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Origin of basalts from the Marquesas Archipelago (south central Pacific Ocean): isotope and trace element constraints

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Basalts from the Marquesas Archipelago display significant variations according to magmatic type in $^{143}\text{Nd}/^{144}\text{Nd}$ (0.512710–0.512925) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70288–0.70561) suggesting heterogeneities at various scales in the mantle source, with respectively the highest and lowest values in tholeiites compared to alkali basalts. This relationship is the reverse from that observed in the Hawaiian islands. Systematic indications of magma mixing are recognized from the relationships between trace element and isotopic ratios. Tholeiites from Ua Pou Island which have unradiogenic Sr (about 0.7028) plot close to basalts from Tubuai and St. Helena, i.e. distinctly below the main mantle trend in the Nd vs. Sr isotopic diagram. It is suggested that the source of these tholeiites is ancient subducted lithosphere which has suffered previous extraction of liquid with island arc tholeiite composition. The trace element and isotopic data of the basalts from the other Marquesas Islands imply the contamination of an equivalent source by an enriched component. This latter has trace element characteristics of the upper crust.

1. Introduction

In contrast to MORB, ocean island basalts (OIB) are generated from various parts of the mantle [1,2] and their isotopic heterogeneities imply the existence of at least four different reservoirs [3–6]. Various hypotheses have been proposed for the origin of the OIB source, the most common being mixing of depleted mantle with either primitive mantle, ancient subducted oceanic crust and sediments or pieces of sub-continental lithosphere.

Isotopic data are not sufficient by themselves to choose between the different hypotheses. However, when coupled with incompatible trace element data, they may be especially efficient for characterizing the various reservoirs [7–11].

In the following, new Nd, Sr, and Pb isotopic data are reported on the basalts of the Marquesas Islands. They confirm the isotopic heterogeneities already recognized in French Polynesia [11–14] and lead us to the identification of three distinct reservoirs. The trace element data previously ob-

tained [15] are combined with the isotope data in order to discuss the origin of these reservoirs and to constrain the origin of the Marquesas basalts.

2. Geological background and previous studies

The Marquesas Archipelago consists of 12 islands and several seamounts that represent the tops of large intraplate volcanoes rising more than 4000 m above Paleocene oceanic crust (Fig. 1).

The ages of these islands range from 6.3–5.3 Ma at Eiao [16] to 1.3 Ma at Fatu Hiva [17]. They tend to decrease in a southeast direction and suggest a migration rate of volcanic activity of about 9.9 cm/yr [17].

The volcanic rocks have been described by several authors [18,19]. The main petrographic type is olivine basalt associated with subordinate but variable amounts of differentiates. Major element compositions distinguish three main types: olivine tholeiite, transitional basalt and alkali basalt. Analyzed rocks have $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ ratios ranging from 0.78 to 0.39, the spread in this

