Correlated Os–Pb–Nd–Sr isotopes in the Austral–Cook chain basalts: the nature of mantle components in plume sources

P. Schiano [a,c,*], K.W. Burton [a,d], B. Dupré [a,e], J.-L. Birck [a], G. Guille [b], C.J. Allègre [a]

[a] *Laboratoire de Géochimie et Cosmochimie, URA-CNRS 1758, Institut de Physique du Globe, UFR des Sciences de la Terre, Université Paris VII, 4 place Jussieu, 75252 Paris Cedex 05, France*
[b] *CEA, DAM-LDG, B.P. no. 12, 91680 Bruyères le Chatel, France*
[c] *Laboratoire 'Magmas et Volcans', Université Blaise-Pascal, CNRS (UMR 6524), OPG Clermont, 5 rue Kessler, 63038 Clermont-Ferrand Cedex, France*
[d] *Laboratoire de Géochimie OMP, UMR-CNRS 5563, 38 rue des 36 ponts, 31400 Toulouse, France*
[e] *Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK*

Abstract

Osmium (Os), strontium (Sr), neodymium (Nd) and lead (Pb) isotopes have been measured on a suite of aphyric basalts from 12 islands of the Austral–Cook island archipelago, an area which exhibits a range in Pb isotope compositions that encompasses almost the entire range displayed by ocean island basalts (OIB). Although the samples have Os concentrations (1.69–34.80 ppt) at the lower end of the range measured for OIB, they display a range of initial $^{187}Os/^{188}Os$ ratios (between 0.1279 and 0.1594) similar to that defined by olivine–phyric, Os-rich OIB. Positive Os–Nd, Os–Pb and negative Os–Sr isotope correlations are documented, indicating that the isotopic arrays represent various proportions of mixing between a HIMU-type end-member represented by Mangaia and Tubuai islands and characterized by radiogenic Os and Pb isotopic compositions, and an end-member represented by Rarotonga island which is characterized by unradiogenic Os and intermediate Sr, Nd and Pb isotopic compositions. The HIMU signature of the mantle component involved in Tubuai–Mangaia mantle sources requires long-term enrichments of U and Th relative to Pb and Re relative to Os, without associated increase in Rb/Sr, that are consistent with recycled oceanic crust. The end-member represented by Rarotonga basalts shows Os, Sr, Nd, and Pb isotopic signatures similar to those presumed for the 'bulk silicate earth' (BSE), which cannot be obtained by mixing the four mantle components (DMM, HIMU and EM1 and 2) generally used to circumscribe the Sr–Nd–Pb isotopic data of OIB. The primitive-like isotopic characters of this end-member might be ascribed to the presence of undepleted material from a lower segment of the mantle in the source of the Austral–Cook island basalts (and more specifically Rarotonga basalts); however, such a hypothesis is challenged by both the absence of a primordial ^3He signature and the non-primitive Ce/Pb and Nb/U values for the Austral–Cook island basalts. Alternatively, assuming that the primitive-like isotopic composition of the

* Corresponding author. Tel.: +33-4-7334-6711; Fax: +33-4-7334-6744; E-mail: schiano@opgc.univ-bpclermont.fr

Rarotonga samples reflects mixing proportions between the HIMU component and a mantle component characterized by unradiogenic Os, Nd and Pb and radiogenic Sr isotopic composition relative to BSE, the involvement of recycled, old subcontinental lithosphere in the genesis of this component should then be considered. © 2001 Elsevier Science B.V. All rights reserved.

1. Introduction

Since isotopic heterogeneities in oceanic basalts were first identified [1–3], considerable effort has been made to understand the relationships between the various long-lived radiogenic isotopic ratios and the consequences of the identification of distinct mantle reservoirs which have persisted in the convecting mantle through time. Isotopic variations in oceanic basalts are usually explained in terms of binary mixing and/or ageing relationships between end-members identified as the various extremes of the data arrays. On the basis of Sr–Nd–Pb isotopic data four end-members have been identified [4–6], termed DMM ('depleted mid-ocean ridge basalt (MORB) mantle'), HIMU ('high $^{238}U/^{204}Pb$ mantle'), EMI ('enriched mantle 1') and EM2 ('enriched mantle 2') [6] (Fig. 1). DMM is widely assigned to the upper mantle depleted in all incompatible elements during extraction of the continental crust, whereas models for the origin of enriched mantle components range from metasomatic enrichment to recycling processes. For instance, it is generally proposed that the isotopic characteristics of the HIMU mantle component (very high Pb and relatively low Sr isotope ratios) are ultimately derived from ancient oceanic crust stored for 1–2 Gyr at the base of the upper (or lower) mantle [7–9] and

incorporated into mantle plumes. On the other hand, it has also been proposed that the isotopic signatures found in plumes could reflect the entrainment into the mantle convection system of
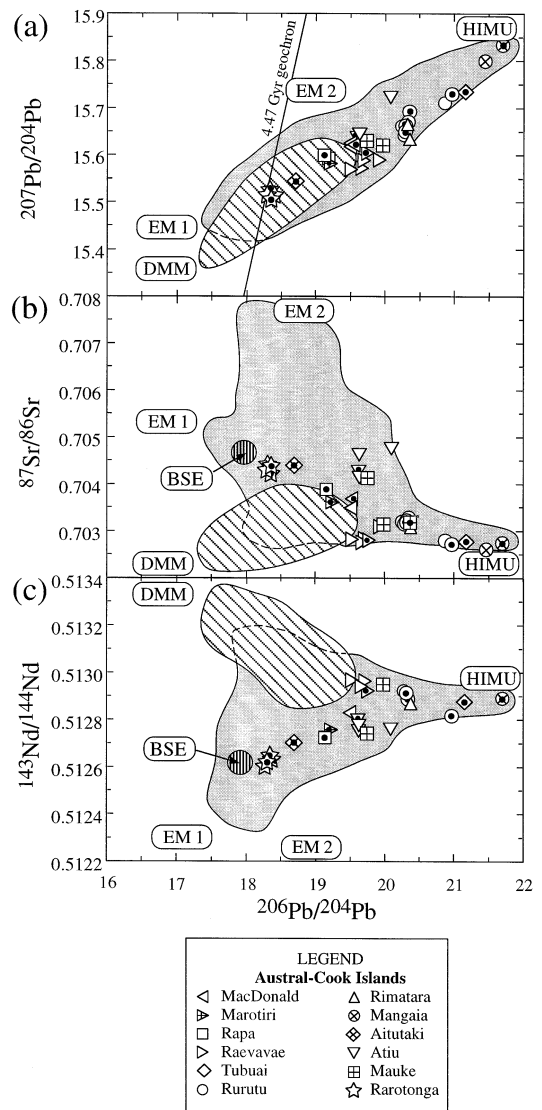

