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Temporal geochemical evolution in oceanic intra-plate volcanics: a case study from the Marquesas (French Polynesia) and comparison with other hotspots

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Abstract. Sr-, Nd-isotopic and trace element data are reported for a suite of Marquesan volcanic rocks. These data complement earlier work on the island of Ua Pou and reveal that the marked shifts in source composition between shield-building and post-shield eruptives noted there are common to most islands in the archipelago. In addition, there appears to be a relationship between the magnitude of these shifts and the repose period between shield-building and post-shield activity such that, the longer the period of volcanic inactivity, the larger the isotopic and trace element differences between the two phases of volcanism. This, coupled with the compositional uniformity of the shield-building phase, and its close geochemical similarity to depleted mantle reservoirs, implies a strong lithosperic control on magmatic evolution: models invoking entrainment of asthenospheric material during plume ascent are not readily compatible with the observed time-compositional paths. Comparisons with other oceanic islands reveal two 'end member' styles of temporal evolution, herein termed 'Marquesan' and 'Hawaiian', and attributed to the interaction between the oceanic lithosphere and respectively weak and strong plumes, terms used to denote penetrative capacity and not necessarily size or buoyancy flux. Many other plumes may display characteristics intermediate between these extremes. The state of stress and temperature within the oceanic lithosphere in the region of an ascending diapir is also likely to exert a strong control on the geochemical evolution of OIB suites.

Introduction

The geochemical characteristics of most ocean island basalt (OIB) suites can be interpreted in terms of multi-component mixing processes involving up to five distinct end-members (e.g. White 1985; Zindler and Hart 1986). However, many recent studies of OIB show considerable structure in the data for individual islands and, in particular, often reveal an apparent temporal shift in source composition, as revealed by isotope and trace element analyses, between shield-building and post-shield phases of volcanism: for example, a geochemical study of the island of Ua Pou in the Marquesas (Duncan et al. 1986). In the case of the Marquesas, considerable debate has focused on the question of whether such changes reflect the influence of distinct plume sources (e.g. Dupuy et al. 1987) or the interaction of a single plume with the oceanic lithosphere or asthenosphere (e.g. Duncan et al. 1986). In the present study, new isotope and trace element data have been obtained on Marquesan samples for which a detailed K-Ar chronology is already available. These have then been combined with existing data, collated from the literature, to provide a synthesis of the geochemical evolution of the Marquesan chain, thus allowing comparison with other oceanic intra-plate settings.

Geology and previous work

The Marquesas comprise a group of 12 volcanic islands and associated seamounts which rise as discrete volcanic edifices from oceanic crust of Palaeocene age in the south central Pacific (Fig. 1). The group stretches northwesterly from Fatu Hiva (10°35′ S 138°35′ W) to Eiao (8°00′ S 141°27′ W) in an approximatcly linear arrangement, sub-parallel to the other volcanic archipelagos of the region. Most of the islands are small but often attain heights in excess of 1000 m, with rugged relief.

Early accounts of the geology of the Marquesas are provided by Lacroix (1928), Chubb (1930) and Obellianne (1955), while, more recently, major and trace element data have been published by Bishop and Woolley (1973), Brousse and Guille (1978), Brousse et al. (1978) and Liotard et al. (1986). Trace element, isotopic, and geochronological studies have been provided by Duncan and McDougall (1974), Vidal et al. (1984), Duncan et al. (1986), and Dupuy et al. (1987). These papers reveal a considerable trace element and isotopic heterogeneity within the Marquesan lavas which is comparable to, if not greater than, that observed in most other OIB suites.

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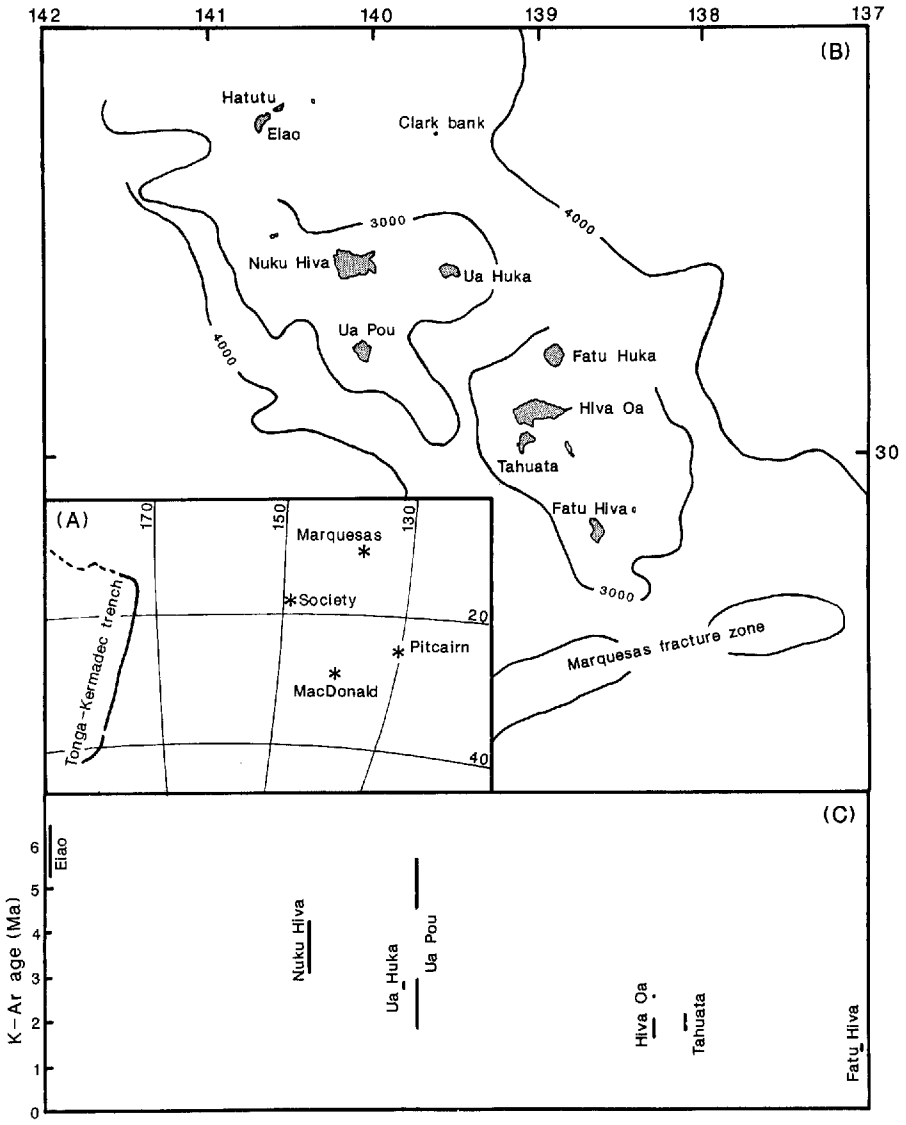

