Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 260 (2007) 98–114
EPSL
www.elsevier.com/locate/epsl

Hf–Nd evidence for the origin and distribution of mantle domains in the SW Pacific

J.A. Pearce [a,*], P.D. Kempton [b], J.B. Gill [c]

[a] School of Earth, Ocean and Planetary Sciences, Cardiff University, Cardiff CF10 3YE, UK
[b] NIGL, British Geological Survey, Keyworth, Nottingham NG12 5GG, UK
[c] Department of Earth Sciences, University of California Santa Cruz, Santa Cruz CA 95064, USA

Received 12 January 2007; received in revised form 10 May 2007; accepted 11 May 2007
Available online 23 May 2007
Editor: R.W. Carlson

Abstract

Pb isotope systematics have already been used successfully to demonstrate that the lavas of the arc-basin terrains of the SW Pacific are derived from two mantle domains, one of Pacific-like character and the other of Indian-like character. However, the mobility of Pb during subduction and alteration has mainly restricted the fingerprinting of domains to fresh lavas of MORB composition. We demonstrate that the less alteration-sensitive Hf–Nd isotope projection also discriminates successfully between 'Pacific' and 'Indian' domains, and thus enables us to extend mantle domain fingerprinting to the back-arc basin basalts and boninites of the Lau and North Fiji Basins and the volcanic arc lavas of the Kermadec, Tonga and Vanuatu arcs. Fingerprinting is facilitated by the observation that the Hf isotope ratio is independent of subduction-input parameters, indicating that Hf has been essentially conservative during the subduction process. Subducted Nd has been added to the mantle source, but subtracting this numerically using the magnitude of negative Hf anomalies filters out the subduction effect. The data show that the 'Indian' domain provides the source for magmas erupted at ridges, and arcs near these ridges, that have propagated southwards following the 12 Ma collision of the Ontong-Java Plateau with the Vitiaz Trench. This indicates that the 'Indian' domain is actually derived from SOPITA mantle (South Pacific Isotopic and Thermal Anomaly) — mantle modified by the Samoa and other plumes outboard of the trench which only entered the SW Pacific arc-basin system after the Ontong-Java Plateau collision removed the slab barrier at < 12 Ma. In the west, mantle flows beneath the network of south-propagating ridges in the North Fiji and NW Lau Basins, undergoing progressive depletion until the final loss of plume components produces an N-MORB mantle (Indian MORB Mantle) composition in the south North Fiji Basin and Central Lau Spreading Centre. In the east, newly-depleted Samoan plume mantle provides the source for the boninites and depleted arc tholeiites of the northern Tonga arc.

Keywords: hafnium; isotopes; trace elements; subduction; mantle domains

1. Introduction

The arc-basin complexes of the SW Pacific provide a well-known natural laboratory for studying subduction-related magmatism and geodynamics. Here, we utilize the wide distribution of volcanism and wide range of tectonic settings to geochemically test hypotheses for the origin and distribution of mantle domains and the nature of mantle flow within them.

Fig. 1 gives the present-day configuration of the SW Pacific study region. It is a product of 50 Ma or more of subduction from the east and north-east which initially created a continuous island arc (the Vitiaz Arc) and a

* Corresponding author. Fax: +44 29 2087 4326.
E-mail address: PearceJA@cardiff.ac.uk (J.A. Pearce).

0012-821X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2007.05.023

series of back-arc basins (e.g., South Fiji Basin, North Loyalty Basin and Solomon Sea Basin) behind a trench known as the Vitiaz Trench (e.g. Malahoff et al., 1982; Dunkley, 1983; Parson et al., 1990; Parson and Tiffin, 1993; Parson and Hawkins, 1994; Auzende et al., 1995; Lagabrielle et al., 1997; Pelletier et al., 1998). At 12–10 Ma, the Ontong-Java Plateau collided with this trench causing subduction along the western part of the trench to cease and subduction beneath the Vanuatu arc to reverse polarity (Dunkley, 1983). This in turn led to clockwise rotation of the Vanuatu arc and anticlockwise rotation of Fiji from about 6 Ma, and clockwise rotation of the Tonga arc from about 3 Ma (Malahoff et al., 1982). Basins formed during this period are here termed

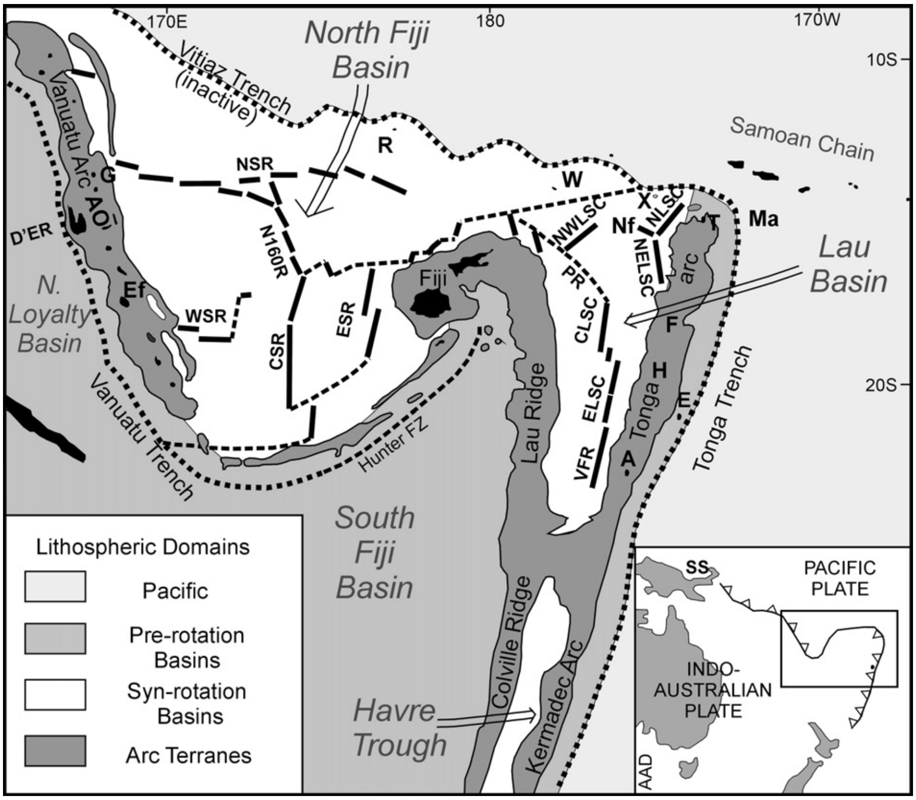

Fig. 1. Map of the SW Pacific region showing subaerial exposures as black. In the NE is the Samoan plume track, and the off-track Machias seamount (Ma). In the east is the Tonga–Lau system made up of the active Tonga arc and the remnant Lau Ridge arc, separated by the Lau Basin. The latter formed at a series of spreading centres. These are, from S to N, the Eastern Lau Spreading Centre (ELSC) with the Valu Fa Ridge (VRF) at its southern tip, the Central Lau Spreading Centre (CLSC), and the North-western, North-eastern and Northern Lau Spreading Centres (NWLSC, NELSC and NLSC). The Tonga arc comprises (seamounts excluded) Tafahi (T) and nearby Niuatopatapu in the Northern arc, Fonualai (F) to Hunga Ha'apai (H) in the Central arc and Ata (A) in the Southern arc. There is also localised volcanism in the Peggy Ridge (PR) 'leaky' transform fault and the northern, back-arc island of Niua Fo'ou (Nf). In the west, subduction is of opposite polarity, to the NE beneath the active Vanuatu arc. Behind it, in the North Fiji Basin (NFB in the text) contains a complex of spreading centres and fracture zones. The main spreading centres are the Central Spreading Ridge (CSR) (made up of N-15, N–S and 174E segments), the N160 Ridge, and the Northern, Western and Eastern Spreading Ridges (NSR, WSR and ESR). The NSR is probably made up slow-spreading ridge segments within a dominantly transform zone. Like the Peggy Ridge, the Fiji Fracture Zone (FFZ) also exhibits localised volcanic activity in pull-apart basins. There are also a number of volcanic seamounts and islands south of the inactive Vitiaz Trench, including Rotuma (R) and Wallis Island (W). The Vanuatu arc comprises an arbitrarily-defined Central arc (from Gaua, G, to Efate, Ef) separating a Southern and Northern arc. Behind it, is a series of volcanically-active troughs including the Aoba Basin (AO). The D'Entrecateaux Ridge (D'ER) is subducting beneath the central part of the arc. Solomon Sea (SS), which together with the North Loyalty Basin (NLB in the text), South Fiji Basin (SFB in the text) and Eua (E)) describe the early evolution of the region, is marked in the inset together with the approximate location of the Australian–Antarctic Discordance (AAD).In the Tonga region, the ELSC and NWLSC started spreading by propagation from either end of the Peggy Ridge at about 5.5 Ma (Parson et al., 1990; Parson and Tiffin, 1993; Parson and Hawkins, 1994). At 1.5 Ma ago, the CLSC had begun to propagate southwards from the Peggy Ridge at the expense of the ELSC and the NLSC had begun to propagate from the Mangatolu Triple Junction to the trench–transform intersection in the north. The North Fiji Basin has undergone an even more complex evolution in which the CSR started spreading by southward propagation from a pre-existing E–W to NE–SW ridge-transform system within the past 3–2 Ma and the ESR started spreading within the past 1.5 Ma or less (see (Loock et al., 1990) for a possible tectonic model).