TABLE 1

Sr and Nd isotope data for Marquesas Archipelago

Island	Ref. and type	Analysis No.	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	La/Ce	K/Rb	Ba/La	Sm/Nd	Th/La	Hf/Lu	Rb/Sr	La/Yb	Zr/Nb
Eiao	EAO-03 TH	6559	420	0.70411	26.7	0.512890	0.443	505	8.3	0.27	0.119	14.9	0.026	8.8	10.3
	EAO-11 TH	6565	491	0.70406	34.2	0.512925	0.408	337	6.2	0.27	0.121	16.4	0.033	10.0	
Hatutu	HTT-01 AL	6456	455	0.70472	33.4	0.512806	0.447	326	12.0	0.21	0.152	19.7	0.062	17.1	7.2
	HTT-05 TR	6458	423	0.70433	30.1	0.512867	0.427	631	9.5	0.25	0.138	15.8	0.024	9.6	9.2
	HTT-19 TR	6465	335	0.70448	24.6	0.512859	0.427	336	9.0	0.24	0.101	16.5	0.063	12.6	7.9
Banc J. Goguel	BJG-06 AL	6471	1180	< 0.7062	39.3	0.512772	0.437	513	8.9	0.20	0.132	16.8	0.009	14.3	8.3
	BJG-08 AL	6507	1890	< 0.7070	38.6	0.512820	0.439	484	10.9	0.21	0.129	17.6	0.003	15.9	7.3
Nuku Hiva	NH 77B TR	3642	587	0.70438	43.9	0.512810	0.465	330	10.7	0.19	0.155	20.6	0.073	19.5	6.0
	NH 78A TH*	7471	435	0.70378	30.9	0.512889	0.373	286	9.5	0.25	0.110	19.7	0.057	9.5	
	NH 77T TR*	7472	559	0.70422	46.0	0.512848	0.410	448	10.0	0.21	0.124	18.1	0.045	13.9	
Ua Pou	UAP-03 AL	6592	972	0.70483	61.5	0.512749	0.490	203	12.3	0.18	0.137	19.5	0.041	27.1	4.5
	UAP-11 TH	6597	548	0.70288	43.3	0.512919	0.404	349	4.8	0.24	0.087	27.4	0.027	14.5	10.3
	UAP-17 TH	6600	434	0.70293	40.3	0.512921	0.349	609	1.6	0.25	0.096	21.8	0.007	8.5	11.6
	UAP-24 TH	6602	610	0.70318	57.9	0.512904	0.366	590	5.8	0.23	0.087	28.2	0.018	12.0	
	UAP-26 AL	6604	910	0.70499	60.7	0.512718	0.541	58	11.4	0.19	0.121	21.2	0.092	28.8	5.1
	UP 73F AL*	7467	539	0.70512	29.9	0.512710	0.447	153	13.3	0.22	0.169	18.8	0.108	21.6	
	UP 74H AL*	7468	1360	0.70522	71.6	0.512724	0.428	177	10.0	0.18	0.154	27.8	0.085	33.8	
Ua Huka	UH 67H TR*	7469	646	0.70458		0.512750		344					0.022		
	UH 68F2 AL*	7470	473	0.70561	29.2	0.512741	0.416	268	13.1	0.22	0.176	20.4	0.091	16.2	
Fatu Huku	FTK-04 TR	6446	416	0.70501	28.2	0.512809	0.417	332	12.1	0.23	0.097	17.9	0.063	12.8	8.4
	FTK-09 TR	6450	577	0.70546	40.5	0.512781	0.437	358	11.5	0.23	0.130	20.5	0.071	14.0	9.0
	FTK-13 TR	6453	794	0.70427	39.4	0.512901	0.393	396	10.9	0.23	0.084	18.1	0.033	11.3	8.5
Hiva Oa	HVO-01 AL	6570	595	0.70475	40.4	0.512780	0.489	286	11.1	0.21	0.135	22.1	0.064	19.0	7.4
	HVO-07 TR	6575	399	0.70491	26.5	0.512813	0.455	381	11.3	0.25	0.110	19.0	0.055	12.3	9.7
	HVO-27 AL	6589	594	0.70483	38.6	0.512834	0.508	525	11.2	0.22	0.105	22.0	0.020	18.7	7.8

Trace element data from [15] and our unpublished data. Isotope data with * from [13].

Ratios are normalized to ⁸⁶Sr/⁸⁸Sr = 0.1194 and to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219. Values for NBS 987 standard: ⁸⁷Sr/⁸⁶Sr = 0.71025 ± 4 (2σ) and La Jolla standard = 0.51186 ± 3 (2σ).

Samples from Goguel Seamount (BJG) have been strongly altered by seawater. The data presented in this table have been obtained after leaching in 2N HCl for 30 minutes.

TH = tholeiites, TR = transitional basalts, AL = alkali basalts.