Fig. 1. **A** Location map showing four major, presently active hotspots in the south-central Pacific region. **B** The Marquesan archipelago, after Admiralty Chart 4607 (Southeast Polynesia). Water depths in metres. **C** K-Ar age ranges for various Marquesan islands (data from Duncan 1975; Brousse and Bellon 1974). Note extended period of volcanism at Ua Pou

K-Ar geochronology of subaerial lavas (Duncan and McDougall 1974) shows a general age progression to the southeast implying a plate migration rate of ~9.9 cm/yr, although some marked irregularities in this general trend seem to occur e.g. volcanic activity at Ua Pou spans most of the range noted in the other islands (Fig. 1c). In common with many other oceanic islands, the initial shield-building phase of volcanism is often separated from post-shield activity by a hiatus, during which erosion of the volcanic edifice can occur and, in addition, a detailed isotopic study of Ua Pou has shown that, on this island, the shield-building and post-shield volcanics also appear to have very distinct sources (Duncan et al. 1986). Coupled with these variations is a pronounced increase in alkalinity with time throughout the archipelago, which is largely attributed to a steady decrease in the degree of partial melting (Vidal et al. 1984; Liotard et al. 1984).

Analytical techniques

Samples analyzed in this study are a subset of those collected for K-Ar geochronology by Duncan (1975); sample locations and major element analyses can be found in this reference. Trace element concentrations were determined at the Department of Earth Sciences, Oxford by X-ray fluorescence techniques on pressed powder pellets, using a Philips PW1400 spectrometer with data processing by PDP11 minicomputer. Calibration lines were constructed using up to 25 recommended USGS standards. Details of counting times, operating conditions and detection limits can be found in Woodhead (1987). Precision is generally better than 5%. Uranium concentrations were determined by isotope dilution and precision, based upon duplicate sample dissolutions, is estimated to be better than 1%.

Sr and Nd were separated at the Australian National University by conventional ion exchange techniques on 100 mg samples, after a brief 6N HCl wash to remove any potential surficial contaminants: chemical and loading blanks are negligible. Uranium samples were separated on anion exchange columns in 7N HNO_3 and the U eluted in H_2O. Sr and Nd samples were run on single Ta and Re-Ta double filaments respectively; uraniums were run on single Ta filaments with H_3PO_4 (as for Sr). All isotope ratio determinations were performed on a Finnigan MAT 261 mass spectrometer used in static multi-collector mode.

$^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios are normalized to $^{86}Sr/^{88}Sr = 0.1194$ and $^{144}Nd/^{146}Nd = 0.7129$ respectively. Over the course of this study analysis of NBS 987 Sr standard and the La Jolla Nd standard provided mean values of $^{87}Sr/^{86}Sr = 0.710208 \pm 4$ and $^{143}Nd/^{144}Nd = 0.511869 \pm 2$ respectively. 2σ precision in Table 1 refers to within-run statistics.

Table 1. New isotope analyses for Marquesan samples. 2σ precision refers to within-run statistics

Sample no.	Island	Age (Ma)	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$
73-11 (S)	Nuku Hiva	3.89	0.704007±14	0.512895± 9
73-12 (S)	Nuku Hiva	4.22	0.704012±15	0.512892±10
73-13 (S)	Nuku Hiva	3.93	0.703892±16	0.512899±10
73-18	Nuku Hiva	3.02	0.704369±14	0.512848± 9
73-19 (S)	Nuku Hiva	3.79	0.703502±13	0.512939± 7
73-22	Nuku Hiva	3.76	0.704472±13	0.512835± 8
73-6	Ua Huka	2.71	0.705447±15	0.512756± 4
73-8	Ua Huka	2.78	0.705440±17	0.512782± 7
73-28	Hiva Oa	1.59	0.704850±16	0.512825± 8
73-31	Hiva Oa	1.58	0.705011±15	0.512838± 9
73-32 (S)	Hiva Oa	2.47	0.703584±25	0.512925± 4
73-33	Hiva Oa	1.99	0.705330±19	0.512799±12
73-40	Tahuata	2.04	0.704316±18	0.512825± 7
73-43	Tahuata	1.78	0.704109±14	0.512845±11
73-44 (S)	Fatu Hiva	1.39	0.703769±17	0.512907± 8
73-47 (S)	Fatu Hiva	1.30	0.703855±13	0.512740± 9