→

Fig. 1. $^{206}Pb/^{204}Pb$ versus (a) $^{207}Pb/^{204}Pb$; (b) $^{87}Sr/^{86}Sr$; and (c) $^{143}Nd/^{144}Nd$ diagrams showing Austral–Cook island basalts relative to fields representative of MORB (dashed fields) and OIB (shaded fields). Symbols are given in the accompanying legend. Dotted symbols indicate samples analyzed for Os isotopes. Also marked are the approximate locations of the mantle components DMM, HIMU, EM1 and EM2, the compositions representing the primitive mantle (BSE, estimated from the Sr–Nd isotopic correlation and from the Nd composition of chondrites [11,44]), and the 4.47 Gyr (the mean age of the differentiation of the core [45]) geochron.

delaminated, recycled bulk portions of old sub-continental lithosphere [10].

Calculations made using isotope and trace element mass balance for the mass fraction of mantle depleted during continental crust extraction (e.g. [11–14]) strongly argue for the persistence of some undepleted lower part of the Earth's mantle. Furthermore, the high $^3He/^4He$ ratios measured for some oceanic island basalts are interpreted to reflect the involvement of a relatively undegassed source in some plumes (e.g. [15–17]). However, participation of undepleted mantle segments in the isotopic variations observed for oceanic island basalts (OIB) remains controversial, because the primitive mantle composition is not a radiogenic end-member in the Sr–Nd–Pb isotope taxonomy; that is, it locates within the arrays defined by oceanic basalts in binary diagrams between these isotopes (Fig. 1). In addition, Hofmann and co-authors [13] have shown that the concentration ratios Ce/Pb and Nb/U are not consistent with primitive mantle sources for OIB. Recently, it has been suggested that some arrays for OIB in the isotopic space converge on a depleted component (termed FOZO) midway between the DMM–HIMU join and regarded as entrained lower mantle [18]. Note, however, that if the FOZO component is enriched in primitive He, it has not primitive Sr and Nd isotopic compositions but rather depleted [18].

The present study aims to improve on the existing situation by measuring both Os isotopes together with Sr, Nd and Pb isotopes on a suite of basalts from the Austral–Cook island archipelago, an area which exhibits very large variations in Pb isotope compositions of OIB [19–22]. Because basaltic components rapidly develop high $^{187}Os/^{188}Os$ ratios relative to their mantle sources, Os isotopes can be used as efficient tracers for recycled basaltic materials in the mantle. The samples display correlations between Os and Sr, Nd and Pb isotopic compositions indicative of a mixing process between an Os-radiogenic component showing the HIMU signature and related to recycling of oceanic crust and a new component clearly distinct from the DMM and characterized by low $^{187}Os/^{188}Os$, $^{206}Pb/^{204}Pb$, $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$ ratios.

2. Samples and results

The Austral–Cook island chain shows an overall age progression from the currently active MacDonald seamount to Mangaia island (~ 18 Ma, see [23]), consistent with motion of the Pacific plate toward the Northwest and thus supporting a hotspot origin for these islands [24]. More precisely, Diraison [25] and Chauvel and co-authors [22] have subdivided the volcanic activity in this region into three linear traces of volcanism called the 'Tubuai, Atiu and Rarotonga hotspot trends', respectively. The samples analyzed in this study include 35 alkali basalts, basanites and related differentiated rocks (detailed accounts of their petrology and major element chemistry are found elsewhere [22,26,27]) from 12 islands, including MacDonald, Marotiri, Rapa, Raevavae, Tubuai, Rurutu, Rimatara, Mangaia, Aitutaki, Atiu, Mauke and Rarotonga. They are all aphyric lavas, in order to avoid potential alteration of the Os isotopic composition due to the presence of some unradiogenic, Os-rich sulfide hosted by mantle olivine xenocrysts [28]. Os and Re separation and measurements were made using techniques described previously in [29]. Total procedural blanks for Os during the course of this study were 0.075 ± 0.015 pg/g, $^{187}Os/^{188}Os = 0.220 \pm 0.009$ and for Re were 10.6 ± 0.8 pg/g ($n = 8$).

Sr, Nd and Pb isotopic values reported in Table 1 are consistent with previously determined isotopic compositions for islands within the Austral–Cook island archipelago (e.g. [9,19–21]); that is, the samples display fairly restricted ranges in $^{87}Sr/^{86}Sr$ (0.702653 ± 18–0.704805 ± 36) and $^{143}Nd/^{144}Nd$ (0.512629 ± 13–0.512980 ± 14) and a very large range in $^{206}Pb/^{204}Pb$ (18.256–21.657) that encompasses almost the entire range displayed by OIB. Fig. 1 shows that the lavas display isotopic variations which primarily require the presence of two isotopically distinct mantle components in their sources; a HIMU-type component, which is clearly identifiable in basalts from Tubuai and Mangaia volcanoes, and another component best observed in basalts from Rarotonga and Aitutaki islands. The location of the Rarotonga and Aitutaki samples in the