'syn-rotation' while those preceding the docking of the Ontong-Java Plateau are termed 'pre-rotation'.

Most previous isotopic studies of mantle domains focused on Pb isotopes. Loock et al. (1990) first found that lavas from the Valu Fa Ridge plotted along mixing lines in Pb isotope space that extended from the 'Pacific' MORB field towards Western Pacific sediments, and so they proposed that a boundary between 'Indian' and 'Pacific' mantle domains existed to 'the east of the Lau Basin'. Haase et al. (2002) extended this Pacific domain south into the northern Havre Trough. Hergt and Hawkesworth (1994) demonstrated that the young Lau spreading centres propagated into lithosphere of 'Pacific' provenance, and proposed that opening of the back-arc basin enables mantle of 'Indian' affinity to advect into a region of mantle of 'Pacific' affinity. Crawford et al. (1995) and others (Peate et al., 1997; Turner et al., 1999) identified a distinct geochemical shift in isotope signatures from 'Pacific' to 'Indian' provenance in the Central part of the Vanuatu arc that first appeared at 2–3 Ma. They attributed this shift to intra-arc extension above the colliding d'Entrecasteaux Ridge, allowing upwelling of mantle asthenosphere of 'Indian' signature into lithosphere of 'Pacific' signature.

Although there is agreement that the 'Pacific' domain represents the ambient mantle for the easternmost Australian plate, the origin of the 'Indian' mantle domains is still debated. The three principal competing hypotheses (e.g., Crawford et al., 1995; Hickey-Vargas et al., 1995) are: 1) the northward migration of Australia towards the Indonesian subduction system could have displaced intervening mantle of 'Indian' provenance into the Southwest Pacific; 2) the 'Indian' signature could be the product of local contamination of mantle of 'Pacific' provenance by subducted materials or delaminated Gondwana sub-continental lithosphere; and 3) the 'Indian' signature is unrelated to the Indian Ocean and is instead related to the Samoan plume or, more generally to the South Pacific Isotopic and Thermal Anomaly (SOPITA) (Staudigel et al., 1991).

Linked to the origin of the two mantle domains is the nature of Western Pacific mantle flow. Much of the discussion about mantle flow has focused on the third option above. A 'plume component' in the geochemistry of some lavas of the Vanuatu–Fiji–Tonga region has been recognised for some time on the basis of Nd–Sr (Volpe et al., 1988; Gill and Whelan, 1989) and He (Poreda and Craig, 1992; Turner and Hawkesworth, 1998) isotope ratios, incompatible trace elements (e.g., Eissen et al., 1994; Auzende et al., 1995) and magma temperatures (Sobolev and Dimitriev, 1994), and attributed to channelling of Samoan plume mantle into the arc-basin system. Seismological evidence for trench-parallel flow also supports the isotopic evidence for southward flow of plume-related mantle (Giardini and Woodhouse, 1986; Smith et al., 2001).

This paper uses Hf–Nd element and isotope systematics to refine the location of the mantle domain boundary, and resolve some of the questions surrounding the origin of the Indian mantle domain and nature of mantle flow. Equivalent studies of the Mariana system (Pearce et al., 1999) and Australian–Antarctic Discordance (Kempton et al., 2002) demonstrated that the Hf–Nd isotope plot provides an alternative projection to the Pb isotope plot for distinguishing 'Pacific' from 'Indian' mantle. It is less sensitive to subduction and alteration processes than Pb isotope plots — which is important in the SW Pacific where so many volcanic rocks have a subduction influence. However, even the Hf–Nd projection requires a correction for the subduction component. For this, it is particularly useful if the high field strength element, Hf, is conservative (immobile). One of the findings of the Mariana study (Pearce et al., 1999), that of effective Hf immobility, was contested by Woodhead et al. (2001) and some consensus has since emerged that Hf is mobile under some conditions and immobile under others (Münker et al., 2004; Barry et al., 2006; Tollstrup and Gill, 2005). Assessment of Hf mobility, or otherwise, during SW Pacific subduction will be one by-product from this study.

This study is based primarily on Hf and Nd isotope and element analyses of a representative set of samples from the whole SW Pacific region. Locations of recent (<3 Ma) lavas analysed include the Kermadec arc, the Valu Fa Ridge, the Central and Eastern Lau spreading centres, the Tonga arc, the Northern Lau spreading centre, Niua Fo-ou, Fiji alkaline lavas, the North Fiji basin, the Vanuatu arc, and Machias seamount. In addition some older lavas were analysed from Eua, the South Fiji Basin, the North Loyalty Basin and the Lau Ridge together with cored sediments from sites outboard of the Tonga and Vanuatu trenches. We include published data from the Kermadec arc, Havre Trough and Solomon Sea from Kempton et al. (2002). Table 1 lists the sample characteristics and Hf and Nd isotope data. Table S1 gives the complete dataset, including major elements, trace elements and Sr and Pb isotope ratios. Analytical information is in the Table S1 caption.

2. Fingerprinting of SW Pacific MORB and OIB using Hf–Nd Covariations

As noted in the Introduction, $^{208}Pb/^{204}Pb–^{206}Pb/^{204}Pb$ has long been the basis of discrimination between

Table 1
Hf–Nd isotope data for the samples used in this paper

	Region	Location	Sample no.	Rock type	Age Ma	$^{176}Hf/^{177}Hf$	$^{143}Nd/^{144}Nd$	εHf	εNd	εNd(m)
Pre-rotation basins										
1	SFB	Site 205	32R-3	Th/B	33	0.283125	0.513062	12.64	8.25	8.81
2	SFB	Site 285A	9R-4	Th/B	27	0.283161	0.513098	13.86	8.88	8.91
3	NLB	Site 286	36R-1	Th/B	33	0.283145	*0.512906*	13.18	*5.18*	*5.18*
Tonga–Kermadec remnant arcs										
4	Tonga F/A	Eua	85-60	Th/A	46	0.283153	0.513081	13.45	8.23	8.26
5	Tonga F/A	Eua	3-3-4	Th/BA	46	0.283140	0.513074	13.05	8.33	8.39
6	Tonga F/A	Eua	6-18-3	Th/A	46	0.283130	0.513066	12.76	8.18	8.33
7	Tonga F/A	Eua	6-19-2	Th/A	46	0.283153	0.513086	13.64	8.48	8.51
8	Tonga F/A	Eua	6-19-7	Th/BA	46	0.283164	0.513079	13.54	8.27	8.74
9	Tonga F/A	Eua	7-26-7	Th/A	46	0.283141	0.513075	13.14	8.35	8.36
10	Lau Ridge	Lau V. Grp	71-380	CA/BA	6.4	0.283134	0.513068	12.83	8.36	9.20
11	Lau Ridge	Lau V. Grp	71-385	CA/A	7	0.283131	0.513043	12.65	7.87	9.40
12	Lau Ridge	Korobasaga	69-831	CA/BA	3.6	0.283172	0.513065	14.13	8.30	9.90
13	Lau Ridge	Korobasaga	VB595	CA/BA	3	0.283148	0.513069	13.33	8.37	9.28
14	Lau Ridge	Korobasaga	KH4	CA/BA	3	0.283166	0.513082	13.95	8.63	9.86
Tonga–Kermadec Arc										
15	Kermadec	Raoul	7005	Th/D	0	0.283138	*0.513047*	12.94	*7.94*	*8.83*
16	Kermadec	Macaulay	10380	Th/B	0	0.283126	*0.512972*	12.52	*6.48*	*8.26*
17	Kermadec	L'Esperance	14831	Th/BA	0	0.283126	*0.512974*	12.53	6.52	*8.03*
18	S. Tonga	Ata	ATA8-8	CA/B	0	0.283184	*0.513061*	14.57	*8.21*	*9.61*
19	C.Tonga	Tofua	23208	Th/BA	0	0.283185	*0.513001*	14.59	*7.04*	*8.05*
20	C. Tonga	Hunga	1115501	Th/BA	0	0.283198	*0.513032*	15.07	*7.65*	*8.11*
21	C. Tonga	Late	LATE 13	Th/A	0	0.283195	*0.512935*	14.96	*5.75*	*7.11*
22	C. Tonga	Fonualai	FON-8	Th/D	0	0.283190	*0.512970*	14.78	*6.44*	*7.68*
23	N. Tonga	N'topatapu	NTT28/2	Th/A	0	0.283215	*0.512891*	15.68	*4.90*	*6.53*
24	N. Tonga	N'topatapu	NTT26/1	Th/A	0	0.283223	*0.512896*	15.95	*5.00*	*6.36*
25	N. Tonga	N'topatapu	NT64-T8	Th/A	0	0.283233	*0.512895*	16.31	*4.97*	*6.01*
26	N. Tonga	Tafahi	TAF3/2	Th/BA	0	0.283227	*0.512941*	16.10	*5.87*	*6.50*
27	N. Tonga	Tafahi	TAF40	Th/BA	0	0.283220	*0.512955*	16.32	*6.14*	*6.26*
Syn-rotation basins										
28	Lau Basin	NLSC	16-26/2	HCB	0	0.283047	*0.512745*	9.72	2.05	3.50
29	Lau Basin	NLSC	16-55/4	HCB	0	0.283017	*0.512764*	8.67	2.41	2.41
30	Lau Basin	NLSC	2218-1	Th/B	0	0.283135	0.512847	12.85	4.04	4.37
31	Lau Basin	NLSC	2218-8	Th/B	0	0.283140	0.512875	13.02	4.58	5.13
32	Lau Basin	CLSC	11-1-1	Th/B	0	0.283253	0.513124	16.99	9.44	9.63
33	Lau Basin	CLSC	15-1-4	Th/B	0	0.283230	0.513110	16.19	9.17	9.17
34	Lau Basin	ELSC	20-5-2	Th/A	0	0.283247	0.513087	16.78	8.72	8.74
35	Lau Basin	ELSC	22-1-1	Th/B	0	0.283243	0.513068	16.67	8.35	8.48
36	Lau Basin	ELSC	25-2-1	Th/BA	0	0.283244	0.513072	16.69	8.43	8.60
37	Lau Basin	Valu Fa R.	16-151-1	Th/B	0	0.283137	0.513055	12.90	8.10	9.04
38	Lau Basin	Valu Fa R.	16-151-3	Th/B	0	0.283095	0.513079	11.42	8.56	9.42
39	Lau Basin	Valu Fa R.	L1-11	Th/A	0	0.283205	0.513149	15.31	9.93	10.69
Ocean island basalts										
40	Fiji	Vanua Levu	WQ7b	A/B	2.8	0.282988	0.512849	7.69	*4.09*	*4.09*
41	Fiji	Vanua Levu	WQ28	A/B	2.7	0.283007	0.512841	8.34	*3.95*	*3.95*
42	Samoa	Machias	16-95-2	A/B	0	0.282731	0.512511	−1.44	*−2.52*	*−2.52*
43	Samoa	Shield	33920	A/B	0	0.283002	0.512863	8.14	*4.36*	*4.36*
44	N. Lau basin	Niua Fo'ou	31462	Th/B	0	0.283041	*0.512819*	9.52	*3.49*	*3.49*
45	N. Lau Basin	Niua Fo'ou	31477	Th/B	0	0.283042	*0.512827*	9.56	*3.65*	*3.65*
46	N. Lau Basin	Inner trench	16-10/2	A/Bn	0	0.282887	0.512746	4.08	*2.06*	*2.06*
Vanuatu arc										
47	N. Vanuatu	Vot Tande	VGA1	CA/BA	3.5	0.283146	*0.513018*	13.23	*7.40*	*9.32*