K-Ar ages from Duncan and McDougall 1974. (S) = Shield-building lava

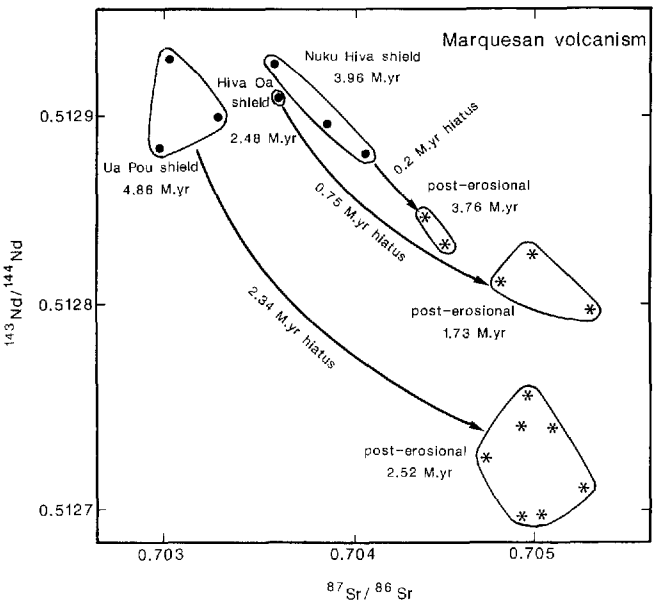

Fig. 2. $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ for the islands of Ua Pou, Nuku Hiva and Hiva Oa. Shield building and post-shield eruptives identified on the basis of field relations, K-Ar dating (Duncan 1975) and normative mineralogy. Extent of volcanic hiatus established on the basis of published K-Ar data

Results

New isotope and trace element data from this study are presented in Tables 1 and 2. The data used in the figures also include analyses from the literature (Vidal et al. 1984; Duncan et al. 1986; Liotard et al. 1986; Dupuy et al. 1987) and where possible, as in the case of the isotope data, ratios from the literature have been corrected to account for inter-laboratory variation in the measured values of reference standards. The new Sr and Nd data obtained are comparable to previous work. However, in the past, some discrepancy has been noted in the precise Pb isotopic composition of tholeiitic rocks from the island of Ua Pou: data obtained by Dupuy et al. (1987) showed significantly higher $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios than those obtained by Duncan et al. (1986) for the same samples. Both are somewhat unusual, plotting to high $^{206}Pb/^{204}Pb$, similar to some 'HIMU' type sources (the term HIMU is used to define sources which appear to have evolved under conditions of extremely high U/Pb and Th/Pb ratio), but without the concommitant high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios typical of these i.e. they fall *below* the 'mantle array'. There must remain some doubt, therefore, as to whether these samples may have suffered some form of Pb contamination (see McDonough and Chauvel 1991, for further discussion of this issue). As these same samples were the only ones from Ua Pou available to this study, no new Pb-isotopic analyses have been attempted here.

Table 2. New trace element analyses (all values in ppm) for Marquesan samples

Sample	73-6	73-8	73-11	73-12	73-13	73-18	73-19	73-22	73-28	73-31	73-32	73-33	73-40	73-43	73-44	73-47
Zn	130	107	105	113	112	103	112	108	121	128	110	118	108	109	112	118
Cu	34	60	95	101	76	43	91	61	81	86	81	14	74	61	57	105
Ni	234	366	170	86	395	138	70	100	57	51	246	25	314	91	593	119
Co	97	83	80	71	78	56	62	52	42	65	69	35	71	53	93	67
Cr	353	620	392	153	690	289	179	84	25	25	387	35	495	84	846	151
V	335	329	335	346	307	238	338	303	339	349	276	252	300	310	257	312
Ba	545	439	206	206	174	669	185	531	555	702	351	556	393	354	249	303
Ga	24	21	22	22	19	23	23	26	27	29	23	27	21	25	18	25
Rb	52	50	18	27	13	85	18	60	64	79	27	83	34	36	16	55
Sr	752	533	400	442	365	766	448	811	857	947	681	688	529	575	462	572
Y	31	26	32	33	43	32	34	32	42	51	33	44	27	35	27	374
Zr	242	210	214	255	215	287	261	320	400	389	348	423	214	295	255	277
Nb	36	33	22	27	20	52	25	46	58	59	44	56	37	40	34	39
Pb	6	5	3	2	6	5	3	6	6	7	5	9	4	4	5	4
U	1.15	1.00	0.59	0.68	0.45	1.64	0.55	1.61	1.77	1.74	1.11	2.06	1.01	1.08	0.72	0.85