Table 1
Sr, Nd and Pb isotope data for samples from the Austral–Cook islands

Sample	^{87}Sr/^{86}Sr	^{143}Nd/^{144}Nd	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb
MacDonald					
MCD-64	0.703703 ± 26		19.509	15.619	39.319
MCD-201	0.703532 ± 28	0.512842 ± 14	19.475	15.617	39.269
MCD-202			19.476	15.625	39.288
Marotiri					
MRT-205	0.703611 ± 21	0.512762 ± 18	19.181	15.580	39.018
Rapa					
RPA-02	0.703902 ± 10	0.512736 ± 27	19.101	15.599	39.078
RPA-31			19.153	15.592	39.021
Raevavae					
RVV-01	0.702796 ± 19	0.512952 ± 30	19.620	15.572	39.235
RVV-02	0.702832 ± 18	0.512938 ± 16	19.708	15.604	39.342
RVV-04	0.702884 ± 11	0.512974 ± 22	19.661	15.587	39.222
RVV-05	0.702858 ± 10	0.512980 ± 14	19.472	15.570	39.144
RVV-06	0.703139 ± 25		19.869	15.589	39.355
Tubuai					
TBA-17	0.702832 ± 10	0.512891 ± 12	21.115	15.734	40.306
Rurutu					
RRT-01	0.702746 ± 20	0.512829 ± 26	20.921	15.728	40.091
RRT-06	0.702828 ± 16		20.830	15.710	40.030
RRT-09	0.703260 ± 15	0.512927 ± 14	20.260	15.648	39.665
RRT-17	0.703203 ± 15		20.270	15.660	39.750
RRT-31	0.703185 ± 18	0.512932 ± 10	20.240	15.640	39.680
RRT-56	0.703227 ± 22		20.210	15.660	39.660
RR 05	0.703300 ± 9[a]	0.512897 ± 5[a]	20.29[a]	15.67[a]	39.76[a]
Rimatara					
RMT-04	0.703112 ± 27	0.512878 ± 9	20.332	15.627	39.858
RMT-11			20.288	15.664	39.734
Mangaia					
MGA-01	0.702653 ± 18		21.420	15.799	40.341
MG-2A1	0.702800 ± 20	0.512897 ± 13	21.657	15.832	40.634
Aitutaki					
AKI-01	0.704429 ± 28	0.512715 ± 60	18.647	15.544	38.685
Atiu					
ATU-02	0.704805 ± 36	0.512770 ± 21	20.044	15.723	40.215
ATU-03	0.704200 ± 10	0.512784 ± 10	19.581	15.636	39.504
ATU-04	0.704315 ± 18	0.512805 ± 25	19.573	15.635	39.473
ATU-11	0.704661 ± 20	0.512766 ± 30	19.581	15.642	39.575
Mauke					
MKE2	0.703207 ± 21		20.328	15.692	39.891
MKE3	0.704156 ± 28	0.512753 ± 17	19.697	15.629	39.510
MKE10	0.703149 ± 15	0.512958 ± 20	19.934	15.619	39.438
Rarotonga					
RTG1	0.704444 ± 22	0.512656 ± 26	18.290	15.512	38.721
RTG2	0.704438 ± 30	0.512647 ± 29	18.302	15.519	38.759
RTG3	0.704287 ± 28	0.512639 ± 41	18.285	15.528	38.774
RTG4	0.704366 ± 26	0.512629 ± 13	18.256	15.518	38.724

All errors are $2\sigma_m$.
Reproducibility of Pb isotope analysis is 0.05%/a.m.u., based on repeated lead NBS standard measurements.
^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd data were calibrated against reference values for standards: ^{87}Sr/^{86}Sr = 0.710255 ± 20 for NBS 987 and ^{143}Nd/^{144}Nd = 0.511841 ± 10 for La Jolla.
[a] Data from [22].

Table 2
Re–Os isotope data of basalts from Austral–Cook islands

	Sample	Age[a] (Ma)	$^{187}Os/^{188}Os$ measured[c]	Re (ppt)	Os (ppt)	$^{187}Re/^{188}Os$[d]	$(^{187}Os/^{188}Os)$ initial
MacDonald	MCD-64	< 0.35	0.1439 ± 0.0008	391	16.96	111	0.1439 ± 0.0010
Marotiri	MRT-205	3	0.1600 ± 0.0026	93	1.85	242	0.1479 ± 0.0034
Rapa	RPA-02	5	0.1528 ± 0.0009	115	9.82	57	0.1481 ± 0.0014
Raevavae	RVV-02	6	0.1710 ± 0.0023	370	8.11	221	0.1490 ± 0.0041
Tubuai	TBA-17	9	0.3054 ± 0.0014	657	3.32	975	0.1594 ± 0.0087
Rurutu	RRT-01	12	0.1658 ± 0.0014	265	18.16	71	0.1515 ± 0.0026
	RRT-17	1.45	0.1612 ± 0.0004	145	1.69	415	0.1512 ± 0.0028
	RRT-09	1.45	0.1504 ± 0.0006	278	3.00	448	0.1396 ± 0.0032
	RR 05	1.11[b]	0.1652 ± 0.0016	343	3.33	498	0.1560 ± 0.0016
Mangaia	MG-2A1	18	0.1768 ± 0.0038	542	33.47	79	0.1533 ± 0.0051
Aitutaki	AKI-01	1	0.1370 ± 0.0006	51	27.43	9	0.1368 ± 0.0007
Aitu	ATU-04	8	0.1637 ± 0.0011	334	9.17	177	0.1402 ± 0.0026
Mauke	MKE-02	6	0.1561 ± 0.0011	954	34.80	123	0.1439 ± 0.0021
Rarotonga	RTG-01	1.5	0.1402 ± 0.0003	500	4.91	492	0.1279 ± 0.0044
	RTG-03	1.5	0.1577 ± 0.0015	606	2.93	994	0.1329 ± 0.0027

All errors are $2\sigma_m$.
Errors on the initial $^{187}Os/^{188}Os$ ratios represent the combined uncertainties on sample ages, and analytical reproducibility on the measured $^{187}Os/^{188}Os$. $\lambda = 1.663 \times 10^{-11}$ yr^{-1} [62].
[a]The mean age (K–Ar ages from [25]) is given and used to calculate the initial $^{187}Os/^{188}Os$ ratio.
[b]G. Guille, unpublished data (K–Ar ages).
[c]$^{187}Os/^{188}Os$ normalized to $^{192}Os/^{188}Os = 3.08271$; given ratios are blank-corrected and corrected using measured $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios of 0.002047 and 0.00037, respectively. IPG-Paris 1.2 and 10 pg internal standards yield 0.1744 ± 9 ($n = 8$) and 0.1740 ± 6 ($n = 12$), respectively.
[d]$^{187}Re/^{188}Os$ ratio determined to a precision of $\pm 1.0\%$.

