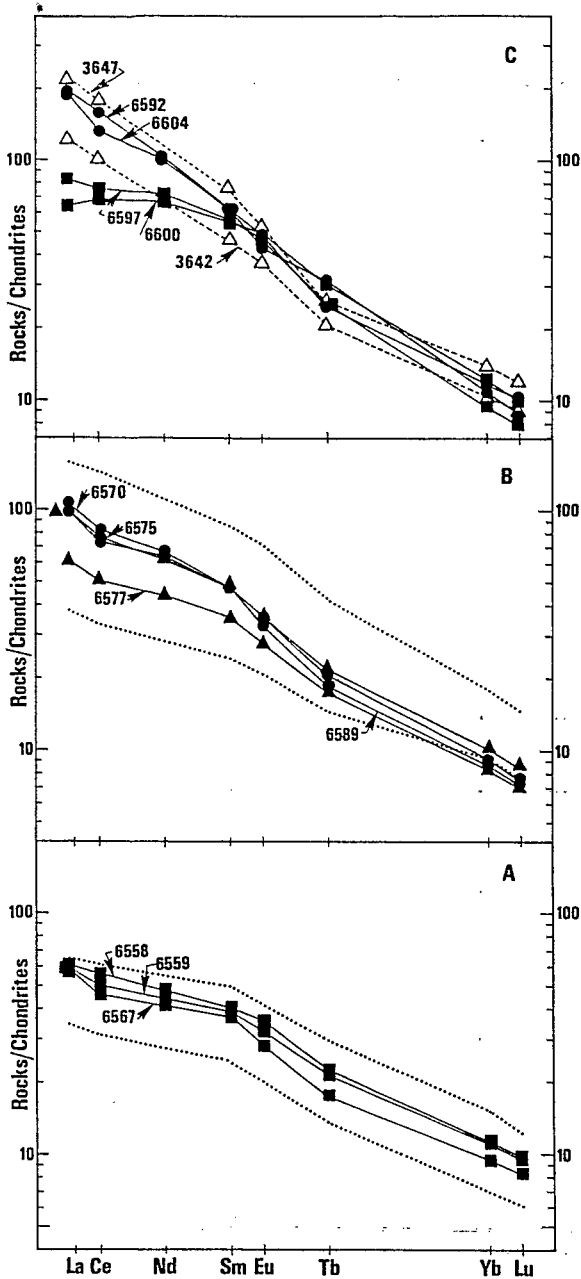


Fig. 2. Chondrite-normalized REE abundances of the Marquesas basalts. A – Tholeiites (full squares) from Eiao; dotted lines delineate the field of Hawaiian tholeiites (Basaltic Volcanism Study Project, 1981); B – Transitional (full triangles) and alkalic (full circles) basalts from Hiva Oa; dotted lines show the field of Hawaiian alkalic basalts (Basaltic Volcanism Study Project, 1981), C – Tholeiites (full squares) and alkalic (full circles) basalts from Ua Pou, and transitional (open triangles) basalts from Nuku Hiva

tend to have higher concentrations of Rb, Th, Ba, Ce and P. However, some ratios such as P_2O_5/Ce are similar in both chains and their values (~ 75) are very close to that given for OIB by Sun and Hanson (1975).

Discussion

Duncan and Compston (1976) and Vidal et al. (1984) have shown that significant isotopic heterogeneity exists in the

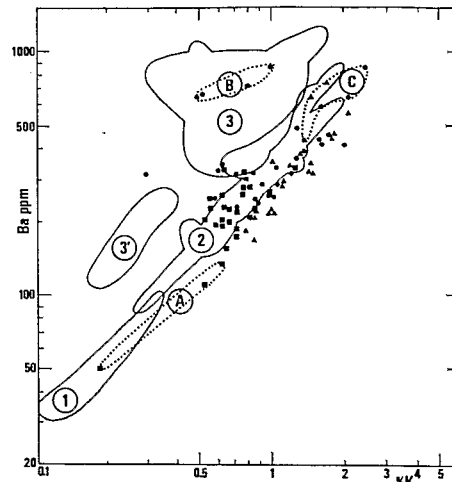


Fig. 3. Ba vs K diagram for the Marquesas samples (full squares: tholeiites; full triangles: transitional basalts, full circles: alkalic basalts). Fields delineated by solid lines are: 1 – tholeiites, 2 – alkalic basalts and 3 – post-erosional basalts from various Hawaiian islands (Frey and Clague 1983). 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)