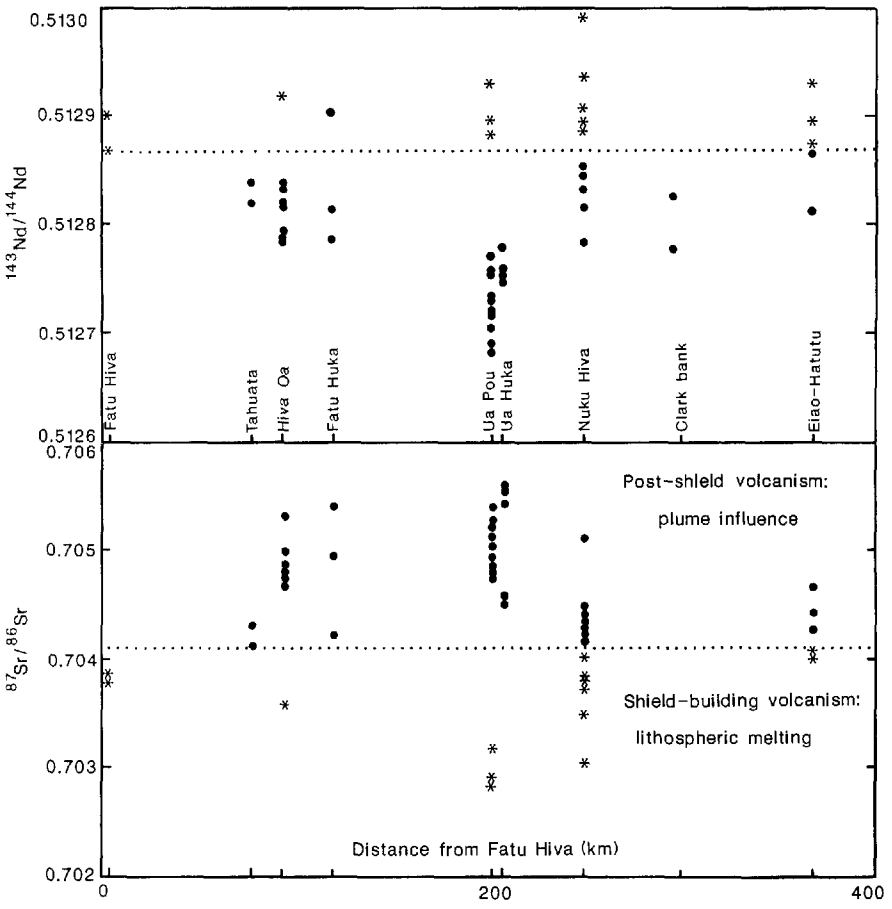

Fig. 3. Variation in $^{143}Nd/^{144}Nd$, and $^{87}Sr/^{86}Sr$ for all analyzed Marquesan lavas. In each case consistent differences are observed between shield building and post-shield volcanics. These variations are mirrored by Zr/Nb, K/Rb, Nb/U, La/Nb, La/Yb, Th/La and Ba/La ratios

Table 3. Comparison of trace element ratios in Marquesan volcanics with N-type and P-type MORB (data from this study, Dupuy et al. 1987; Sun and McDonough 1989)

	Rb/Sr	Sm/Nd	Zr/Nb	Ba/Nb	Ba/Zr	Nb/U	La/Yb
Post-shield	0.18–0.23	0.06–0.17	2–8	9–13	1.2–4.15	30–35	15–35
Shield-building	0.02–0.04	0.23–0.27	7–12	4–9	0.3–1.0	40–80	8–15
P-MORB	0.03	0.28	9	7	0.8	46	3
N-MORB	0.006	0.36	32	3	0.08	50	0.8

Duncan (1975) distinguished shield-building from post-shield lavas on the basis of field relations and petrology, prior to K-Ar dating. In the present study, this original classification is retained with respect to the samples from Ua Pou, Nuku Hiva and Hiva Oa. These samples strongly suggest that the vast majority of shield-building volcanic products in the Marquesas are tholeiitic, a notion universally held in the literature. Therefore, the criterion of normative mineralogy, and in particular the presence of normative hypersthene, has been used to define shield-building lavas when using literature data where age/field data are not quoted.

As previously noted, a geochemical study of Ua Pou island highlighted a profound change in source composition, as revealed by isotope and trace element data, between shield-building lavas, generally of tholeiitic composition, and more alkaline, post-shield volcanics. The data obtained in this study reveal that shield-building lavas from Hiva Oa and Nuku Hiva, two other islands in the Marquesan group, also have distinct isotopic and trace element signatures (Fig. 2), as originally predicted by Duncan et al. 1986. A compilation of analyses from the literature, forming an extensive data base, demonstrates that this is a recurring phenomenon: at each island in the chain alkaline, post-shield lavas show consistent differences in isotopic and trace element composition from their tholeiitic, shield-building counterparts (Fig. 3). In each case, the initial, shield-building phase is rather uniform in isotopic composition, being essentially identical on Fatu Hiva, in the south, to Eiao, in the far north. $^{143}Nd/^{144}Nd$ ranges from 0.5129–0.5130 and $^{87}Sr/^{86}Sr$ from 0.7030–0.7040. Incompatible trace element ratios, although more variable between islands, are also relatively constant at Ba/Zr ~ 1, Zr/Nb ~ 10, Nb/U ~ 40–50 (Table 3).

Post-shield volcanism is generally alkaline in character and shows both more 'evolved' and more variable isotopic ratios with, for example $^{143}Nd/^{144}Nd$ ranging

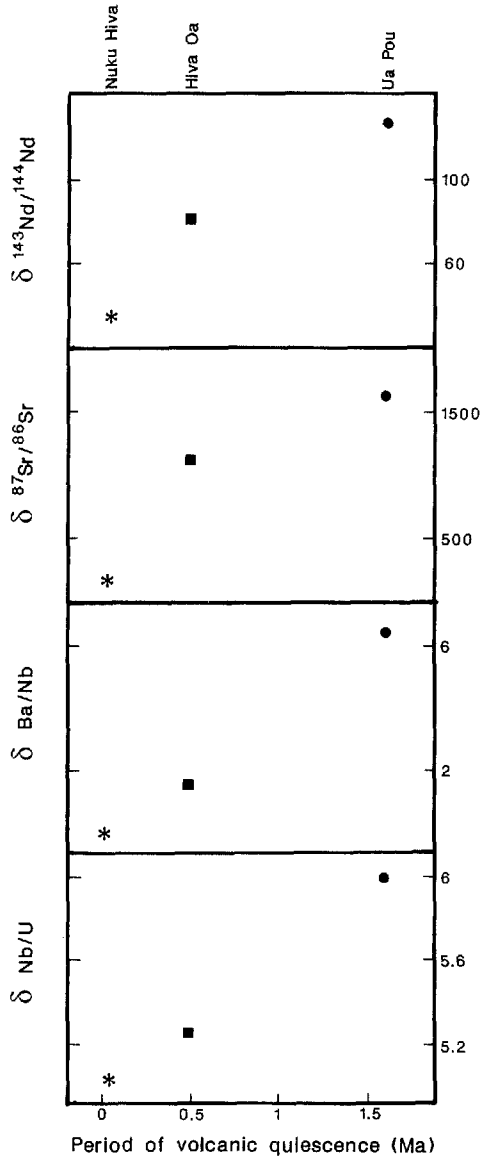

Fig. 4. δ functions (see text for definition) versus period of volcanic quiescence, as determined from K-Ar data, for the islands of Ua Pou, Nuku Hiva and Hiva Oa. The duration of volcanic inactivity appears to be correlated with degree of shift in isotope and trace element ratios

from 0.51285–0.51270, depending upon location in the chain. In general, post-shield lavas are also characterized by lower Zr/Nb, K/Rb and Nb/U and higher La/Nb, Ba/Nb, La/Yb, Th/La and Ba/La (Duncan et al. 1986; Dupuy et al. 1987).