$^{143}Nd/^{144}Nd$ vs. $^{206}Pb/^{204}Pb$ space suggests that this component could be EM1, or an intermediate DMM–EM (1 or 2) component. It should also be noted that some samples from Atiu and Raevavae islands deviate slightly from the Sr–Pb and Nd–Pb isotopic arrays defined by the bulk of the data and this seems to indicate the slight participation of DMM-type and EM2-type components to the isotopic variations.

Os isotope ratios vary greatly within the Austral–Cook island chain, with $^{187}Os/^{188}Os$ ranging from 0.1279 (RTG-01 sample from Rarotonga) to 0.1594 (RR5 sample from Tubuai) (Table 2). These isotopic results are in good agreement with earlier analyses of olivine–phyric, Os-rich basalts from the Austral–Cook islands [30–32]; this coherency indicates that although the samples have Os concentrations (1.69–34.80 ppt) at the lower end of the range measured for OIB, their Os isotopic compositions are likely to be primary features and do not relate to secondary contami-

nation processes as it has been sometimes proposed for Os-poor basalts [31,33–35]. The present analyses fail to reveal any overall correlation between Os concentrations and isotopic compositions, nor between basalt type and Os concentration or isotope ratio. For example, a MgO-rich alkali basalt from Rapa (RPA-02 with MgO = 13.10 wt% and Mg# = 0.70 [27]) has an Os content of 9.82 ppt ($^{187}Os/^{188}Os = 0.1481 \pm 14$) whereas two differentiated basalts from MacDonald (MCD-64 with MgO = 4.75 wt% and Mg# = 0.46 [26]) and Tubuai (TBA-17 with MgO = 5.41 wt% and Mg# = 0.45 [26]) have Os concentrations of 16.96 ($^{187}Os/^{188}Os = 0.1439 \pm 10$) and 3.32 ppt ($^{187}Os/^{188}Os = 0.1594 \pm 87$), respectively. This indicates that there is no direct relationship between Os abundance (and $^{187}Os/^{188}Os$ ratios) of the samples and their degree of differentiation.

A plot of $^{187}Os/^{188}Os$ versus Sr, Nd and Pb isotopic ratios reveals the existence of correlations of those parameters (Fig. 2), which to a good first
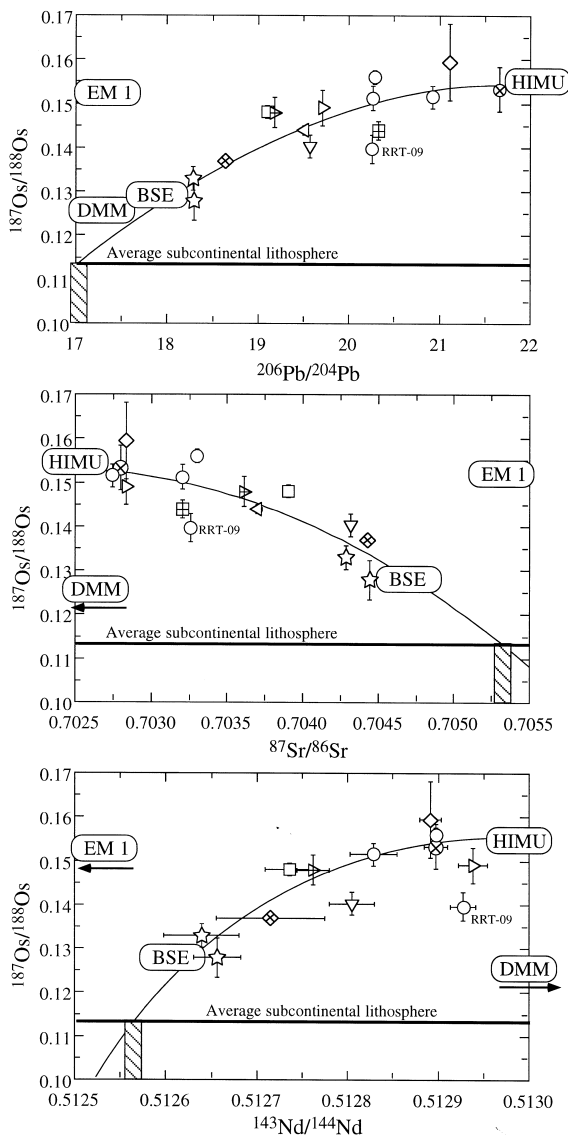
Fig. 2. $^{187}Os/^{188}Os$ versus (a) $^{206}Pb/^{204}Pb$; (b) $^{87}Sr/^{86}Sr$; and (c) $^{143}Nd/^{144}Nd$ diagrams for Austral–Cook island basalts. Symbols as in Fig. 1. Approximate locations of the mantle components HIMU, DMM and EM1, and the compositions representing the BSE are shown for reference. Also reported is the average $^{187}Os/^{188}Os$ ratio (0.113 ± 9, [60]) for the subcontinental lithospheric mantle. The Austral–Cook chain basalts show an array consistent with HIMU–BSE or subcontinental lithosphere binary mixing. Note, however, that the Rurutu sample RRT-09 suggests the slight participation of DMM to the isotopic variations.

approximation are indicative of binary mixing between a HIMU-type end-member characterized by radiogenic Os isotopic composition and an end-member characterized by low $^{187}Os/^{188}Os$, $^{206}Pb/^{204}Pb$, $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$ ratios. In Section 3, we discuss the nature of these two components and their implications for the geochemical evolution of the Earth's mantle.