(continued on next page)

Table 1 (*continued*)

	Region	Location	Sample no.	Rock type	Age Ma	$^{176}Hf/^{177}Hf$	$^{143}Nd/^{144}Nd$	εHf	εNd	εNd(m)
Vanuatu arc										
48	N. Vanuatu	Urep'para	UA10	CA/B	0.5	0.283161	*0.513011*	13.75	*7.24*	*8.83*
49	N. Vanuatu	Mota Lava	ML'C23	CA/B	0.2	0.283196	*0.513028*	15.00	*7.57*	*9.79*
50	N. Vanuatu	Mota	MO'C4	CA/B	0.5	0.283134	*0.513022*	12.80	*7.45*	*9.64*
51	N. Vanuatu	Vanua Lava	VMAC6	CA/B	0.5	0.283151	*0.512965*	13.39	*6.34*	*8.16*
52	C. Vanuatu	Gaua	GM60	Sh/B	1.7	0.283153	*0.512966*	13.49	*6.37*	*8.18*
53	C. Vanuatu	Merelava	MLM7	Th/B	0.01	0.283218	*0.513049*	15.77	*7.98*	*8.82*
54	C. Vanuatu	Aoba	AOW1	CA/B	0.1	0.283088	*0.512954*	11.18	*6.13*	*7.20*
55	C. Vanuatu	Ambrym	AM27	Sh/B	0.1	0.283111	*0.512890*	12.00	*4.88*	*6.29*
56	C. Vanuatu	Paama	PAM20	CA/B	2	0.283200	*0.512950*	15.14	*6.05*	*7.23*
57	C. Vanuatu	Epi	EPW70	CA/B	0.4	0.283136	*0.512946*	12.88	*5.97*	*7.74*
58	C. Vanuatu	Tongoa	TOW5	CA/B	2	0.283172	*0.512950*	14.17	*6.05*	*7.58*
59	C. Vanuatu	Nguna	NGA 23	CA/B	0.7	0.283156	*0.512941*	13.58	*5.87*	*8.29*
60	C. Vanuatu	Efate	EA258	CA/B	0.5	0.283115	*0.512939*	12.14	*5.84*	*8.50*
61	S. Vanuatu	Erromango	E46	CA/B	0.3	0.283173	*0.513052*	14.19	*8.04*	*9.59*
62	S. Vanuatu	Tanna	TAC75	CA/B	2.4	0.283158	*0.513057*	13.68	*8.15*	*10.04*
63	S. Vanuatu	Futuna	F'C18	CA/B	3	0.283119	*0.513015*	12.32	*7.33*	*8.37*
64	S. Vanuatu	Anatom	AY'C20	CA/B	0.6	0.283162	*0.513039*	13.79	*7.79*	*9.43*
North Fiji basin										
65	NFB	NS	15-11-1	Th/B	0	0.283186	*0.513011*	14.65	*7.24*	*7.61*
66	NFB	NS	14-7-2	Th/B	0	0.283218	*0.513111*	15.77	*9.19*	*9.34*
67	NFB	N160	53-9-1.7	Th/B	0	0.283139	*0.512903*	12.96	*5.13*	*6.40*
68	NFB	N160	54-10-1	A/B	0	0.282967	*0.512797*	6.91	*3.06*	*3.06*
69	NFB	N160	58 8-9-1	Th/B	0	0.283204	0.513049	15.29	*7.98*	*7.97*
70	NFB	N160	58 8-9-7	A/B	0	0.283079	*0.512885*	10.85	*4.78*	*4.78*
71	NFB	triple jtn	4 21-3	Th/B	0	0.283275	0.513127	17.79	9.50	9.50
72	NFB	triple jtn	4-21-5	Th/B	0	0.283273	*0.513157*	17.72	*10.09*	*10.09*
Subducted sediment										
73	Pacific	Site 204	2R-4	Pel. Clay	0	0.282929	*0.512460*	5.54	*−3.51*	
74	Pacific	Site 204	3R-2	Pel. Clay	0	0.283123	*0.512879*	12.42	*4.66*	
75	Pacific	Site 204	4R-4	Pel. Clay	0	0.283003	*0.512882*	8.16	*4.72*	
76	Pacific	Site 204	7R-1	Volc. Sst	0	0.283014	*0.512901*	8.56	*5.09*	
77	Pacific	Site 204	8R-3	Volc. Sst	0	0.283014	*0.512927*	8.56	*5.60*	
78	Pacific	Site 204	9R-1	Volc. Sst	0	0.283003	*0.512872*	8.19	*4.53*	
79	NLoyB	Site 286	5R-2	nano-tuff	0	0.282984	*0.512454*	7.49	*−3.63*	
80	NLoyB	Site 286	6R-4	nano-tuff	0	0.283144	*0.512803*	13.16	*3.18*	
81	NLoyB	Site 286	12R-2	nano-tuff	0	0.283056	*0.512541*	10.03	*−1.93*	
82	NLoyB	Site 286	17R-4	nano-tuff	0	0.283135	*0.513054*	12.83	*8.08*	

Analyses were carried out at the NERC Isotope Geosciences Laboratory (NIGL) using methods described in Nowell et al. (1998) and Kempton et al. (2000), except for some published Nd values in italics: Ewart and Hawkesworth (1987) and Ewart et al. (1998) for samples 15–19, Acland (1996) for 20–26, Turner et al. (1997) for 41–42, and Nohara et al. (1994) and Peate et al. (1997) for 44–79. $^{176}Hf/^{177}Hf$ is reported relative to a JMC 475 standard value of 0.282160. Our Nd isotope ratios have been quoted relative to a La Jolla Nd standard value of 0.511860, within 0.00001 of values quoted by Ewart and Hawkesworth (1987), Nohara et al. (1994), Ewart et al. (1998), Acland (1996), Peate et al. (1997) and Turner et al. (1997). Full analytical details and errors, together with the major element, trace element and Sr, Pb isotope data and any calculated indices used in the text (Boespflug et al., 1990; Kempton, 1995; Patchett and Tatsumoto, 1980; Pearce et al., 1995; Peate et al., 2001; Royse et al., 1998; Salters et al., 2002; Todt et al., 1996), may be found in Table S1. εNd(m) refers to estimated mantle values, i.e. corrected for subduction input by the method outlined in the text. Key to rock types: Th = tholeiitic; CA = calc–alkaline; Sh = shoshonite; A = alkalic; Bn = basanite; HCB = high-Ca boninite; B = basalt; BA = basaltic andesite; A = andesite; D = dacite. See Fig. 1 caption for location abbreviations.

'Pacific' and 'Indian' domains: 'Indian' domains are characterised by higher $^{208}Pb/^{204}Pb$ for a given $^{206}Pb/^{204}Pb$. However, for lavas with subduction components, there is a question over how much the component element (Pb) informs us about the provenance of the subducting plate and how much it informs us about the mantle wedge. To 'see through' the subduction effect, and hence attain a more complete coverage of SW Pacific lavas, we here use Hf–Nd systematics. To do this, we first classify the MORB lavas (plus back-arc samples with small subduction components and MORB-like lavas from Niua Fo'ou) using the $^{208}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$

discriminant and then use the results to define the 'local' discriminant on the Hf–Nd diagram.