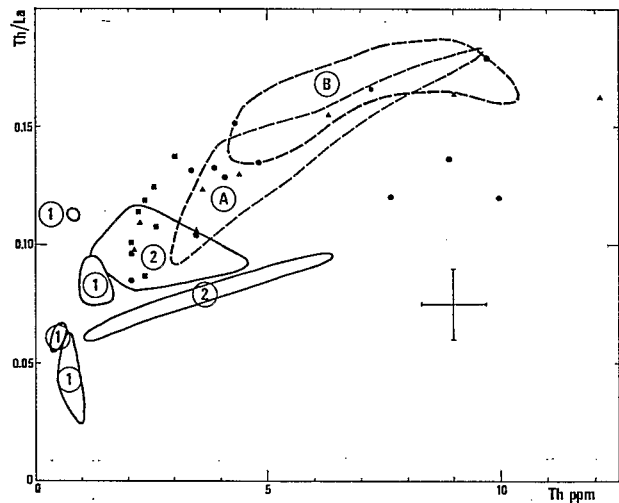


Fig. 4. Th/La vs Th diagram for the Marquesas samples (symbols as in Fig. 3). Fields outlined by dashed lines represent rocks from the Society Islands (Dostal et al. 1982), A: alkalic and B: transitional basalts. Fields delineated by solid lines represent Hawaiian Island rocks: 1 – tholeiites (Basaltic Volcanism Study Project, 1981, Roden et al. 1984 and Chen and Frey, 1983). 2 – alkalic basalts (Basaltic Volcanism Study Project, 1981, Clague and Frey, 1982 and Chen and Frey, 1983). Samples with Th 6 ppm correspond to alkalic basalts from Ua Pou and Nuku Hiva and transitional basalts from Nuku Hiva. Cross corresponds to two standard deviations

volcanic rocks of the Marquesas, both in a single island and between islands. The variations of ratios involving the most incompatible elements suggest that Marquesas basalts were derived from at least three different sources. However, in spite of the large variability of trace element distribution, there is evidence that, in some cases, the different magmatic types may have been derived from the same source rock

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

	EIAO	HATUTU		HIVA OA		FATU HUKU	UA POU		NIUKU HIVA		BJG
	Th	Th	Alk	Tr	Alk	Tr	Th	Alk	Tr	Alk	Alk
<i>n</i>	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
Zr/Nb	10.3	9.00	7.5	9.1	7.6	8.8	10.9	5.1	5.6	5.8	7.8
Sr/Ba	1.8	2.2	1.8	1.8	1.8	1.7	6.1	1.4	1.3	1.4	—
La/Yb	9.3	10.6	15.5	14.2	18.8	13.2	11.5	28.9	21.7	24.6	15.1
K/Ba	27	34	32	33	25	39	44	6	27	32	14

n – number of samples, Th – tholeiites, Alk – alkalic basalts, Tr – transitional basalts, BJG – Banc Jean Goguel

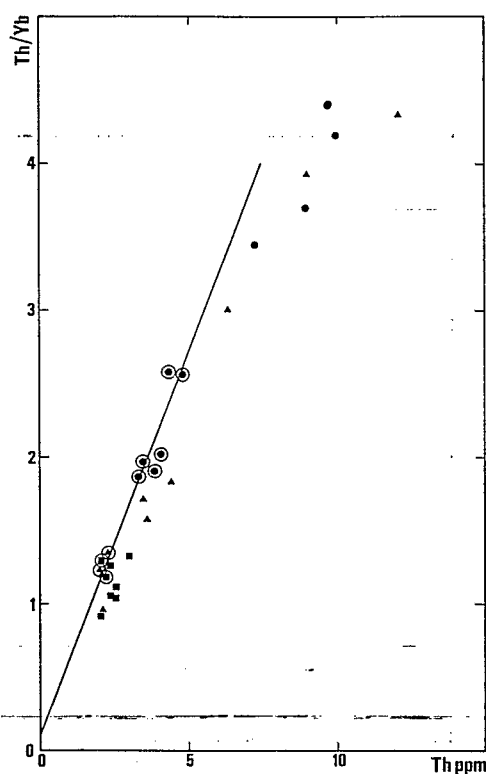


Fig. 5. Th/Yb vs Th diagram for the Marquesas samples (symbols as in Fig. 3). Encircled symbols correspond to samples with $[Mg] \geq 0.67$ used in the calculation of the regression line ($Th/Yb = a Th + b$ with $a = 0.515 (+0.012)$ and $b = 0.115 (+0.036)$)