Shield-building volcanism appears to be separated from post-shield activity by a marked hiatus of variable duration (Fig. 2): thus, at Ua Pou, the period of volcanic quiescence is around 2 Ma while at Nuku Hiva it appears to be only 0.2 Ma. Clearly estimation of the size of these periods of inactivity is affected to some extent by sampling statistics. However, considering the relatively large number of samples available for Ua Pou, where this hiatus appears to be the largest, it is likely that the data have some real age significance. If we accept these premises, then it is of great interest to note that the duration of volcanic inactivity appears to correlate with the size of the isotopic and trace element shifts noted between volcanic phases on each island (Fig. 2). Thus, for example, at Ua Pou, where we observe a very long apparent hiatus, the change in Nd isotopic character between the most isotopically 'evolved' shield volcanics and the most 'depleted' post-shield volcanics is large, of the order of 2 epsilon units. In contrast, at Nuku Hiva, where post-shield volcanics were erupted relatively soon after the shield-building phase, we observe only a minor shift in Nd isotope composition, of the order of 0.3 epsilon units. Hiva Oa shows intermediate behaviour in terms of the duration of its hiatus and the size of the isotopic shift observed. These features are displayed in Fig. 4, which shows a general positive correlation between the duration of volcanic inactivity and the term, δNd (defined as the smallest observed difference in isotopic composition between shield-building and post-shield lavas $\times 10^4$), a corresponding δSr term, and similar functions for Ba/Nb and Nb/U.

Discussion

Shield-building volcanism in the Marquesas: the origin of the depleted component

Considerable effort has been (and still is) directed towards characterization of the four or more mantle end-members involved in OIB genesis. For speculation on the origin of the 'enriched' components in the Marquesas, the reader is referred to the more recent references in the second section. However, attention here focuses on the depleted end-member which appears to dominate the shield-building phase of Marquesan volcanism. At least three contrasting models of magmagenesis can be considered (Duncan et al. 1986). In the first, a relatively homogeneous mantle plume enters the lower lithosphere, large degrees of partial melting produce a tholeiitic plume-lithosphere mix whose composition varies according to the degree of melting and the proportions of melt contributed. As the volcano migrates away from the plume, temperatures at the base of the lithosphere decrease and then smaller degrees of partial melting produce magmas of alkali basalt character. These pass through the same conduit which has earlier yielded a low temperature melting fraction, hence wall-rock assimilation is less and the plume composition dominant. Alternatively, isotopically distinct phases of volcanism may originate within the plume itself, either as a result of original heterogeneity (i.e. a plume source having a depleted character in part) or of the incorporation of asthenospheric material during ascent. Tholeiitic melts are then generated over the centre of the plume while smaller volume alkali basalt melts form over the perimeter.

Compositionally, the shield-building phase is very similar in all the Marquesan islands, in terms of both isotope and many trace element ratios and, further, bears a close resemblance to transitional or 'P-type' Mid Ocean Ridge Basalt or MORB (Table 3). This sub-type

is widely regarded as normal, 'N-type' MORB, which has been contaminated by a small component derived from a plume source and, indeed, P-MORBs are generally found on elevated portions of ocean ridges in the vicinity of active hotspots e.g. on the mid-Atlantic ridge close to the Icelandic plume (e.g. White and Schilling 1978).

Distinction between the alternative models presented here is not an easy undertaking since the lower lithosphere may, in part, form by accretion from the convecting asthenosphere and, hence, be compositionally very similar to the latter. However, of the models proposed, original heterogeneity in the plume source can probably be discounted, given both the regularity of the time-composition paths observed at each island and the close correspondence in geochemistry between shield building eruptives and depleted mantle reservoirs. A choice between entrainment of asthenospheric material in a rising diapir and lithospheric involvement is more problematic. In recent years experimental and theoretical studies have provided a variety of hypotheses for the physical nature of plumes. A distinction has been made between the large spherical 'heads' of newly initiated plumes and the longer lived 'tails' which approximate to a cylindrical conduit in form. Griffiths and Campbell (1990) have postulated that the former may incorporate surrounding mantle material during ascent as the result of conduction of heat into a thin boundary layer surrounding the sphere. However, although plume heads have been proposed as the progenitors of flood basalt and oceanic plateau volcanism (e.g. White and MacKenzie 1989; Mahoney and Spencer 1991), in these models oceanic island basalts are generally thought to be the surface expression of the longer lived tails. For simple vertical conduits, Loper and Stacey (1983) have shown that very little heat is lost during magma ascent and thus assimilation of surrounding mantle is minimal, but experiments by Griffiths and co-workers (e.g. Richards and Griffiths 1989; Griffiths and Campbell 1991) imply that plume tails, deflected by horizontal shear flow in the mantle, *can* incorporate material by a coupling of heat conduction and non-axisymmetric flow in the conduit. Entrainment is most likely in the upper mantle where shear flow and plume inclination are the greatest: plumes then assume the form of paired conduits with heated, entrained material in between the pair, and continuous lateral shear produces a V-shape in plan-section. It has been suggested that thermal entrainment of this kind might explain the 'open horseshoe' pattern of Sr-isotope enrichment noted in the Galapagos islands (Geist et al. 1988), although this suggestion has now been refuted by Feighner and Richards (1991) in favour of a lithospheric control.