3. Discussion

3.1. Nature of the HIMU component

As illustrated in Fig. 2, samples with extreme HIMU-type signature (i.e. with the most radiogenic Pb isotopic composition) from Mangaia and Tubuai possess the most radiogenic Os ratios with $^{187}Os/^{188}Os$ up to 0.159 ± 9. These results are consistent with previously reported values for HIMU-type OIB [30,33] and confirm that a $^{187}Os/^{188}Os$ value of ~ 0.155 is representative of the Os isotopic composition of the HIMU mantle component [30]. The extreme enrichments in ^{206}Pb and ^{208}Pb coupled with unradiogenic $^{87}Sr/^{86}Sr$ ratios of the HIMU basalts require long-term enrichments of U and Th relative to Pb, without associated increase in Rb/Sr. It is generally proposed that the origin of such signature is related to recycling of old oceanic crust [7,8], the U/Pb enrichment responsible for the very radiogenic Pb isotopic composition of HIMU basalts occurring during hydrothermal alteration or during the subduction process itself [9,36,37]. Likewise, the higher than bulk-Earth $^{187}Os/^{188}Os$ ratios for HIMU basalts suggest a time integrated high Re/Os mantle component, which is also consistent with an ancient basaltic source component. Indeed, because Os is highly compatible with the solid mantle residue of melts and Re is moderately incompatible, basalts have very high Re/Os ratios, which translate into high $^{187}Os/^{188}Os$ ratios with time. Recycled basaltic components in OIB could thus be easily identified by their elevated $^{187}Os/^{188}Os$ ratios, and they would generate a positive correlation between Pb and Os isotopes similar to that defined by the basalts from the Austral–Cook island chain. As discussed for example in [30],

none of the other models invoked to explain the HIMU component (e.g. mantle metasomatism [38] or extraction of Pb into the core [39]) could readily account for the Os–Pb–Sr–Nd isotopic systematic of the HIMU-type basalts. Our results on HIMU-type basalts from the Austral–Cook island archipelago give thus additional support to the Hofmann and White [8] model of recycling of oceanic crust.

3.2. Nature of the Os-unradiogenic component in the Austral–Cook island chain sources

The Rarotonga samples defining the extreme of the mixing curves of Fig. 2 require the existence of a mantle component characterized by its low $^{187}Os/^{188}Os$ ratio (< 0.130). The peridotitic part of the MORB mantle, as defined from unaltered abyssal peridotites [40] and the most unradiogenic MORB [41], has low $^{187}Os/^{188}Os$ ratios ranging between 0.123 and 0.128. However, the Sr and Nd isotopic ratios inferred for the sources of the Rarotonga samples preclude their derivation from the strictly defined DMM. For example, the $^{87}Sr/^{86}Sr$ ratio (not lower than 0.7045, see Fig. 2) inferred for the Os-unradiogenic end-member of the Austral–Cook island array is much higher than depleted mantle values. A similar conclusion can be reached by considering Nd isotopes. This indicates that the depleted part of the mantle cannot be considered as one extreme of the arrays defined by the basalts from the Austral–Cook island chain, even if a slight participation for some samples could induce scatter in the isotopic trends (Fig. 2).

In Sr–Nd–Pb space, the data extend towards the EM1 component (Fig. 1). Moreover, Hart and co-authors [42] identified a two-component mixing line (termed 'LoNd' array) between HIMU and EM1 within the whole OIB data set, by connecting the lowest $^{143}Nd/^{144}Nd$ samples of selected islands on the Sr–Nd isotopic diagram. However, the few Os isotope data available for EM1-type OIB [31,43] suggest that they are characterized by $^{187}Os/^{188}Os$ ratios as high as those of HIMU-type basalts, and therefore they do not plot along the correlations defined in this study.

In summary, oceanic crustal recycling appears to be the most plausible explanation to generate the HIMU component identifiable in Tubuai and Mangaia basalts. However, there are no conditions under which mixing the four mantle components generally used to circumscribe the Sr–Nd–Pb isotopic data of OIB could generate the isotopic arrays identified in this study. A corollary of this statement is that the lavas from the Austral–Cook chain show evidence of the contribution to OIB of a distinct mantle component, which is likely to be intermediate between the four end-member components in the Sr–Nd–Pb isotopic space.

In the following, we discuss two possibilities for the source of the Os-unradiogenic component identified in this study: (1) an undepleted lower layer of the mantle; and (2) delaminated subcontinental lithosphere.

3.2.1. Undepleted lower mantle source

Fig. 1 shows that samples from Rarotonga have Sr and Nd isotopic compositions in the approximate vicinity of the bulk silicate earth (BSE, the undifferentiated mantle segment remaining after core formation) estimates [11,44] and Pb isotopic compositions that plot on the 4.47 Gyr geochron (the locus of compositions that have evolved in a closed system since the differentiation of the core [45]) in the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram. In addition, their $^{187}Os/^{188}Os$ ratios are consistent with those measured for carbonaceous chondrites (~ 0.127) [46,47] or estimated for a hypothetical undepleted (fertile) mantle (~ 0.129, see [48]). Hence, with respect to Sr, Nd, Pb and Os isotopes, the Rarotonga end-member is close to the expected primitive mantle composition. Therefore, primitive-like material from an undepleted lower segment of the Earth's mantle could potentially provide a source for the Os-unradiogenic Austral–Cook chain basalts and mixing between this lower mantle component and the HIMU mantle component would generate the isotopic arrays of Fig. 2. Note that a mantle component with intermediate Sr, Nd and Pb isotopic composition relative to the global mantle end-members has recently been defined as the convergent point (or area) of isotope arrays for oceanic basalts [18,49]. However, this component (termed

'FOZO' [18] or 'C' [49] and considered as located within the lower mantle) does not have a primitive-like Sr–Nd–Pb isotopic composition.