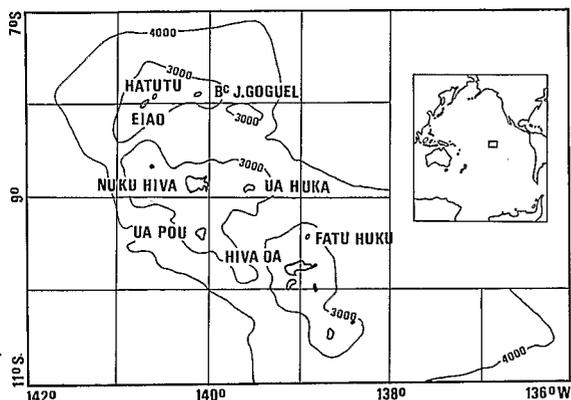


Fig. 1. Map showing the Marquesas Archipelago (after [15]).

ratio is generally attributed to low-pressure fractionation. This process is dominated by olivine and/or clinopyroxene crystallization as shown by the variation of Ni, Co and Cr [15].

The incompatible element (IE) concentrations, including REE, P and Ti increase with the differentiation and the degree of undersaturation and exhibit good positive interelement correlations. Trace element abundances and corresponding ratios also display large variations among basalts belonging to the same magmatic type. This is in

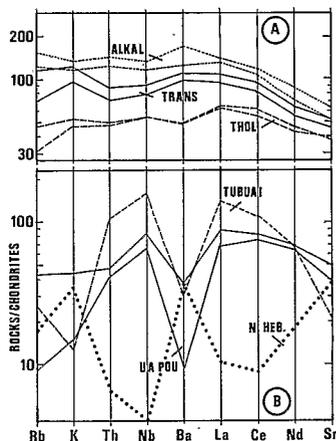


Fig. 2. Highly incompatible elements normalized to chondrites. A. Selection of representative samples: tholeiites from Eiao, transitional basalts from Fatu Huku, and alkali basalts from Nuku Hiva. B. Tholeiites from Ua Pou (UAP-11 and 17) compared with tholeiite from Tubuai (TBA-09). The dotted line shows the data for New Hebrides [36]. Data for Marquesas samples from [15], for Tubuai: our unpublished data. Normalization values from [43].

particular true for Ua Pou island where the tholeiitic basalts—clearly older than the alkali basalts [14]—are relatively depleted in K, Rb, Sr, Ba. Their normalized pattern (Fig. 2) differs from all other basalts from the Marquesas Archipelago and resemble those of Tubuai/Austral Archipelago (our unpublished data) and Mangaia/Cook Islands [11]. Other small but distinct differences according to magmatic type and islands are shown by ratios involving elements of about the same degree of incompatibility (e.g. Ba/La, Nb/La, etc., Table 1) and suggest the existence of chemical heterogeneities at various scales in the source regions. The upper mantle source for most basalts from the Marquesas was enriched in IE compared to a primordial mantle and had higher than chondritic ratios of several elements such as P/Ce, La/Ce [15].

3. Isotopic data

Nineteen samples from various islands in the Marquesas Archipelago, that were previously analyzed for trace elements [15], have been selected for Nd and Sr isotope determinations. The new data, all obtained in the Clermont-Ferrand laboratory, are reported with those published previously [13] in Table 1. Four new samples have been analyzed in the same laboratory for lead isotopes (Table 2). Among the latter, the three Ua Pou tholeiites have also been analyzed elsewhere [14]. The results are in excellent agreement with ours for $^{143}\text{Nd}/^{144}\text{Nd}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ but differ for $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$. Our measured values of these two latter ratios (measured in duplicate) are significantly higher than the previously reported values [14].

Nd-Sr isotopes. The Nd-Sr isotopes (Fig. 3) confirm the large range [13] of isotopic composition within a single island as well as the archipelago. The extreme isotopic variability observed for the basalts from Nuku Hiva is duplicated (and even increased) by the Ua Pou samples. The Marquesas samples now exhibit nearly the entire range of isotopic ratios observed in oceanic islands. In contrast to Hawaii [20], alkali basalts from the Marquesas archipelago have higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ than tholeiitic basalts in a given island and fall mainly within the Dupal