Fig. 2a gives the $^{208}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ plot with the discriminant boundary separating MORB of 'Pacific' and 'Indian' character. The field across the AAD is given for reference (Kempton et al., 2002). The results essentially confirm those reported in the literature [e.g. (Loock et al., 1990; Hergt and Hawkesworth, 1994; Crawford et al., 1995; Peate et al., 1997; Haase et al., 2002)]. Thus, of the recent MORB, the North Fiji Basin, the Central, Eastern and Northern Lau Basins have 'Indian' affinities while the Havre Trough has 'Pacific' affinities. Of the volcanic rocks from the early (Eocene–Oligocene) history of the basin that have no, or very small, subduction signatures, the South Fiji Basin, and Solomon Basin both have 'Pacific' affinities; however, the North Loyalty Basin sample has 'Indian' affinities.

The data plotted on the Hf–Nd diagram (Fig. 2b) give the same separation: samples classifying as 'Indian' using Pb isotopes also have low εNd for a given εHf and samples classifying as 'Pacific' have high εNd for a given εHf. It is thus apparent that Hf–Nd isotopes also effect the discrimination into two domains, for which a discriminant boundary can be drawn by eye. This SW Pacific discriminant has the equation $\varepsilon Hf = 1.522\varepsilon Nd + 1.26$. Despite small differences with the boundary of Pearce et al. (1999) for the Mariana region ($\varepsilon Hf = 1.6\,\varepsilon Nd$) and a larger difference in gradient with that of Kempton et al. (2002) for the Australian–Antarctic Discordance ($\varepsilon Hf = 2.65 * \varepsilon Nd - 8.94$), the convergence of the three discriminants at an average MORB composition means that all three discriminants give the same separation of the SW Pacific MORB into the two mantle domains (see the inset diagram in Fig. 2b). Thus, the Hf–Nd isotope projection can be used instead of Pb–Pb to fingerprint the many lavas from the region that have subduction signatures.

3. Fingerprinting of SW Pacific arc lavas and BABB using Hf–Nd covariations

3.1. Fingerprinting of SW Pacific SSZ lavas using uncorrected Pb–Pb and Hf–Nd isotope covariations

The first stage of the application of Hf–Nd discriminants to the subduction-modified lavas uses the isotope plots in Fig. 3, which do not take subduction-mobility into account. In Fig. 3a (for the Tonga–Kermadec arcs), the primary data reveal that the North Tonga arc forms a horizontal trend well within the 'Indian' field. The Central and South Tonga arcs form a horizontal trend within the 'Indian' field at lower εHf values and the Kermadec arc forms a trend that crosses the discriminant boundary into the 'Pacific' field at still lower εHf values. In Fig. 3b (for the Vanuatu arc), the principal axis of dispersion is sub-vertical rather than horizontal with the Central arc plotting in the 'Indian' field, while the northern and southern arcs span the boundary between the 'Indian' and 'Pacific' fields.

The compositions of subducted sediments are shown in the inset diagrams. These are highly variable and more analyses are needed for complete characterisation.

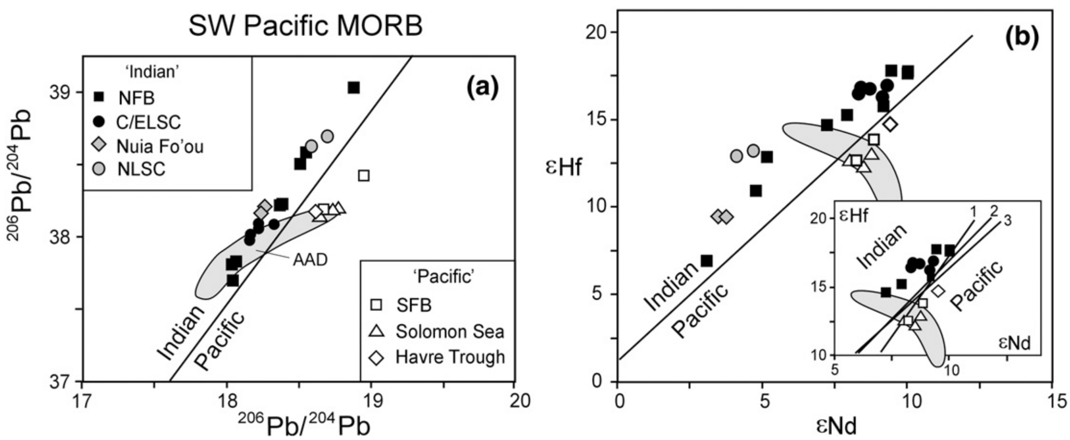

Fig. 2. Pb–Pb and Hf–Nd isotope plots for SW Pacific MORB and OIB used to calibrate the Hf–Nd isotope discrimination line between 'Pacific' and 'Indian' mantle domains. (a) Shows the discriminant in Pb isotope space based on the plots of Pearce et al. (1999) and Kempton et al. (2002); data from this paper and Woodhead et al. (2001) highlight the separation of SW Pacific data for samples with little or no subduction input into 'Pacific' and 'Indian' domains. (b) Shows the same data in Hf–Nd isotope space, demonstrating that these isotopes also affect the separation. The inset to this diagram compares this 'Pacific'–'Indian' discrimination (boundary 2) from this paper with those of Kempton et al. (2002) for the AAD (boundary 1) and Pearce et al. (1999) for the Marianas (boundary 3) showing that all three would discriminate the SW Pacific samples in the same way.

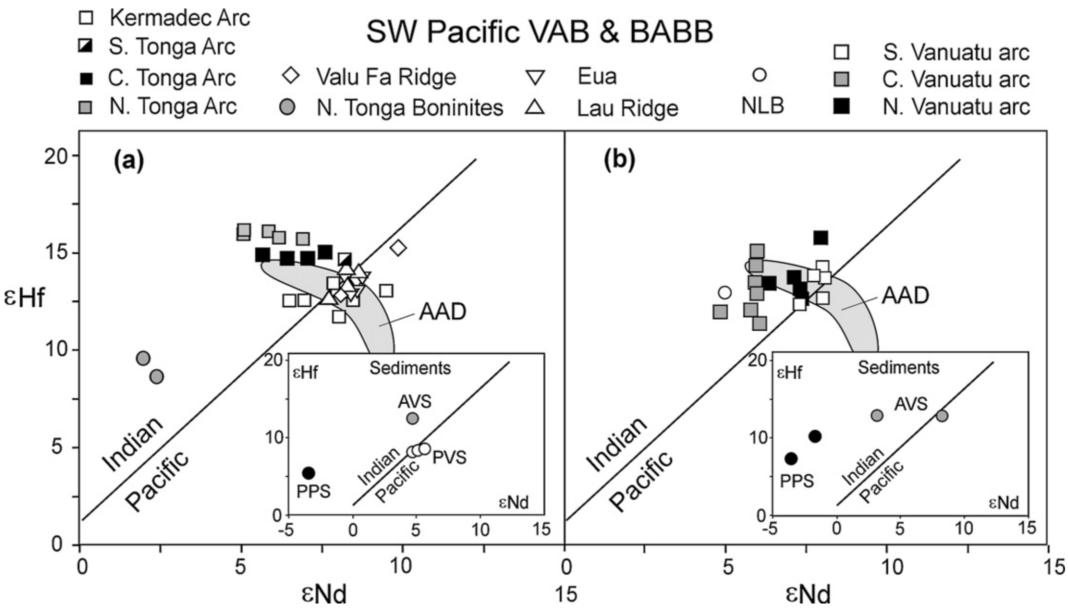

Fig. 3. εHf–εNd isotope plots for SW Pacific samples with high subduction inputs (a) for the Tonga–Kermadec system and (b) for the Vanuatu system. Subducted sediments are shown in the insets (PVS = Pacific intraplate Volcanogenic Sediments; AVS = Arc-derived Volcanogenic Sediments; PPS = Pacific pelagic sediments). The diagram highlights differences between the different arcs and provides an indication of mantle domain, but precise fingerprinting requires correction for Nd mobility (see Figs. 4–6).

However, the need for large numbers of analyses may be circumvented by treating them as mixtures in varying proportions of three components: a recent volcanic arc input (AVS = arc volcanogenic sediment) which could plot in the 'Indian' or 'Pacific' field according to its provenance; a volcanogenic component (PVS = Pacific volcanogenic sediment) which lies in the radiogenic part of the Pacific field; and a pelagic (ferromanganoan micro-nodule) component (PPS = Pacific pelagic sediment) which has low εNd and moderate εHf and lies well within the 'Indian' field. Subducted crust (see Fig. 2a) plots in the 'Pacific' field for the Tonga–Kermadec system but could plot in the 'Indian' (North Loyalty Basin) or 'Pacific' (South Fiji Basin) field for the Vanuatu system.

The predominantly horizontal trends formed by the Tonga and Kermadec arcs in Fig. 3a indicate that the Nd/Hf ratios in the subduction components are very high — unless the subduction components plot on extensions of these trends with high εHf and low εNd. The evidence for a significant flux of sediments with εHf lower than the lavas implies that the second option is more likely, i.e. Hf exhibits near-conservative behaviour in which any Hf flux is too small to be seen by the mantle wedge. In contrast, the more vertical trends followed by the Vanuatu arcs in Fig. 3b likely require a combination of variable mantle and subduction components.

However, none of the data points on Fig. 3 are true mantle values as the ubiquitous negative Hf element anomalies (Fig. S1) indicate that some Nd is subduction-derived. Moreover, the mobility of Hf is still debated. Thus, in order to make a confident interpretation of the data, we need a full assessment of Nd and Hf mobility and correction of the data for the subduction input.