However, despite the isotopic evidence discussed above, the hypothesis that the data document the presence of undepleted material in the source of the Austral–Cook island basalts (and more specifically Rarotonga basalts) is challenged by helium isotope and trace element systematics. Hanyu and Kaneoka [50] and Hanyu and co-authors [51] have shown that HIMU-type basalts from Tubuai, Mangaia and Rurutu islands have low $^3He/^4He$ ratios relative to MORB and basalts from Rarotonga island have normal MORB-like $^3He/^4He$ ratios. If the low $^3He/^4He$ values for the HIMU-type basalts could be accounted for by crustal recycling [50], the absence of a primordial ^3He signature (i.e. higher $^3He/^4He$ ratios relative to MORB) for the Rarotonga basalts suggests that at least portions of their source reservoir are relatively degassed, when one would expect a lower mantle source component to escape degassing. This suggests that the Os-unradiogenic component involved in the Austral–Cook island chain sources is non-primitive and thus characterized by a radiogenic (i.e. low $^3He/^4He$) helium isotope signature. Alternatively, the MORB-like $^3He/^4He$ ratios for the 1.5 Ma old Rarotonga basalts could reflect shallow-level contamination by radiogenic helium [52] or in-grow radiogenic helium [53].

Important arguments against primitive mantle sources for OIB are based on their trace element abundances. The contrasting Nb/U and Ce/Pb ratios (which comprise two elements with nearly identical bulk partition coefficients) of oceanic basalts, primitive mantle and continental crust estimates have led Hofmann and co-authors [13] to conclude that both MORB and OIB cannot be derived from primitive mantle sources or predominantly, recycled continental crust. Previous studies [19,26,27] of basalts from the Austral–Cook archipelago (including basalts from Rarotonga and Aitutaki with BSE-like Sr, Nd and Pb isotopic compositions) show that they display Nb/U and Ce/Pb ratios indistinguishable from the mean value of both MORB and OIB; that is so say, these ratios do not have primitive values. Therefore, if Nb/U and Ce/Pb have not been frac-

tionated by recent events [54,55] and directly reflect the long-term characteristics of oceanic basalt sources, this observation would appear to be a strong argument against the hypothesis that the Os-unradiogenic mantle component identified in the Austral–Cook island basalts is derived from a primitive or relatively undepleted reservoir of the mantle.

3.2.2. Subcontinental lithospheric source

An alternative to the above interpretation of the mixing arrays of Fig. 2 is to consider that the primitive-like isotopic composition of the Rarotonga samples reflects fortuitous mixing proportions between the HIMU component and a mantle component characterized by unradiogenic Os, Nd and Pb and radiogenic Sr isotopic composition relative to BSE. The involvement of recycled bulk portions of ancient subcontinental lithosphere in the genesis of this component should then be considered, because mantle peridotites from beneath continents are unique in having consistently lower than primitive $^{187}Os/^{188}Os$ ratios [56–59]. Extending the isotopic arrays of Fig. 2 towards a $^{187}Os/^{188}Os$ value of 0.113 (average value for subcontinental lithosphere, see [60]) would result in high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ values (Fig. 2), which are consistent with those reported for portions of the subcontinental mantle from the studies of mantle xenoliths (e.g. [56]). Moreover, McKenzie and O'Nions [10] have shown that the mantle part of the continental lithosphere may provide an appropriate source for OIB. Ancient subcontinental lithosphere is colder and denser than the asthenosphere and, therefore, it may be delaminated and recycled into the convecting mantle. If this interpretation is correct, thus the results of the present study suggest that recycled oceanic crust and subcontinental lithosphere appear to be complementary to each other in terms of the enrichments and depletions recorded by the U–Pb system.

4. Conclusion

Os, Sr, Nd and Pb isotope data in basalts from the Austral–Cook island archipelago require the

contribution to OIB of an Os-unradiogenic mantle component, which is distinct from the four mantle components (DMM, HIMU, EM1 and 2) generally used to circumscribe the Sr–Nd–Pb isotopic data of OIB and could be sited in the subcontinental lithosphere or the lower mantle. Mixing between this Os-unradiogenic component and the HIMU mantle component provides a simple explanation for the Os, Sr, Nd and Pb isotopic variations (that encompasses almost the entire Pb isotope range displayed by OIB) of the Austral–Cook island basalts. Note, however, that the relatively simple picture of mantle heterogeneities drawn by the suite of basalts from the Austral–Cook island chain analyzed in this study disregards the role of recycled continental material, which although recycled into the mantle as very small amounts (1–2%, see [37,61]) remains the main control of Sr and Nd isotopic variations in OIB.

Acknowledgements

References

[1] G. Faure, P.M. Hurley, the isotopic composition of strontium in oceanic and continental basalt: application to the origin of igneous rocks, J. Petrol. 4 (1963) 31–50.

[2] P.W. Gast, G.R. Tilton, C. Hedge, Isotopic composition of lead and strontium from Ascension and Gough islands, Science 145 (1964) 1181–1185.

[3] M. Tatsumoto, Genetic relations of oceanic basalts as indicated by lead isotopes, Science 153 (1966) 1094–1101.

[4] C.J. Allègre, D.L. Turcotte, Geodynamic mixing in the mesosphere boundary layer and the origin of oceanic islands, Geophys. Res. Lett. 12 (1985) 207–210.

[5] W.M. White, Sources of oceanic basalts: radiogenic isotope evidence, Geology 13 (1985) 115–118.

[6] A. Zindler, S.R. Hart, Chemical geodynamics, Ann. Rev. Earth Planet. Sci. Lett. 14 (1986) 493–571.

[7] C.G. Chase, Oceanic island Pb: two-stage histories and mantle evolution, Earth Planet. Sci. Lett. 52 (1981) 277–284.

[8] A.W. Hofmann, W.M. White, Mantle plumes from ancient oceanic crust, Earth Planet. Sci. Lett. 57 (1982) 421–436.