TABLE 2

Lead isotope data for Ua Pou Island

Ref. and type	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	Pb	μ	Th/U	U	Ce	Ce/Pb
UAP-11 TH	19.858	15.540	39.394	1.76	28	3.16	0.75	67	38
	19.858	15.532	39.373						
UAP-17 TH	19.993	15.564	39.662	1.3	15	6.80	0.30	61	47
	19.963	15.554	39.576						
UAP-24 TH	19.608	15.548	39.204	1.0	37	4.33	0.57	78	78
	19.626	15.558	39.173						
UP-73F AL*	19.23	15.62	39.23	3.3				77	23
UP-74H AL	19.228	15.635	39.260	6.7				188	28

The ²⁰⁶Pb/²⁰⁴Pb ratios can be considered as initial ratios, assuming an upper limit of age of 5 Ma [14,16,17]. Data with * from [13]. Values for NBS standard: ²⁰⁶Pb/²⁰⁴Pb = 0.059119, ²⁰⁷Pb/²⁰⁴Pb = 0.91372, ²⁰⁸Pb/²⁰⁴Pb = 2.1623. Precision: 0.1% for ²⁰⁶Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb, 0.15% for ²⁰⁷Pb/²⁰⁴Pb. Pb contents determined by ID except for sample UP-73F which has been analyzed by XRF. Pb isotope determination techniques have been described elsewhere [42].

anomaly OIB field [21]. Furthermore, tholeiites from Ua Pou plot below the mantle array and close to St. Helena, Tubuai and Mangaia islands [11,13,22].

In each of the three islands (Ua Pou, Nuku Hiva, Fatu Huku) which display the largest isotopic variations, ¹⁴³Nd/¹⁴⁴Nd vs. ⁸⁷Sr/⁸⁶Sr ratios define a trend similar to that of the Society Islands basalts with a shallower slope than the mantle array [23]. If this trend results from binary mixing then one end-member has an ε_{Nd} lower

than that of the MORB source. In fact ternary mixing involving depleted MORB mantle (DMM), enriched mantle (EM) and a third component (HIMU) appears more likely [5].

Pb isotopes. The Pb isotopes (Fig. 4) also clearly separate the Ua Pou tholeiites from all other basalts from the Marquesas Archipelago. The latter are enriched in ²⁰⁷Pb and ²⁰⁸Pb relative to ²⁰⁶Pb and fall within the Dupal OIB field above the NHRL [5]. The tholeiites from Ua Pou (Table 2)

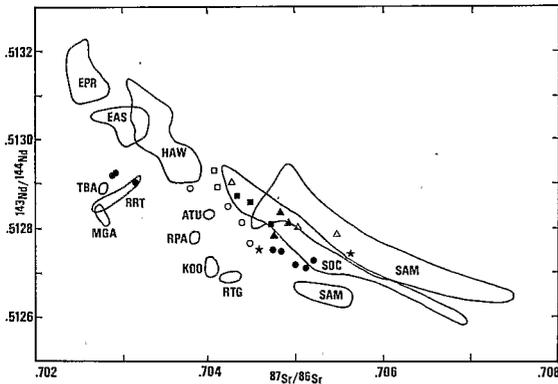


Fig. 3. ⁸⁷Sr/⁸⁶Sr vs. ¹⁴³Nd/¹⁴⁴Nd showing data for Marquesas basalts (from [13] and present data) as follows: □ = Eiao, ■ = Hatutu, ○ = Nuku Hiva, ● = Ua Pou, ★ = Ua Huka, △ = Fatu Huku, ▲ = Hiva Oa). Fields represent data for EPR = East Pacific Rise, EAS = Easter Island, HAW = Hawaiian Islands, SOC = Society Islands, SAM = Samoan Islands, KOO = Koolau (Oahu/Hawaiian Islands), STH = Saint Helena, and for the Austral and Cook Islands as follows: TBA = Tubuai, RRT = Rurutu, ATU = Atiu, RPA = Rapa, RTG = Rarotonga. Data are from references 4, 11, 13, 44-48.