composition by variable degrees of partial melting. This is best exemplified by Hatutu island where alkalic and tholeiites basalts co-exist. The ratios involving elements with similar *D* (e.g. Nb/La, Ti/Zr, Tb/Y) are comparable in both magmatic types whereas ratios such as La/Yb and La/Hf are higher in alkalic basalts. Inversely, ratios such as Zr/Nb with $D_{Zr} > D_{Nb}$ are lower in the alkalic basalts. The variation of these ratios is accompanied by an enrichment of trace elements in alkalic basalts proportional to their degree of incompatibility. These observations indicate a petrogenetic

link between the two magmatic types. Similarly, the data in Table 2 may suggest that transitional and alkalic basalts of Hiva Oa were generated by different degrees of partial melting from source rocks with very similar composition.

The composition of one of the upper mantle sources for the Marquesas lavas has been calculated using a set of samples assumed to have been generated from a single source. The set of samples includes tholeiites of Eiao and Hatutu islands, transitional basalts from Hiva Oa and Fatu Huku and alkalic basalts from Hatutu and Hiva Oa islands. The calculation was done by the total inverse method of Tarantola and Vallete (1982) applied to the equilibrium

partial melting equation (Shaw 1970) $C^l = \frac{C_o}{D_r + F(1 - D_r)}$

where C_o , D_r and F are, respectively, the composition of the source, the bulk partition coefficient (solid/liquid) involving residual minerals, and degree of partial melting.

Minster and Allegre (1978), Allegre et al. (1983a, b) and Dupuy et al. (1985) described in detail the application of the inverse method to petrogenetic processes. The principle of the method is to adjust all parameters simultaneously in such a way that they constrain each other. All parameters are considered to a certain degree to be unknown within a range of error. The adjustment is done through a set of equations which take into account the uncertainty of the data. The values thus obtained should satisfy the equations within the given limits of error.

The selection of 'a priori' parameters of C_o , D_r and F is as follows: The values of F ($10\% \pm 5$) was estimated from the major elements following the procedure of Sun et al. (1979), assuming a pyrolitic source composition. This value is in agreement with data from experimental petrology (Jaques and Green 1980). Following Treuil and Joron (1975) and more recently Clague and Frey (1982) and Feigenson et al. (1983) C_o and D_r were estimated using the behaviour of trace elements on a rectangular plot C_x^l/C_y^l vs C_x^c/C_y^c (C_x^c and C_y^c concentrations of element (*x, y*) in liquid) (e.g. Fig. 5). Two different approaches have been considered. In the first approach, $C_o^{Th} = 0.2$ ppm was calculated from the tholeiites assuming $F = 10\%$ and $D^{Th} \sim 0$. C_o and D_r for other elements can be derived from this value. For the second approach, the value C_o^{Yb} was taken as 0.4 ± 0.1 ppm which corresponds to the range of the Yb

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

	Starting model 'a priori' parameters		Inverse model adjusted parameters		<i>H</i>
	<i>D_r</i>	<i>C_o</i>	<i>C_o</i>		
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)		

	<i>F</i> %	<i>F</i> %
Tholeiite		8.1 (1.0)
Transitional basalt	10 ± 5%	6.5 (0.08)
Alkali basalt		5.2 (0.06)

Values in brackets correspond to standard deviation; *C_o* – 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

contents of ultramafic xenoliths. The value was used to calculate *C_oTh* from which *C_o* 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 uncertainty in the parameters, the averages of the extreme values obtained from the two methods with the standard deviation expressed as $\frac{\text{max-min}}{2\sqrt{3}}$ (Table 3) were used for the inverse method calculations. In addition to *F*, *D_r* and *C_o*, a value of *C¹* was also selected from the six most primitive samples from among those having the same ratio of the most incompatible elements (tholeiites 6567, 6559, transitional basalts 6577, 6446, alkalic basalts 6456, 6457).