[9] C. Chauvel, A.W. Hofmann, P. Vidal, HIMU-EM: The French Polynesian connection, Earth Planet. Sci. Lett. 110 (1992) 99–119.

[10] D. McKenzie, R.K. O'Nions, Mantle reservoirs and ocean island basalts, Nature 301 (1983) 229–231.

[11] R.K. O'Nions, N.M. Evensen, P.J. Hamilton, Geochemical modeling of mantle differentiation and crustal growth, J. Geophys. Res. 84 (1979) 6091–6101.

[12] C.J. Allègre, S.R. Hart, J.F. Minster, Chemical structure of the mantle and continents determined by inversion of Nd and Sr isotopic data: II) Numerical experiments and discussion, Earth Planet. Sci. Lett. 66 (1983) 191–213.

[13] A.W. Hofmann, K.P. Jochum, H.M. Seufert, W.M. White, Nb and Pb in oceanic basalts: new constraints on mantle evolution, Earth Planet. Sci. Lett. 79 (1986) 33–45.

[14] C.J. Allègre, A.W. Hofmann, R.K. O'Nions, The argon constraints on mantle structure, J. Geophys. Res. 23 (1996) 3555–3557.

[15] J.E. Lupton, H. Craig, Excess ^{3}He in oceanic basalts: evidence for terrestrial primordial helium, Earth Planet. Sci. Lett. 26 (1975) 133–139.

[16] M.D. Kurz, W.J. Jenkins, S.R. Hart, D. Clague, Helium isotopic variations in volcanic rocks from Loihi Seamount and the island of Hawaii, Earth Planet. Sci. Lett. 66 (1983) 388–406.

[17] K.A. Farley, J.H. Natland, H. Craig, Binary mixing of enriched and undegassed (primitive?) mantle components (He, Sr, Nd, Pb) in Samoan Lavas, Earth Planet. Sci. Lett. 111 (1992) 183–199.

[18] S.R. Hart, E.H. Hauri, L.A. Oschmann, J.A. Whitehead, Mantle plumes and entrainment isotopic evidence, Science 256 (1992) 517–520.

[19] Z.A. Palacz, A.D. Saunders, Coupled traces element and isotope enrichment in the Cook–Autral–Samoa islands, Southwest Pacific, Earth Planet. Sci. Lett. 79 (1986) 270–280.

[20] Y. Nakamura, M. Tatsumoto, Pb, Nd and Sr isotopic evidence for a multicomponent source for rocks of Cook–Austral Islands and heterogeneities of mantle plumes, Geochim. Cosmochim. Acta 52 (1988) 2909–2924.

[21] T. Kogiso, Y. Tatsumi, G. Shimoda, H.G. Barczus, High μ (HIMU) ocean basalts in southern Polynesia: New evidence for whole mantle scale recycling of subducted oceanic crust, J. Geophys. Res. 102 (1997) 8085–8103.

[22] C. Chauvel, W.F. McDonough, G. Guille, R. Maury, R. Duncan, Contrasting old and young volcanism in Rurutu island, Austral chain, Chem. Geol. 139 (1997) 125–143.

[23] D.L. Turner, R.D. Jarrard, K–Ar dating of the Cook–Austral Island chain: a test of the hot-spot hypothesis, J. Volcanol. Geotherm. Res. 12 (1982) 187–220.

[24] R.A. Duncan, I. McDougall, Linear volcanism in French Polynesia, J. Volcanol. Geotherm. Res. 1 (1976) 197–227.

[25] C. Diraison, Le volcanisme aérien des archipels polynésiens de la Société, des Marquises et des Australes-Cook. Téphrostratigraphie, datation isotopique et géochimie comparées. Contribution à l'étude des origines du volcanisme intraplaque du Pacifique central. Thesis, Université de Bretagne Occidentale, 1991.

[26] C. Dupuy, H.G. Barsczus, J.M. Liotard, J. Dostal, Trace element evidence for the origin of ocean island basalt: an example from the austral islands (French Polynesia), Contrib. Mineral. Petrol. 98 (1988) 293–302.

[27] C. Dupuy, H.G. Barszus, J. Dostal, P. Vidal, J.M. Liotard, Subducted and recycled lithosphere as the mantle source of ocean island from southern Polynesia, central Pacific, Chem. Geol. 77 (1989) 1–18.

[28] K.W. Burton, P. Schiano, J.-L. Birck, C.J. Allègre, Osmium isotope disequilibrium between mantle minerals in a spinel-lherzolite, Earth Planet. Sci. Lett. 172 (1999) 311–322.

[29] J.-L. Birck, M. Roy-Barman, F. Capmas, Re–Os isotopic measurements at the femtomole level in natural samples, Geostand. Newsl. 20 (1997) 9–27.

[30] E.H. Hauri, S.H. Hart, Re–Os systematics of HIMU and EMII oceanic island basalts from Pacific Ocean, Earth Planet. Sci. Lett. 114 (1993) 353–371.

[31] L. Reisberg, A. Zindler, F. Marcantonio, W. White, D. Wyman, B. Weaver, Os isotope systematics in ocean island basalts, Earth Planet. Sci. Lett. 120 (1993) 149–167.

[32] M. Roy-Barman, C.J. Allègre, $^{187}Os/^{186}Os$ in Oceanic Island Basalt: Tracing oceanic crust recycling in the mantle, Earth Planet. Sci. Lett. 129 (1995) 145–161.

[33] F. Marcantonio, A. Zindler, T. Elliott, H. Staudigel, Os isotope systematics of La Palma, Canary islands: evidence for recycled crust in the mantle source of HIMU ocean islands, Earth Planet. Sci. Lett. 133 (1995) 397–410.

[34] C.E. Martin, S.B. Shirey, R.W. Carlson, F.A. Frey, C.Y. Chen, Osmium isotopic variations in lavas from Haleakala volcano, Maui, Hawaii: implications for plume–lithosphere interactions, EOS 71 (1991) 280.