3.2. Assessment of Nd and Hf mobility during SW Pacific subduction

The volcanic arc basalts from the SW Pacific range from mainly island arc tholeiites in the Tonga and Kermadec arcs to mainly calc–alkaline basalts in the Vanuatu arc. Chondrite-normalized, extended REE patterns (Fig. S1 shows some representative patterns) reveal variable negative anomalies in Hf for all of the arc samples. The key to correct the isotope compositions for subduction input is to assume that the negative Hf anomalies result from selective Nd addition from the subduction zone. The precise correction applied depends on whether or not Hf exhibits conservative (subduction-immobile) behaviour.

A good test is to plot Hf isotope ratio against a subduction indicator. Nd/Hf can usefully be used in this case to specifically test whether Nd is mobile while Hf is immobile. This method works provided the subduction component and mantle have different isotope compositions. Fig. 4 shows this 'subduction immobility' test for the active Tonga–Kermadec (Fig. 4a,c) and Vanuatu (Fig. 4b,d) arcs. The respective MORB compositions

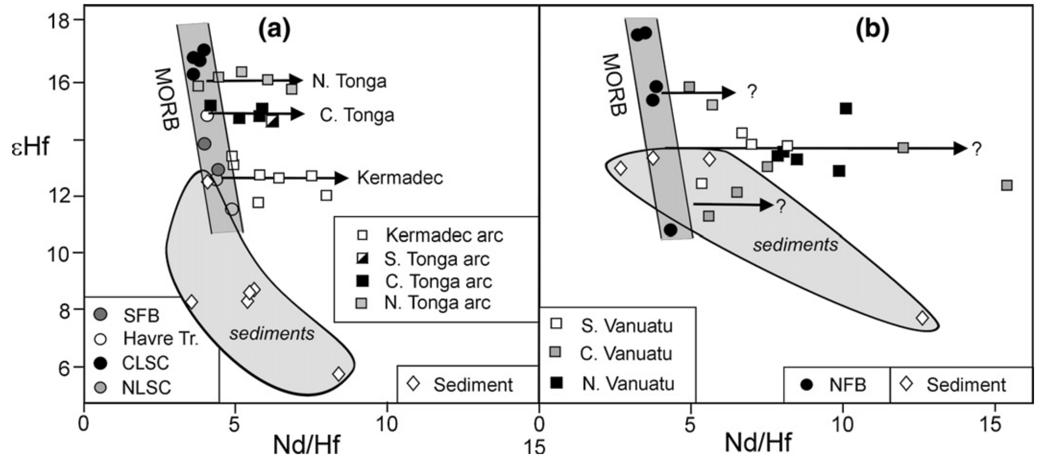

Fig. 4. εHf plotted against Nd/Hf as a test of Hf mobility in (a) the Tonga–Kermadec and (b) the Vanuatu arcs. The horizontal trends for each part of the Tonga–Kermadec arc system indicate either Hf immobility or addition of a component with similar εHf and high Nd/Hf. The plot also indicates that arc lavas and their adjacent back-arc basins need not have the same mantle sources. Any horizontal trends in the Vanuatu system are masked by mantle heterogeneity, but there is still no obvious relationship between εHf and Nd/Hf that would indicate Hf mobility. See the caption to Fig. 1 for explanation of the abbreviations.

define the mantle array, which has a steep negative slope as Nd is slightly more incompatible than Hf. For the Tonga–Kermadec system, the North Tonga, Central Tonga and Kermadec arcs each form separate trends with near-constant Hf isotope ratios and variable Nd/Hf ratios. Horizontal trends are difficult to explain if Hf is significantly subduction-mobile as both pelagic and volcanogenic sediments have low Hf isotope ratios compared to the lavas. The simplest explanation is thus that the subduction component has negligible Hf, i.e. that high-field strength elements are effectively immobile.

For the Vanuatu system (Fig. 4b), the Nd/Hf displacement is greater than for Tonga–Kermadec as its lavas have a greater subduction component on average. However, the greater mantle and subduction component heterogeneity (Peate et al., 1997; Crawford et al., 1995) results in less clear trends than in the Tonga–Kermadec arc. Although some sediments have high Hf isotope ratios, the weighted average (Peate et al., 1997) should still be low enough to produce detectable negative gradients on this projection should Hf be significantly subduction-mobile. Thus there is no evidence for Hf mobility in the Vanuatu arc, although more detailed work is needed to provide a definitive interpretation.

Note also that Woodhead et al. (2001) argued that, because the Havre Trough and CLSC have higher εHf than the Kermadec arc and Central Tonga arcs respectively, Hf must be mobile. However, the reverse holds for NLSC, which has a much lower εHf than the North Tonga arc. Moreover, the North Fiji Basin has an εHf range which exceeds the full range of Vanuatu values. In addition, even for the cases of the CLSC–Central Tonga and Havre–Kermadec pairs, it is not possible to draw mixing lines between the basins and the arcs: the arcs have separate sub-horizontal trends. This decoupling of arc and back-arc compositions may be a consequence of the trench-parallel flow that characterises at least part of the region (Giardini and Woodhouse, 1986).

These diagrams therefore demonstrate that there is no direct evidence for Hf mobility, even in North Tonga where mantle temperatures may have been at their highest and the mantle at its most depleted (Sobolev and Dimitriev, 1994) and so most sensitive to Hf addition. For a homogeneous mantle source, the trends are near-horizontal and neither trend leads to an end-member sediment or crustal composition. This implies that Hf element and Hf isotopes can be used to fingerprint the studied SW Pacific samples without manipulation even when they contain subduction components. Of course, it is possible, within error, to have negative gradients, but these still require high Nd/Hf in the subduction components and so any corrections for Hf mobility will be small. However, Nd cannot be used without the correction performed below.

3.3. Hf–Nd discriminant diagrams corrected for subduction-derived Nd

The εNd value for the mantle wedge (εNd_w) can be expressed as:

$$\varepsilon Nd_w = \varepsilon Nd_m(1 - \Delta Nd) + \varepsilon Nd_{sz}\Delta Nd \qquad (1)$$

where, εNd_m and εNd_{sz} refer to the εNd values of the mantle and subduction components respectively and ΔNd refers to the mass fraction of Nd in the mantle

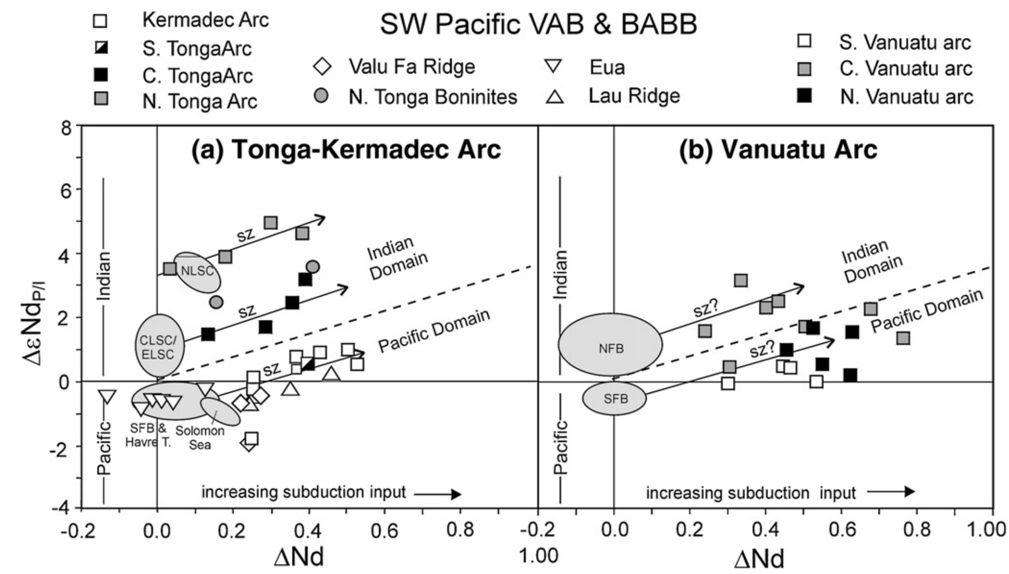

Fig. 5. εNd (plotted here as $\Delta\varepsilon Nd_{P/I}$, the displacement from the discriminant boundary) plotted against the proportion of subduction-added Nd in the mantle wedge (ΔNd). The positive correlations demonstrate that the apparent 'Indian' character of many of the arc lavas in Fig. 3a can be explained by addition of subduction-derived Nd to mantle wedge sources and thus the plot allows the true affinity of the lavas to be deduced by back extrapolation to ΔNd=0. Arc lavas of 'Indian' character back-extrapolate to the Northern, Central and Eastern Lau Spreading Centres. Arc lavas of 'Pacific' character back-extrapolate to the Havre Trough, South Fiji Basin and Solomon Sea Basin. Similar trends are assumed for the Vanuatu arc but they are less clear. The slope of the trends, and the values of $\varepsilon Nd_{P/I}$, can be used to calculate subduction-corrected εNd.

wedge that is derived from the subduction component (Pearce et al., 1999). ΔNd is a function of the negative Hf anomaly on extended REE plots and can be determined from deviations from mantle arrays on plots such as Nd/Yb against Hf/Yb (Pearce et al., 1999) or εHf against Nd/Hf (Fig. 4). The methodology, and plots for the samples used in this paper, may be found in Fig. S1 and the calculated ΔNd values are listed in Table S1.

Eq. (1) cannot be solved directly for εNd_m because εNd_{sz} is also unknown. However, a graphical solution is possible for arc segments with Hf immobile and constant εNd_m and εNd_{sz}, by manipulating the equation as:

$$\varepsilon Nd_w = (\varepsilon Nd_{sz} - \varepsilon Nd_m) \cdot \Delta Nd + \varepsilon Nd_m. \quad (2)$$

In such cases, ΔεNd and ΔNd have a linear relationship, with a slope dependent on the difference in εNd values of the mantle and subduction components and an intercept dependent on the true εNd value of the mantle.