In the Marquesas, two factors argue strongly in favour of a high level (lithospheric or crustal) control on temporal evolution, thus implying that entrainment is of lesser importance: (1) the striking repetition of time-composition paths observed at each island where shield building eruptives have been sampled (Ua Pou, Nuku Hiva, Hiva Oa, Fatu Huka and Eiao-Hatutu), coupled with the compositional uniformity of the shield building phase, and (2) the observation that prolonged periods of quiescence between shield-building and post-shield phases of volcanism appear to produce larger isotopic and trace element differences between the two phases, presumably due to an increase in the influence of the plume component on the post-shield eruptives with time. Such an observation is readily accommodated by a model in which plume-derived melts gradually accumulate in high level magma chambers prior to eruption. The longer the time interval, the greater the volume of plume melt accumulated and hence the nearer the magma composition approaches that of the plume (a simple dilution effect assuming a small lithospheric melt component is present). The geochemistry of the Marquesan shield-building volcanics would therefore appear to be more easily explicable in terms of a repeated, regular process of plume-lithosphere interaction beneath each volcano (note here that a rigid definition of 'lithosphere' is not adopted as it is not possible within the bounds of this data set to establish at what depth interactions occur; the term is used merely to contrast with asthenospheric entrainment). If this is the case, the similarity in isotope and trace element ratios between the shield building eruptives and P-type MORB is not at all surprising, indeed it is to be expected. These observations do not discount the likelihood of asthenospheric involvement but merely suggest that temporal geochemical trends in the Marquesan volcanics are largely controlled by other factors.

It has been noted (e.g. Wyllie 1988) that the thermal structure imposed by a plume impinging on the lower lithosphere is not conducive to extensive melting of the latter. However, it seems likely that, if plumes are to reach the surface at all, some form of plume-lithosphere interaction must occur, especially where emplacement of high temperature picritic melts (e.g. Clague et al. 1991) and ponding of magmas in lithospheric and subvolcanic magma chambers are involved. A schematic model for the evolution of Marquesan volcanism is thus presented in Fig. 5. An ascending mantle diapir lodges within the lithosphere, whereupon heat transfer causes melting. Initially, melts with a larger lithospheric component may reach the surface producing the shield-building phase of volcanism. With time, greater proportions of plume-derived material may then ascend along the same lithospheric conduits which have previously yielded melt and eventually reach the surface, after a period of residence in high-level magma chambers. This period of residence would determine the exact ratio of plume: lithospheric melt in the post-shield phase volcanics. Thus, it is likely that the length of the repose period, and hence the composition of the post-shield volcanics, will be governed by variables such as magma chamber size, input/output dynamics, temperature contrasts and volatile content.

Contrasting styles of plume emplacement: 'weak' versus 'strong' plumes

In the light of these data at least two contrasting styles of temporal evolution can be recognized in ocean island

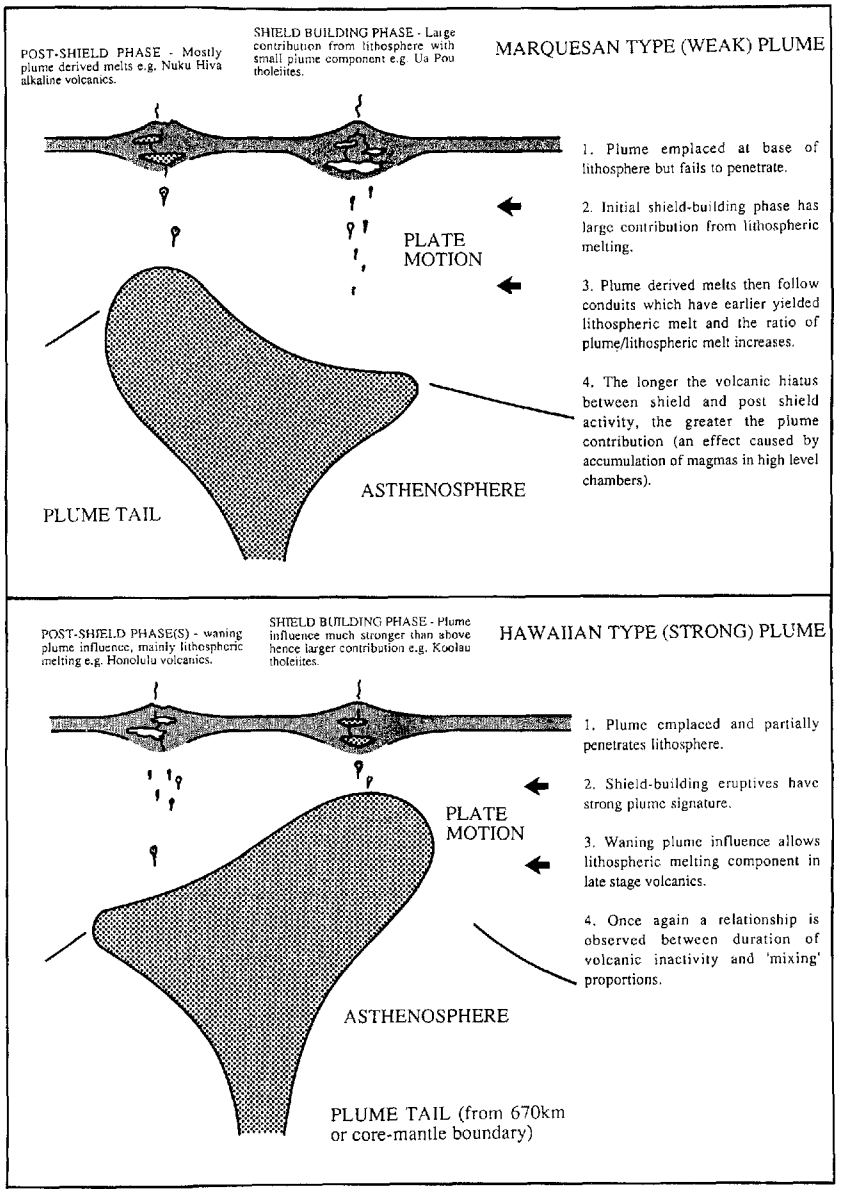

Fig. 5. Schematic diagram showing contrasting lithospheric responses to weak ('Marquesan type') and strong ('Hawaiian type') plumes. See text for discussion