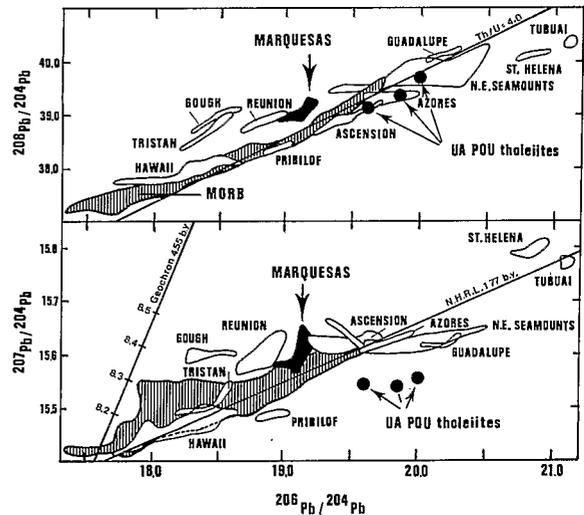


Fig. 4. Pb isotopic ratios for Ua Pou tholeiites (●) as from Table 2 compared with data from selected oceanic islands (after [5]). The Marquesas field is based on data from [13] and includes samples UP-73F and UP-74H (alkali basalts from Table 2).

have relatively lower ^{207}Pb and higher ^{206}Pb and are thus displaced below the 1.7 Gyr secondary Pb-Pb isochron in the $^{207}\text{Pb}/^{206}\text{Pb}$ diagram (Fig. 4). Finally they have less radiogenic Pb than St. Helena, Tubuai or Mangaia. The Ua Pou tholeiites define a sub-horizontal line on the $^{207}\text{Pb}/^{206}\text{Pb}$ diagram which may indicate that the U/Pb ratio of their mantle sources increased recently (several hundred millions of years). Alternatively, this pattern may reflect binary mixing between MORB mantle and a mantle component with composition close to the source of Ua Pou tholeiite UAP-17. In any case, the source of the latter has suffered a recent increase of its U/Pb ratio compared with the other OIB sources.

4. Relationships between isotopic ratios and trace elements

In basalts from the Marquesas Archipelago isotopic ratios clearly vary simultaneously with several trace element ratios. For example, ϵ_{Nd} correlates positively with the following trace element ratios: Sm/Nd, Nb/La, Zr/Nb, K/Rb, K/Ba, and negatively with La/Yb, Rb/Sr, La/Ce, Ba/La and Th/La, some of them being plotted in Fig. 5.

It is noteworthy that these correlations are independent of the relative sensitivity of the elemental ratio to mineral fractionation. Hence, they may reflect the difference in composition between the parent magmas of the three basaltic types, tholeiites and alkali basalts exhibiting extreme values with transitional basalts being intermediate. In some cases the correlation exists between isotopic composition and trace element ratios in a single magmatic type. This is true in particular for $^{143}\text{Nd}/^{144}\text{Nd}$ vs. K/Rb in alkali basalts (Fig. 5).

Because Nd isotopic ratios are not affected by seawater alteration, the low K/Rb ratio (< 200) observed in alkali basalts from Ua Pou is probably a primary feature. Such low ratios, unusual in OIB [24], are characteristic of late-stage differentiation products in granitic systems [25] and are also observed in some kimberlites [26] and oceanic sediments [27,28].

The negative correlations between ϵ_{Nd} and incompatible element abundances (e.g. Th, Rb, Ba, Nb, etc.) recognized in the present study also appear in MORB [29–33] where they are

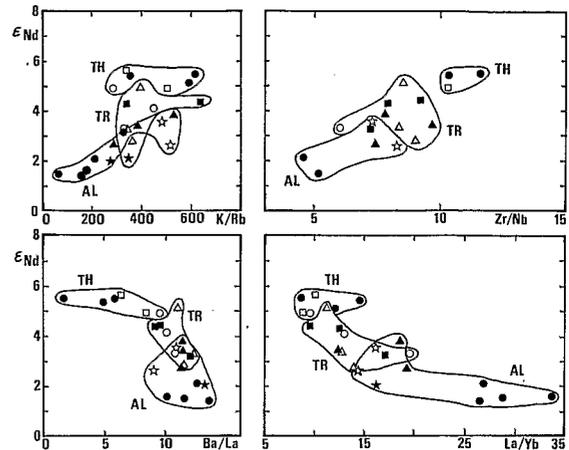


Fig. 5. ϵ_{Nd} vs. element ratios (symbols as in Fig. 3, plus \star = Banc Jean Goguel). Data fields for TH = tholeiites, TR = transitional and AL = alkali basalts.