For the purposes of discriminating Indian and Pacific mantle, it is useful to express the wedge and mantle values as deviations in εNd from the Pacific–Indian discriminant boundary, so if $\varepsilon Nd_{P/I}$ is the value on the discriminant boundary for the measured εHf value, then Eq. (2) becomes (Pearce et al., 1999):

$$\Delta\varepsilon Nd_{P/I} = (\varepsilon Nd_{P/I} - \varepsilon Nd_w) = (\varepsilon Nd_m - \varepsilon Nd_{sz}) \times \Delta Nd + (\varepsilon Nd_{P/I} - \varepsilon Nd_m). \quad (3)$$

Fig. 5 gives the ΔεNd–ΔNd plots for the subduction-modified lavas. Some groups of lavas form diagonal trends with positive slopes, demonstrating that the samples become more 'Indian' with increasing subduction input. For the Tonga–Kermadec system (Fig. 3b), three lava groups extrapolate back to a 'Pacific' source similar to that of the South Fiji Basin and Havre Trough: the Kermadec arc, the Lau Ridge (Tonga remnant arc), Ata (southernmost Tonga arc) and the Valu Fa Ridge. The remainder of the Tonga arc extrapolates back to an 'Indian' source: the Central arc to the ΔεNd value of the ELSC and CLSC, and the Northern arc to the higher ΔεNd value of the NLSC tholeiites. This implies that mantle domain boundaries may be found within both the Tonga–Kermadec and Vanuatu arcs. The slope of 3.5 is also significant: high proportions of pelagic sediment give steep trends and high proportions of crust and volcanogenic sediment give shallow trends (Pearce et al., 1999). Thus the Tonga–Kermadec system must involve a mixed pelagic–volcanogenic source throughout.

The Vanuatu arc is less clear because the data do not define simple trends in Fig. 3b and b. Thus any extrapolation to mantle composition must involve assumptions about component compositions and about the proportion of pelagic sediment to volcanogenic sediment contributing to the Nd budget: If we assume that the whole Vanuatu arc has the same trend, we can infer that the Central part of the arc carries more of an 'Indian' signal than the northern and southern segments, which in turn carry more of a 'Pacific' signal. If we assume that the trend is comparable to that observed for Tonga–Kermadec, then most of the Central arc would classify as 'Indian', while most of the remainder classifies as 'Pacific', including all the Southern arc. Specifically, the arc would switch from 'Pacific' to 'Indian' at Nguna, and a switch back to 'Pacific' at Mota (see Table 1, where volcanoes are ordered north to south), with Aoba anomalous in having a 'Pacific' signature. Given that negative trends (i.e. negative Hf anomalies *decreasing* with subduction input) are unlikely for a subducting plate with a cover containing low-εNd sediments, we can infer that the Southern arc has a high probability of being 'Pacific'. Using the same type of argument, steep positive trends are unlikely in Central Vanuatu, where the subducting sediment cover has a high volcanogenic component, so we can infer that the at least part of the Central arc has a high probability of being 'Indian'. However, the argument for Northern Vanuatu being 'Pacific' requires that the trend is at least as steep as that observed for Tonga–Kermadec which, though likely, cannot yet be verified.

Eq. (2) can also be used to subtract quantitatively the subduction contribution to the εNd value of the subduction-related samples. εNd_m values can be estimated, with the caveats for the Vanuatu arc outlined in the last paragraph, by taking the average slope (+3.5) of the Tonga–Kermadec trends, which means the equation becomes $\varepsilon Nd_m = \varepsilon Nd_w - \Delta Nd * 3.5$. Only samples with positive ΔNd need correction. The values obtained are listed in Table 1. We use these values to produce the εHf–εNd plot for the arc lavas corrected for subducted Nd addition shown in Fig. 6. The isotopic signatures are now much clearer than in Fig. 3. For the present Tonga–Kermadec system, the Kermadec arc and South Tonga arc (Ata) classify as 'Pacific', together with the Valu Fa Ridge and the Eua and Lau Ridge remnant arcs. OIB from Fiji and the Tonga inner trench wall, together with the MORB-like basalts from Niua Fo'ou, have 'Indian' signatures — as do the products of the Samoan plume. Similarly, the Central and Northern Tonga arc together with the Central, Eastern and Northern Lau Basins classify as 'Indian'. For the North Fiji–Vanuatu system, the North Fiji Basin and some of the Central Vanuatu arc classify as 'Indian' and the Northern and Southern Vanuatu arc and some of the Central Vanuatu arc classify as 'Pacific'. For the pre-rotation basins, the South Fiji Basin classifies as 'Pacific' while the North Loyalty Basin subducting beneath Central Vanuatu classifies as 'Indian'. These conclusions both support and extend the published work summarised in the Introduction.

4. Implications for the distribution of mantle domains in the SW Pacific

The geodynamic implications of this isotope study are (a) that 'Pacific' mantle has been the ambient mantle beneath the easternmost Australian Plate since at least the Eocene; and (b) that 'Indian' mantle presently predominates in the north of the region having relatively recently displaced the 'Pacific' mantle to the south. The 'Pacific' mantle is similar to the HIMU-type that is widespread beneath fragments of eastern Gondwanaland (Panter et al., 2004). This leads us to the model

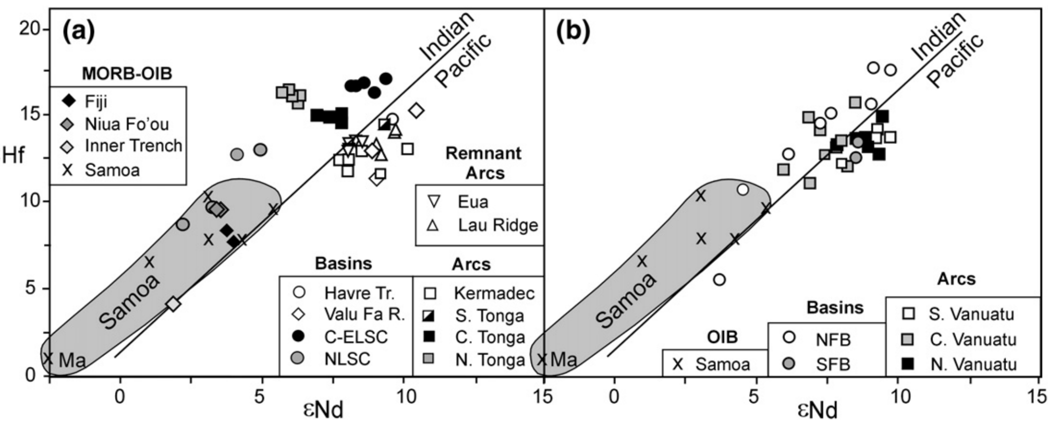

Fig. 6. εHf–εNd isotope plots for all SW Pacific samples from (a) Tonga–Kermadec and (b) North Fiji Basin and Vanuatu using εNd values corrected for subduction input (Table 1) where necessary, enabling fingerprinting of both arcs and basins and allowing the mantle domain boundaries to be identified within the region. The field for Samoa, drawn from data from this paper and Salters et al. (2002) and Patchett and Tatsumoto (1980) demonstrate its potential link to the 'Indian' domain in the SW Pacific; however, EMII-dominated lavas from the Cook–Austral Islands also plot in the 'Indian' field (Lassiter et al., 2004; Salters and White, 1998). Sz = subduction zone component; see the caption to Fig. 1 for explanation of the abbreviations.

depicted in Fig. 7, where the Vitiaz subduction zone formed a barrier to asthenospheric flow prior to OJP collision and so separated 'Indian' mantle north of the subduction zone from 'Pacific' mantle to the south. Once the OJP collided, the barrier to flow was breached allowing mantle to flow through the mantle gateway formed by the detachment of the Vitiaz subducting slab. This concept of mantle flow from beneath the Pacific plate is consistent with other work, notably the geochemical and geophysical tracing of mantle flow south of the trace of the Vitiaz Trench (Giardini and Woodhouse, 1986; Volpe et al., 1988; Poreda and Craig, 1992; Eissen et al., 1994; Turner and Hawkesworth, 1998; Smith et al., 2001) and other isotopic evidence for invasion of 'Pacific' mantle by Indian mantle in Central Vanuatu and the Lau Basin within the past 3 Ma (Hergt and Hawkesworth, 1994; Crawford et al., 1995). As the cross-sections highlight, the removal of the Vitiaz subduction zone coupled with reversal of subduction polarity and rotations of the Vanuatu and Tonga arcs