basalt suites. In the case of the Marquesas, shield-building volcanism may be influenced by substantial lithospheric melting and only in the subsequent post-shield phase is a reasonably 'uncontaminated' plume signal attained. However, in the case of the Hawaiian islands, for example, the situation is reversed with the shield-building lavas having an isotopically enriched, plume-type character, and depleted material dominating the later volcanics (in the case of Hawaiian volcanism a subtle distiction is made between post-shield and post-erosional volcanics e.g. MacDonald 1968, in the interests of simplicity both these groups are combined into one here). Few detailed studies are available for other island groups which integrate geochemical data with K-Ar ages and stratigraphic field relations. However, a survey of the literature suggests that examples of the former ('Marquesan') type of activity include Kerguelen and Samoa, which Pitcairn island and the Tasmantid seamounts may represent other examples of the latter ('Hawaiian') style. What then distinguishes these hotspot types and how can we reconcile these contrasting styles of behaviour? Clearly, reverting to the plume-entrainment model will not help since, in the one case, we are suggesting a plume structure exactly the opposite to that needed to explain the other. In addition, the experiments of Griffiths and Campbell (1991) suggest that entrainment will be greatest for plumes with a smaller buoyancy flux but, using either the data of Davies (1988) or Sleep (1990), no simple correlation is observed between these differing behavioural styles and their respective buoyancy fluxes.

In the case of Hawaiian volcanism, similar arguments apply to those in the first section and thus a lithospheric influence on the depleted component can be suggested: indeed many workers on Hawaii have reached this conclusion (e.g. Chen and Frey 1985). Is it possible, therefore, that the temporal expression of plume-related volcanism in general is related to high level (lithospheric

or even crustal) phenomena? An interesting comparison can be drawn here between the Pitcairn and Kerguelen hotspots: both are classed as EM-I type plumes (EM-I and EM-II are terms defined by Zindler and Hart 1986, to refer to isotopically enriched mantle sources with, respectively, low and high $^{87}Sr/^{86}Sr$) and show almost identical Sr, Nd, and Pb isotopic variations (Woodhead and McCulloch 1989; Gautier et al. 1990). However, temporal evolution is markedly different in each case: in the former, lavas become more depleted with time and, in the case of Kerguelen, the reverse is true. If we are to accept that these two islands represent mixtures of an isotopically identical plume component with a depleted reservoir, then lateral or vertical geochemical variations in plume structure cannot account for these contrasting styles of evolution. Lithospheric involvement has been widely invoked in the case of the Kerguelen-Heard plume (Storey et al. 1988; Gautier et al. 1990) and may thus also apply in the case of Pitcairn island, following the model outlined already. A further clue to this apparent paradox may lie in the regional and temporal expression of these hotspots: the Hawaiian, Pitcairn and Tasman sea plumes form 'sharp', distinct, linear archipelagos with well-defined age progressions in their shield-building phase – those of the Hawaiian-Emperor and Tasmantid chains are well documented and the effects of the Pitcairn hotspot extend from present day activity at the recently discovered Pitcairn seamounts (Stoffers et al. 1990) back in time and space through the Gambier and finally the Duke of Gloucester islands (Duncan et al. 1974). In contrast, the other hotspots have more unpredictable surface expressions: the Marquesas, for example, do not form a *distinct* linear chain and, although an approximate age progression can be recognised, this is by no means entirely systematic e.g. volcanism at Ua Pou, in the centre of the group, spans almost the entire range observed in the other islands. Samoa has no well-defined hotspot track and the Kerguelen plateau is a very large and notably diffuse feature.

It is suggested that the style of emplacement, and hence geochemical evolution, of a given plume may be related to its 'strength' compared to the overlying lithosphere. Note here that a clear distinction is made between the size and strength of a plume. Previous authors have assessed the strength by reference to a calculated annual buoyancy flux (Davies 1988; Sleep 1990) which is, essentially, a measure of the size of a given plume. 'Strength' as discussed here simply relates to a plumes' ability to intrude the lithosphere *i.e.* its penetrative capacity (compare the 'lithsopheric vulnerability' parameter of Pollack et al. 1981), a concept which, in physical terms, is likely to be governed by a number of variables including both size and temperature/viscosity contrasts between the plume and lithosphere (cf. Olson et al. 1988).

The Marquesas may form an example of what is herein termed a 'weak' plume (see McNutt et al. 1989). On lodging at the base or within the lithosphere such plumes may spread laterally in the direction of mantle flow, initiating boundary layer convection (Griffiths and Campbell 1990) and resulting in mixing between the plume and lithospheric melts. Consequently, a shield-building source with a substantial lithospheric component results (Fig. 5). A period of quiescence ensues while further magma 'pulses' build up; subsequent magma batches traverse a conduit which has already yielded its low melting fraction and hence are subject to less addition of lithospheric melt component. As noted, the longer the hiatus between phases, the greater the accumulation of melts from the plume itself and hence the purer the plume signal in the post-shield phase (cf. model for Kerguelen volcanism proposed by Storey et al. 1988).