interpreted a result of mixing between two sources with contrasting compositions. In contrast, the observed relationships between isotopic and trace element ratios in the Marquesas lavas differ from those reported for the Hawaiian Islands [20,34]. For instance, like MORBs, basalts from the Marquesas Archipelago exhibit a positive correlation between $^{143}\text{Nd}/^{144}\text{Nd}$ and Sm/Nd while this correlation is negative in basalts from some of the Hawaiian volcanoes.

5. Interpretation

5.1. Identification of end-members

At least three distinct end-members may be suggested from the observation of Figs. 3 and 4. Following Zindler and Hart [5] these are: the depleted MORB mantle (DMM), the enriched mantle (EM) with low $^{143}\text{Nd}/^{144}\text{Nd}$ and high $^{87}\text{Sr}/^{86}\text{Sr}$, and the high U/Pb, low Rb/Sr component labelled HIMU. Furthermore, the correlation between ϵ_{Nd} and element ratios as exemplified by Fig. 5 may help in deciphering the nature of the enriched mantle. For $\epsilon_{\text{Nd}} < 1$, this end-member component should have La/Ce > 0.55, Th/La > 0.15, Ba/La > 13, Nb/La < 1, K/Rb < 200, Rb/Sr > 0.15. Such values are never found in undersaturated magmas such as nephelinite and basanite. They are occasionally encountered in some kimberlites [26] but in fact they are more

typical of upper crust and continentally derived marine sediments [28].

In a first approximation, the third end-member is roughly represented in Fig. 3 by the tholeiites of Ua Pou with Nd-Sr isotope compositions close to St. Helena, Tubuai [13] and Mangaia [11,22], marked by low $^{87}\text{Sr}/^{86}\text{Sr}$ implying a long-term depleted source perhaps similar to MORB. The tholeiites of Ua Pou differ from all other Marquesas basalts by their relative depletion of alkali and alkali-earth elements [15]; this characteristic is also observed in Tubuai (our unpublished results), Mangaia [11] and St. Helena [35] basalts. All these basalts display trace element patterns which are the mirror-image of island arc tholeiites (IAT) [36] patterns (Fig. 2). This generalization applies also to the high field strength (HFS) elements when considering such ratios such as Hf/Lu. Compared with MORB, this ratio is relatively high in tholeiites of Ua Pou and low in IAT (see, for instance, [27]). These differences suggest that the elements gained by IAT are lost to the source of these particular OIB rocks and vice versa. The high U/Pb of Ua Pou tholeiite sources implied by Pb isotopes may be explained in the same way by depletion of Pb in this source. Indeed a relatively high Pb/La ratio [37] and low μ value [38] characterize IAT. The Pb depletion of

the Ua Pou tholeiite source is further supported by the very high Ce/Pb ratio in the Ua Pou tholeiites (Table 2) compared with this ratio in MORB and OIB (average 25 ± 5) reported in [39]. In short, the mantle source of Ua Pou tholeiites appears to be complementary to the IAT. We suggest that the trace element characteristics of Ua Pou tholeiites are inherited from the subduction process as in Mangaia [11] and that the source of the Ua Pou tholeiites was residual, subducted lithosphere that previously melted to form IAT.