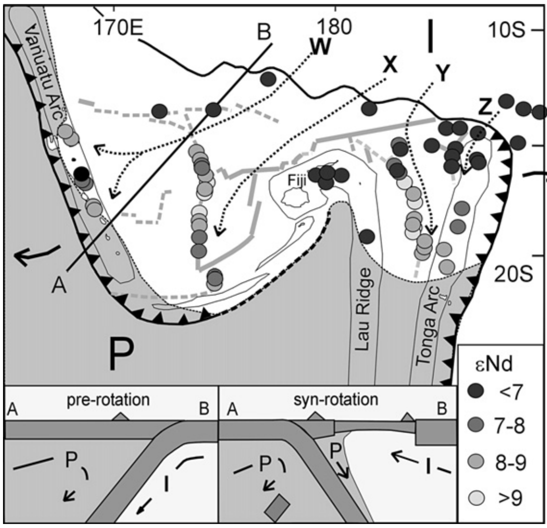

Fig. 7. Hypothesis for the evolution of mantle domains in the SW Pacific based on this work. After the Ontong-Java Plateau collides (to the NW of the study area), reversal of subduction polarity and retreat of the new Vanuatu trench followed by rotation of the Tonga arc enables SOPITA mantle to progressively penetrate the SW Pacific region along flowlines such as those depicted by dashed lines W–Z. The insets show the effect on mantle flow of subduction polarity reversal and rotation of Vanuatu arc with the Pacific (P) and Indian (I) domains marked. The circles indicate εNd values (corrected for subduction where necessary) and demonstrate a chemical gradient from OIB near the Vitiaz Trench to Indian MORB distal in the Lau and North Fiji Basins distal from the Vitiaz Trench. Note that comparison with Fig. 1 indicates that the lithosphere of the Pacific plate in this region is underlain by asthenosphere of 'Indian' affinity, possible because the Pacific plate is of Mesozoic age and so not petrogenetically related to its underlying asthenosphere.

linked to rapid trench roll-back provide the necessary conditions for inflow of 'Indian' mantle. Also relevant is the fact that the subducting plate beneath the Vanuatu arc provides a new barrier to asthenospheric flow from the south

Pinpointing the precise location of the mantle domain boundary in this model is constrained by low sample density and the fact that we can only fingerprint the mantle where we have active volcanism. In the North Fiji Basin, our data show that, to our knowledge, 'Indian' mantle likely underlies all the presently active spreading centres and rifted basins. However, some relict 'Pacific' asthenosphere must remain beneath part of the arc, as it still feeds the Vanuatu arc in the south, and perhaps north — and fed the central arc until 2–3 Ma (Crawford et al., 1995). The Hunter Fracture Zone is less clear: reconstructions have it as a site of subduction (and hence a barrier to flow) during the early rotation of the Vanuatu arc, but as a transform fault at present (e.g. Schellart et al., 2006). Our depiction of the Hunter Fracture Zone as the present domain boundary is therefore purely speculative. We also cannot rule out the possibility that there are relict domains of Pacific asthenosphere between areas of active magmatic activity in the North Fiji basin.

Further east, our data support the model that 'Indian' mantle is presently flowing into the Lau Basin (Volpe et al., 1988; Poreda and Craig, 1992; Hergt and Hawkesworth, 1994; Turner and Hawkesworth, 1998; Haase et al., 2002). For example, our data show that the Lau Ridge remnant arc was fed by 'Pacific' mantle but that most of the present Tonga arc, as well as the Central and Eastern Lau Spreading Centers, was fed by 'Indian' mantle. As the rifted margins of the Lau basin have 'Pacific' Pb affinities (Hergt and Hawkesworth, 1994), it is likely that the Lau Basin was underlain by 'Pacific' lithosphere during its initial (rifting) phase, but that 'Indian' asthenosphere followed the southward propagation of the Central and Eastern Lau spreading centres. Our data place the present-day mantle domain boundary between the 'Pacific' Valu Fa Ridge and 'Indian' Eastern Lau Spreading Centre in the back-arc. For the arc, Figs. 5 and 6 place the boundary between 'Pacific' Ata and 'Indian' Hunga Ha'apai. Some caution is needed, however, as the high εHf of Ata is more similar to Hunga Ha'apai than the volcanoes of the 'Pacific' Kermadec arc (Fig. 3a): analyses of seamounts from the South Tonga arc are therefore needed for verification. The boundary must also lie somewhere beneath the older parts of the Lau Basin, perhaps mirroring the V-shaped boundary between rifted and spread crust (Parson et al., 1990).

In the Northern Lau basin, our data demonstrate that 'Indian' mantle has penetrated at least as far south as the Mangatolu triple junction and Niua Fo'ou and that it had reached the Fijian island of Vanua Levu by 3 Ma. 'Indian' mantle also invaded the mantle wedge beneath the North Tonga arc (Tafahi and Niuatopatapu). It is likely that this basin opened within the last 3 Ma when a tear in the retreating plate allowed the Tonga arc to rotate and mantle to flow south (Zellmer and Taylor, 2001).

One outcome of this study is therefore that the so-called 'Indian' mantle originated outboard of the original Vitiaz trench and beneath the Pacific plate. Clearly a more appropriate term is needed: we propose that 'DUPAL' mantle, which has no regional connotation, or 'SOPITA' mantle, which lies within the DUPAL field but specifically refers to mantle from the Pacific source area (Staudigel et al., 1991), are better terms. Strictly, the 'Indian' domain in the SW Pacific is the western edge of the much larger 'SOPITA' domain.

5. Implications for the origin of the 'Indian' mantle domain and 'Indian MORB Mantle' in the SW Pacific

The mapping of εNd values onto Fig. 7 also illustrates the often-made observation (Volpe et al., 1988; Poreda and Craig, 1992; Eissen et al., 1994; Sobolev and Dimitriev, 1994; Auzende et al., 1995; Turner and Hawkesworth, 1998) that the 'Indian' domain in the SW Pacific has a significant geochemical gradient. It demonstrates that lavas nearest to the Vitiaz Trench have low εNd (<7) and those most distal are of MORB composition with εNd mainly >8, derived from a source sometimes described as 'Indian MORB mantle (IMM)'. There is a region some 200 km wide along the North Fiji and Tonga ridge systems where both high and low values are found. Arc values (corrected for subduction: Table 1) similarly have their highest values near the Vitiaz Trench (e.g. North Tonga) or along flow paths with few ridges (e.g. Central Vanuatu). Such geochemical gradients are common globally in areas of plume–ridge interaction where they have been explained by mixing between enriched and depleted mantle [e.g. (Schilling, 1969; Douglass et al., 1999)], by melt extraction from enriched mantle [e.g., (Phipps Morgan and Morgan, 1999; Pearce, 2005)], or by a combination of both processes. If the gradient is a consequence of mantle flow (melt extraction or mixing) then mantle must flow into the North Fiji Basin, into the Central and Eastern Lau Basin, and into the Northern Lau Basin, i.e. along increasing-εNd flow lines such as W–Z. Because the SW Pacific has a well-defined tectonic evolution and a high density of volcanic 'windows' into the composition of the underlying mantle, it provides a good opportunity to evaluate these two hypotheses.

5.1. Mixing between SOPITA and depleted mantle?

Depending on which model applies, SOPITA asthenosphere forms either the parent material for the formation of the geochemical gradients, or the end-member which mixes with depleted mantle to form the geochemical gradients. Several plumes have potentially contributed to Pacific asthenosphere in this region. Most obvious is the Samoan plume, presently some 300 km to the NW of the Northern Tonga trench and contributing a chain of older seamounts extending along the trace of the Vitiaz trench (Fig. 1). As Hart et al. (2005) point out, north Tonga moved close to the Samoan plume relatively recently. However, this does not preclude a plume contribution to the asthenosphere as plume-enriched asthenosphere can potentially flow thousands of kilometers from the source of enrichment (Phipps Morgan et al., 1995; Niu et al., 1999). The other main candidate is the Cook–Austral plume which left a Cretaceous–mid-Tertiary plume trace north of the Vitiaz trench (Gaina and Muller, 2000).

From the limited εHf–εNd data available to date, the Cook–Austral lavas mainly plot in the 'Pacific' field while, as Fig. 6 showed, Samoa occupies the 'Indian' field at the enriched end of the NFB and Lau trends. Thus, pending more Hf isotope data from the region, we can infer that the Samoan plume is likely to have made the greater contribution to the inflowing SOPITA mantle, as others have postulated using He isotope and Sr–Nd systematics (Volpe et al., 1988; Poreda and Craig, 1992; Turner and Hawkesworth, 1998). It is, however, still possible that the asthenosphere outboard of the SW Pacific is derived in part from enriched asthenosphere displaced eastwards from a shrinking Indian Ocean (Hickey-Vargas et al., 1995) and that the asthenosphere may be a complex mixture of components and melt residues from a long history of asthenospheric flow and plume–asthenosphere interaction (Staudigel et al., 1991; Gaina and Muller, 2000; Lassiter et al., 2004).

If the geochemical gradients are caused by mixing of incoming enriched mantle with a pre-existing depleted reservoir, we should get mixing trends between incoming SOPITA mantle and the ambient 'Pacific' MORB mantle. For the most part, that is not what we observe. In Fig. 6, the 'Indian' domain array for the North Fiji and Lau Basins extends from the Samoa field to higher εNd and εHf values, but there is no component of this trend towards 'Pacific' MORB. Instead, the trend from OIB to

MORB runs within the 'Indian' field and parallel to the discriminant boundary, reaching higher εHf than any Pacific samples. It is likely, therefore, that mantle flowed into both these regions without significant entrainment of ambient 'Pacific' mantle. Any mixing is likely restricted to a narrow zone, perhaps equivalent to the width of the AAD discordance. With the present sampling density, we may observe this discordance best in the Central Vanuatu arc where data cross the 'Pacific–Indian' discriminant boundary in Figs. 5 and 6.