In direct contrast, it is possible that 'strong' plumes, as typified by the Hawaiian style, are far more penetrative and quickly invade the lithospheric cover producing shield-building lavas with a large plume component (in the case of Hawaii two plume components may be required). Delayed melting in the lithosphere, as a thermal response to plume intrusion, then could result in post-shield volcanism with a larger lithospheric component (a comparable model for Hawaiian post-erosional volcanism has been provided by Gurriet 1987). It is interesting to note in this respect that, in a similar manner to the Marquesas, the longer the repose period between shield and post-shield activity, the larger the isotopic difference noted between the two phases: thus, on the island of Oahu, where a hiatus of ~ 1 Ma is observed, the isotopic difference between the shield-building Koolau tholeiites and the post-shield Honolulu volcanics is large (of the order of 3 epsilon Nd units) whereas, in contrast on the island of Kauai, where a hiatus of only ~ 0.25 Ma is noted, the isotopic variation between the tholeiitic Waimea Canyon basalt and the post-shield Koloa volcanics is only of the order of 1 epsilon Nd unit (data from Clague and Dalrymple 1988). Significantly, in this case, it is the post-shield phase of volcanism (again the phase which is proposed to have the largest lithospheric contribution) that is more homogeneous than the shield-building counterpart. Such a concept, involving variable modes of lithospheric interaction, is one way of explaining the polarity in time-composition paths observed between the Hawaiian and Marquesan styles of activity.

Obviously there must exist plumes of intermediate character between these extremes. Indeed, the majority of hotspots may fall into this category, where very little distinction between predominantly plume- or lithosphere-derived melts is possible and the data simply lie on a mixing line between the latter and a number of plume sources, be they EMI, EMII or HIMU in character. In this way hotspots of more uniform geochemical nature (e.g. Reunion) may form, although it must be noted that very detailed studies of some oceanic islands previously considered to be 'homogeneous' now reveal temporal changes in source character e.g. stratigraphic sampling on St. Helena shows a gradual increase in incompatible element enrichment with time, coupled to a small increase in Sr and Pb isotopic ratios. This is interpreted by Chaffey et al. (1989) as reflecting the waning influence of lithospheric melting with time due to a decreasing thermal flux.

These observations suggest an important role for the lithosphere in the genesis of many intra-plate volcanic

suites and thus mention must be made of the Cameroon volcanic line here. This suite of within-plate lavas which straddle a continental margin, reveals no significant variation in isotope or trace element geochemistry between its oceanic and continental segments implying minimal lithospheric involvement. However, the lack of any clear volcanic migration with time (Fitton and Dunlop 1985) and recent geophysical evidence (Myers and Rosendahl 1991) strongly suggest that the Cameroon line is not a true hotspot trace, but may be related to lithospheric fracture systems. As such, it is not strictly relevant to the model presented here but does lead on to a discussion of other factors affecting temporal evolution.

Additional factors

Clearly the state of stress and temperature within the lithosphere must affect the nature of plume-lithosphere interaction to an extent which, in many cases, may override the simplistic model presented. Firstly, access of plume-derived melts to the surface may be greatly enhanced by the presence of lithospheric fractures: an obvious example is provided by Samoa where post-shield lavas (of assumed plume derivation) are erupted along what is essentially a 250-km long fissure, producing recent volcanism *throughout* the chain, in direct conflict with current models for age progressive volcanism in oceanic islands. As a direct consequence of this enhanced ease of access, it is also notable that post-shield lavas on Savaii (one of the larger Samoan islands) may account for up to 30% of the volcanic structure (Kear and Wood 1959), whereas in more typical settings post-shield lavas are volumetrically insignificant ($<1\%$) due, presumably, to a waning heat flux at this time. Similarly, existing fractures may deviate the surface expression of a hotspot from that expected from simple plate kinematic considerations e.g. the Oeno-Henderson-Ducie-Crough lineament (Okal and Cazenave 1985). In addition, note that McNutt et al. (1989) have suggested that *present day* volcanism in the Marquesas is strongly controlled by the location of the Marquesas fracture zone. Secondly, increased temperature in the lithosphere may also facilitate melting thus, for example, partly helping to explain the larger lithospheric contribution to Kerguelen lavas 45 Ma ago, when the island was closer to the southeast Indian Ridge spreading centre (Gautier et al. 1990). Finally, allied to both of these is the phenomenon of 'trapping' of a ridge by a hotspot or vice versa e.g. Iceland trapped a mid-ocean ridge by an episode of ridge-jumping some 9 Ma ago (Morgan 1981): a more detailed appraisal of the importance of these phenomena may be found in Okal and Batiza (1987).

Thus, in conclusion, although a number of distinct mantle plume sources have been recognized, the subsequent style of interaction of the plume with the lithosphere may vary greatly, controlled by density, viscosity and thermal contrasts and the presence of lithospheric fractures. Such variations may have a direct influence on the geochemical evolution of oceanic island volcanoes.

Conclusions

1. The marked changes in isotopic and trace element composition observed between the shield-building and post-shield phases of volcanism on the island of Ua Pou have been shown to occur consistently at each volcanic centre in the Marquesan chain. In addition, a correlation is observed between the duration of the volcanic hiatus separating shield and post-shield activity and the shift in geochemical character between these two phases. The regularity of this process and the marked compositional uniformity of the shield-building phase, coupled with its geochemical similarity to depleted mantle reservoirs suggests that it contains a substantial contribution from the oceanic lithosphere; only in the post-shield phase is a relatively 'uncontaminated' plume composition attained. Models involving entrainment of asthenospheric material during plume ascent are not readily compatible with observed geochemical evolution of the Marquesan basalts.
2. Comparisons with other oceanic islands in which temporal geochemical trends have been documented reveal at least two end-member styles of activity. Weak or 'Marquesan' type plumes may not have sufficient strength to penetrate the lithosphere initially; thus the shield-building phase of volcanism reflects substantial lithospheric melting with minor plume input. Only later, when a low melting fraction from the lithosphere has been extracted, does an uncontaminated plume signal appear (in post-shield volcanics). In direct contrast strong 'Hawaiian' type plumes may quickly penetrate the lithosphere, the shield-building lavas thus having a strong plume signature. Only in the waning stages of activity, as the plume moves away from the site of volcanism, would the proportion of lithosphere to plume melt increase. A continuum of eruptive styles probably exists between these two types.
3. In reality, this simple picture may be complicated by the presence of lithospheric fractures and the proximity of hotspots to spreading ridges or other areas of thermally anomalous lithosphere.

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