5.2. Consequences for the origin of Marquesas basalts

In Fig. 6, the Marquesas basalts plot in the domain delineated by the mixing lines involving three distinct end-members, the third one (enriched component) possibly with variable $^{87}\text{Sr}/^{86}\text{Sr}$. In the simplistic hypothesis of mixing between solid end-members, calculations indicate that this third end-member is present in small but variable proportions in most of the Marquesas basalts. On the other hand it is practically absent from the tholeiites of Ua Pou which result from melting of a source formed by mixing between DMM and HIMU as also suggested from Pb isotopes (Fig. 4).

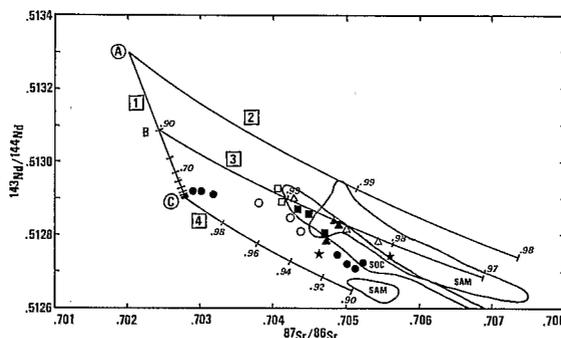


Fig. 6. $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$. 1 = Mixing line between source A: DMM and source C: HIMU with parameters for calculation [5]. 2, 3 and 4 are mixing lines between an enriched component (EC) of composition assumed for the convenience of calculation to be that of marine sediments [28] with respectively A, B and C. The $^{87}\text{Sr}/^{86}\text{Sr}$ of the enriched component is taken as 0.720 for lines 2 and 3 and 0.715 for line 4. The ticks along the mixing lines indicate proportions of mixing (e.g. on line 2 .99 is the proportion of component A). Fields shown are for SOC = Society Islands, SAM = Samoa Islands [48]. Data for the Marquesas Islands: same symbols as in Fig. 3 [13, and present paper]. Model parameters for the end-members considered as solids are as follows:

Component	Sr (ppm)	Nd (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	Reference
DMM	12	0.65	0.7021	0.5133	[5]
HIMU	120	6.5	0.7028	0.5129	[5]
EC	250	33	0.715–0.720	0.5122	[28]

At this point in the discussion a question arises concerning the origin of this enriched component. From isotopic evidence, two alternatives may be suggested: sub-continental mantle or subducted oceanic crust and sediments.

The first alternative implies contamination by a liquid produced from the sub-continental mantle by very low degrees of partial melting in order to justify the estimated elemental ratios of this end-member. Most of these ratios, however, remain exceptional for magmatic liquids and some, such as $\text{Th/La} > 0.15$ or $\text{La/Ce} > 0.55$ have never been observed.

On the other hand high values of these two ratios, common in the upper crust and especially in continentally derived marine sediments favour the second alternative. However, the influence of sediments remains questionable on the basis of recent findings reported in [39].

Nevertheless our hypothesis fits well with a model in which tholeiites of Ua Pou result from an ancient residual subducted lithosphere and in which a simple addition of small but variable amounts of subducted crust and more or less sediments are sufficient to explain trace element and isotopic variations in all other Marquesas basalts. Also, the isotopic data reported in Fig. 6 may indicate that such a model could be applied to the whole region of Polynesia.

6. Conclusion

Basalts from the Marquesas Archipelago display both trace element and isotopic heterogeneities at various scales. Large heterogeneities exist between magmatic types and also within a single type.

The data are consistent with an origin by mixing of magmas generated from chemically distinct end-members, and the chemical variation ranging from tholeiite to alkalic basalt may reflect the proportion of mixing rather than the degree of partial melting. This is also documented on the basis of petrological data [41]. The main component (up to 90% of the mixture) is depleted in incompatible elements and is of the type commonly suggested as the source of MORB. Tholeiites from Ua Pou island resemble in several aspects the Tubuai (Austral Islands) and Mangaia (Cook Islands) basalts. The Ua Pou lavas may result

from a mixture between depleted mantle and residual subducted lithosphere after extraction of IAT. However their source experienced a recent Pb depletion event. All other basalts require addition of a small but variable amount of a third component with high $^{87}\text{Sr}/^{86}\text{Sr}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$.

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