The calculated *D* values fall in the range given by Clague and Frey (1982) for Hawaiian basalts generated by 11% partial melting. The *C_o* values are reported on Table 3 and plotted on Fig. 6.

The calculated incompatible element content of the source is relatively high (3 to 6 times chondritic abundances) but similar to that obtained for the Honolulu volcanics by Roden et al. (1984). In order to refine this comparison, the source composition of alkalic basalts of Oahu (Clague and Frey 1982) was calculated using the inverse method. The results, shown in Fig. 6, are similar to the Marquesas data for most elements except Zr and Hf which are lower, and Ba and Sr which are higher in the Oahu source.

The inverse method indicates that some tholeiites, transitional and alkalic basalts could have been derived from upper mantle sources with closely comparable trace element composition by variable degrees of partial melting (Table 3). A similar conclusion has been reached by Feigenson

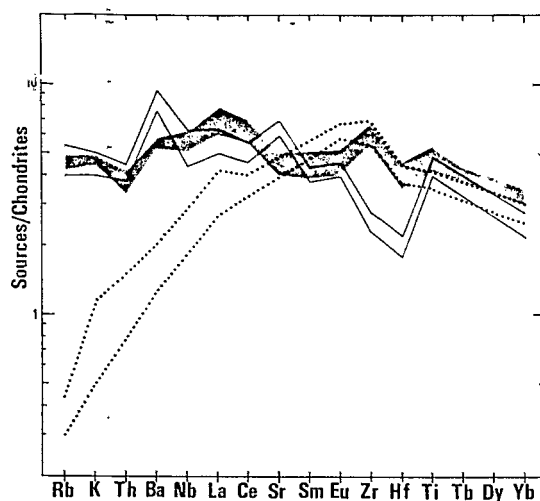


Fig. 6. Chondrite-normalized (Sun et al. 1979) source rock composition for basalts of the Marquesas Islands (*shaded field*). All element contents (except K and Rb) have been calculated by the inverse method. The *C_o* for K and Rb were evaluated by using the *F* value reported in Table 3 and assuming *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 $x \pm s.d$

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 Ua Pou island have geochemical features which imply two different sources. In addition, the composition of the source for some rocks should be relatively depleted in the most incompatible elements; this is particularly true for the tholeiites of Ua Pou and alkalic basalts from Hiva Oa. Unfortunately, not enough samples are available to adequately evaluate their corresponding source composition.

The inverse model calculation has also been applied to the tholeiites of Kohala, Hawaii and the results (Fig. 6) show a strong depletion in the most incompatible elements, with the chondrite-normalized ratios (*Ce/Sm* = 0.8 and *Ce/Ba* = 2) very close to the values reported by Feigenson et al. (1983).

Conclusion

The large compositional variations in the studied samples show that these intraplate rocks were derived by variable degrees of partial melting from a heterogeneous source. Compared to estimates of a primordial upper mantle, the peridotite source of most Marquesas basalts was enriched in incompatible elements. Likewise, it has higher than chondritic ratios of several elements such as La/Yb, Ti/V and P/Ce. The distinct geochemical similarities between this archipelago and the Hawaiian chain (e.g. Clague and Frey 1982; Feigenson et al. (1983) suggest that the upper mantle

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 may be residual as inferred from the relative depletion of K, Rb and Ba.

In some cases, the three magmatic types – tholeiitic, transitional and alkalic basalts – may be produced by a variable degree of melting from sources with rather similar trace element composition. The calculated degree of partial melting ranges from 8% for tholeiites to 5% for alkalic basalts. Relatively low values of partial melting have been also obtained from our calculations for tholeiites of Kohala (9–10%) and for alkalic basalts of Oahu (7–8%). These values are within the range of melting given by Clague and Frey (1982) for Honolulu volcanics.

Acknowledgements. The study was supported by ATP-PIROCEAN N° 0693 (France), ORSTOM (France) and the Natural Sciences and Engineering Research Council of Canada (operating grant A3782). Many thanks are due to Drs. J. Vernières and R. Bayer for their help with the calculations and Dr. K.J. Schultz for critical comments.

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Received January 14, 1985 / Accepted August 6, 1985