[35] E. Widom, S.B. Shirey, Os isotope systematics in the Azores: implications for mantle plume sources, Earth Planet. Sci. Lett. 142 (1996) 451–465.

[36] A. Michard, F. Albarède, Hydrothermal uranium uptake at ridge crests, Nature 317 (1985) 244–246.

[37] B.L. Weaver, The origin of ocean island basalt end-member compositions: trace element and isotopic constraints, Earth Planet. Sci. Lett. 104 (1991) 381–397.

[38] R. Vollmer, Earth degassing mantle metasomatism and isotopic evolution of the mantle, Geology 11 (1983) 452–454.

[39] C.J. Allègre, O. Brévart, B. Dupré, J.F. Minster, Isotopic and chemical effects produced in a continuously differentiating convecting Earth mantle, Phil. Trans. R. Soc. Lond. A 297 (1980) 447–477.

[40] J.E. Snow, L. Reisberg, Os isotopic systematics of the MORB mantle: results from altered abyssal peridotites, Earth Planet. Sci. Lett. 133 (1995) 411–421.

[41] P. Schiano, J.-L. Birck, C.J. Allègre, Osmium–Strontium–Neodymium–Lead isotopic covariations in mid-ocean ridge basalt glasses and the heterogeneity of the upper mantle, Earth Planet. Sci. Lett. 150 (1997) 363–379.

[42] S.R. Hart, D.C. Gerlach, W.M. White, A possible new Sr–Nd–Pb mantle array and consequences for mantle mixing, Geochim. Cosmochim. Acta 50 (1986) 1551–1557.

[43] E.H. Hauri, J.C. Lassiter, D.J. DePaolo, Os isotope systematics of drilled lavas from Mauna Loa, Hawaii, J. Geophys. Res. 101 (1996) 11793–11806.

[44] C.J. Allègre, D. Ben Othman, M. Polvé, P. Richard, The Nd–Sr isotopic correlation in mantle materials and geodynamic consequences, Phys. Earth Planet. Inter. 19 (1979) 293–306.

[45] C.J. Allègre, B. Dupré, E. Lewin, Three time-scales for the mantle, in: A. Basu, S.R. Hart (Eds.), Earth Processes: Reading the Isotopic Code, Am. Geophys. Union, Washington, DC, 1996, pp. 99–108.

[46] J.M. Luck, J.-L. Birck, C.J. Allègre, ^{187}Re–^{187}Os systematics in meteorites: early chronology of the solar system and the age of the Galaxy, Nature 283 (1980) 256–259.

[47] R.J. Walker, J.W. Morgan, Rhenium–osmium systematics of carbonaceous chondrites, Science 243 (1989) 519.

[48] T. Meisel, R.J. Walker, J.W. Morgan, The osmium isotopic composition of the Earth's primitive upper mantle, Nature 383 (1996) 517–520.

[49] B.B. Hanan, D.W. Graham, Lead and helium isotope evidence from oceanic basalts for a common deep source of mantle plumes, Science 272 (1996) 991–995.

[50] T. Hanyu, I. Kaneoka, The uniform and low $^3He/^4He$ ratios of HIMU basalts as evidence for their origin as recycled materials, Nature 390 (1997) 273–276.

[51] T. Hanyu, I. Kaneoka, K. Nagao, Noble gas study of HIMU and EM ocean island basalts in the Polynesian region, Geochim. Cosmochim. Acta 63 (1999) 1181–1201.

[52] D.R. Hilton, J. Barling, G.E. Wheller, Effect of shallow-level contamination on the helium isotope systematics of ocean-island lavas, Nature 373 (1995) 330–333.

[53] A. Zindler, S.R. Hart, Helium: problematic primordial signals, Earth Planet. Sci. Lett. 79 (1986) 1–8.

[54] A.N. Halliday, D.C. Lee, S. Tommasini, G.R. Davies, C.R. Paslick, J.G. Fitton, D.E. James, Incompatible trace elements in OIB and MORB and source enrichment in the sub-oceanic mantle, Earth Planet. Sci. Lett. 133 (1995) 379–395.

[55] K.W.W. Sims, D.J. DePaolo, Inferences about mantle magma sources from incompatible element concentration ratios in oceanic basalts, Geochim. Cosmochim. Acta 61 (1997) 765–784.

[56] R.J. Walker, R.W. Carlson, S.B. Shirey, F.R. Boyd, Os, Sr, Nd, and Pb isotope systematics of southern African peridotite xenoliths: implications for the chemical evolution of subcontinental mantle, Geochim. Cosmochim. Acta 53 (1989) 1583–1595.

[57] R.W. Carlson, A.J. Irving, Depletion and enrichment history of subcontinental lithospheric mantle; an Os, Sr, Nd and Pb isotopic study of ultramafic xenoliths from the northwestern Wyoming Craton, Earth Planet. Sci. Lett. 126 (1994) 457–472.

[58] D.G. Pearson, R.W. Carlson, S.B. Shirey, F.R. Boyd, P.H. Nixon, Stabilisation of Archean lithospheric mantle: a Re–Os isotope study of peridotite xenoliths from the Kaapvaal craton, Earth Planet. Sci. Lett. 134 (1995) 341–357.

[59] L. Reisberg, J.-L. Lorand, Longevity of subcontinental mantle lithosphere from osmium isotope systematics in orogenic peridotite massifs, Nature 376 (1995) 159–162.

[60] S.B. Shirey, R.J. Walker, The Re–Os isotope system in cosmochemistry and high-temperature geochemistry, Annu. Rev. Earth Planet. Sci. Lett. 26 (1998) 423–500.

[61] A.W. Hofmann, W.M. White, Sr and Nd isotopie geochemistry of oceanic basalts and mantle evolution, Nature 296 (1982) 821–825.

[62] C.J. Allègre, J.L. Birck, F. Capmas, V. Courtillot, Age of the Deccan traps using $^{187}Re/^{187}Os$ systematics, Earth Planet. Sci. Lett. 170 (1999) 197–204.