The mixing model consistent with trends entirely within the 'Indian' field requires a reservoir of Indian MORB Mantle (IMM) south of the suture able to mix with inflowing SOPITA mantle. If such a reservoir is present, however, it is unclear why it has not been sampled more extensively in the pre-rotation basins. We identified just one sample of 'Indian' MORB from the region defined as 'Pacific' in Fig. 7, in the basement subducting beneath the Central Vanuatu arc, possibly representing the North Loyalty Basin; this is of uncertain setting and not of regional mantle reservoir scale. Moreover, it is not clear why IMM and SOPITA mantle should mix extensively over 200 km when there is a maximum of 12 Ma for mixing to take place: mantle mixing models at asthenosphere viscosities require much longer time periods than this to produce geochemical gradients over a scale of hundreds of km (e.g. Kellogg and Turcotte, 1990).

5.2. Melt extraction during flow of SOPITA mantle?

The alternative mechanism for the geochemical gradients is melt extraction from a heterogeneous SOPITA mantle carrying enriched components or 'plums' in a depleted matrix. The idea is that, as the asthenosphere flows into the SW Pacific region, it loses small melt fractions by decompression: by flowing from beneath thicker to thinner lithosphere across the Vitiaz lineament, and beneath thinning lithosphere in the North Fiji and Lau Basins. These small melt fractions preferentially extract the most fusible components (the 'plums') to form the OIB so the mantle becomes progressively depleted during flow until MORB mantle composition is reached (Staudigel et al., 1991). The fact that this is 'Indian', rather than 'Pacific', MORB mantle implies that the 'plums' and the less-fusible matrix are genetically linked, perhaps because of chemical exchange between melts and matrix during melting beneath Samoa and/or during subsequent melt extraction. This process of progressive mantle depletion by melt extraction was first termed 'preconditioning' by Kincaid (Kincaid and Hall, 2003) to describe mantle depletion in back-arc basins as mantle flows towards the arc front (McCulloch and Gamble, 1991) and the term was extended by Pearce (Pearce, 2005) to apply to all cases of flow-related mantle depletion en route to a zone of magma genesis.

At first glance, the linear trends observed on the εHf–εNd diagram would seem to favour mixing. However, Phipps Morgan (1999) demonstrated that linear trends may also be the consequence of melt extraction, and he termed these 'melt extraction trajectories' or 'METs'. More effective projections for recognising melt extraction take the form I_1 v T_2/T_1 where I_1 is the isotope ratio and T_2/T_1 is a trace element ratio with the element forming the isotope ratio as the denominator (Phipps Morgan and Morgan, 1999; Pearce, 2005). On such projections, mixing gives linear trends while melt extraction trajectories have topologies that depend on a number of petrogenetic factors and are linear only over part of their range. For this paper, we focus εNd v Yb/Nd (εHf v Yb/Hf can also be used but there are fewer data at present).

Fig. 8b gives the plot of $^{143}Nd/^{144}Nd$ v Yb/Nd for the 'Indian' domain in the SW Pacific; Fig. 8a for the 'Pacific' domain is shown for comparison. As in Fig. 7, the subduction-corrected εNd values from Table 1 have been used where appropriate, together with subduction-corrected Nd from the Table S1. The data form two distinct trends. Samples other than those from North Tonga follow a steep trend, which reaches a plateau with εNd values of 8–10 at high Yb/Nd. The enriched end-member of this trend lies in the upper part of the Samoa field. The steep part of the trend is occupied by samples from the islands south of the trace of the Vitiaz Trench (Fiji, Wallis Island and Rotuma) and most of the samples from the North Fiji Basin, Peggy Ridge and Central Vanuatu arc. The shallow part is occupied by samples from regions distal from the Vitiaz trench, namely the ELSC, CLSC, Central Tonga arc and the southern part of the North Fiji Basin. North Tonga forms a much shallower linear trend, the North Lau Trend, which extends from the Samoa field through the Northern Lau Spreading Centre and Niua Fo'ou to the North Tonga arc. This presence of two trends also supports the melt extraction model for the origin of IMM: if a long-lived IMM reservoir were present, both trends should converge on the same depleted mantle end-member.

The theory behind the interpretation of trends on this projection has been presented in Pearce (2005). Briefly, the use of Nd as the denominator in the diagram means that any mixing trends must be linear. By contrast, melt extraction trajectories are initially linear but then plateau at or near the depleted composition once the 'plums' have been removed. The precise trajectory will depend

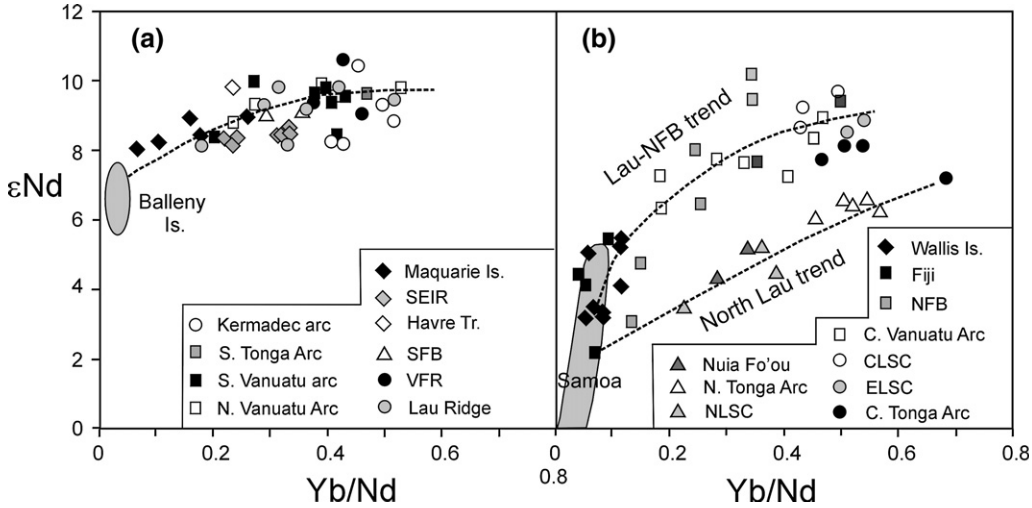

Fig. 8. εNd–Yb/Nb plot for the samples from (a) the 'Pacific' and (b) the 'Indian' domain (the latter divided into Lau–North Fiji Basin (NFB) sub-domain sampled by flowlines W, X and Y in Fig. 7 and the North Lau sub-domain sampled by flowline Z). The trends may be used to infer the nature and effect of mantle flow within each domain away from plume influence: possibly the Balleny plume (Lanyon et al., 1993) in the case of the 'Pacific' domain and Samoa plume in the case of the 'Indian' domain. Loss of melt fractions as the mantle flows beneath relatively thin lithosphere causes the mantle to evolve along melt extraction trajectories (see text and (Pearce, 2005) for details), although mixing may also contribute to the dispersion. In this way, the 'Indian MORB Mantle' of the southern parts of the Lau and North Fiji Basins can be explained by progressive melt extraction from the inflowing and enriched SOPITA mantle as it loses small melt fractions by decompression beneath the complex of spreading centres and extensional basins. Data additional to that already discussed is from Kamenetsky and Maas (2002), Lanyon et al. (1993) and Price et al. (1991).

on a series of factors, particularly temperature and component compositions. Our available data do not distinguish clearly between linear or curved lines although differences in gradient are clear. For North Tonga, the most attractive explanation for its shallow trend (supported by the >1500 °C melt inclusion data — (Sobolev and Dimitriev, 1994)) is high mantle temperature. Melt will then be extracted at higher pressure, i.e. garnet will be a more important residual phase. This has little effect on the extraction of Nd, but will suppress the extraction of Yb. This in turn, will lead to a higher Yb/Nd ratio in the residual mantle for a given degree of melt extraction and the melt extraction trajectory will have a shallower gradient (Pearce, 2005). Composition may also be important. One explanation (Sobolev and Dimitriev, 1994) is that, unlike the North Fiji and Lau Basins, North Tonga is fed by residual mantle from the active Samoa plume. This is superficially consistent with our Hf–Nd data, but the problem requires a detailed and separate evaluation which is in progress.

Thus, we view melt extraction as the higher probability explanation for the geochemical gradients in the 'Indian' domain in the SW Pacific. Heterogeneous SOPITA mantle, made up of enriched 'plums' in a depleted matrix experiences extraction of small melt fractions during flow. Melt extraction might take place in response to decompression as the mantle flows from beneath the thicker Pacific lithosphere into the North Fiji and Lau Basins, and then continue during flow beneath the various spreading axes and basins. The N-MORB of the Eastern and Central Lau Spreading Centres and parts of the North Fiji Basin would be reached given a flow pathway with sufficient opportunity for melt extraction. Therefore the 'Indian' mantle domain forms from SOPITA mantle, with IMM and depleted arc mantle sources the end-products of melt extraction during flow. On a regional scale, there is no evidence of any link between this 'Indian' domain and 'Indian' domains reported from the AAD (e.g., Kempton et al., 2002) or Izu–Bonin–Mariana region (Hickey-Vargas et al., 1995).

6. Conclusions

1. Analysis of MORB from the SW Pacific shows that Hf–Nd isotopes provide an alternative to Pb–Pb for fingerprinting lavas derived from 'Pacific;' and 'Indian' terranes. The 'Pacific' domain can be identified by both methods to be present today beneath the Havre Trough and to have been present during the Eocene–Miocene beneath the Tonga forearc, South Fiji Basin and Lau remnant arc. The 'Indian' domain can be identified as present today beneath the Central, Eastern and Northern Lau Basin, Fiji and the North Fiji Basin.
2. Analysis of arc lavas from the SW Pacific shows that Nd is subduction-mobile but there is good evidence

against significant Hf mobility, particularly in the Tonga and Kermadec arcs. All samples have negative Hf anomalies on extended REE patterns, reflecting Nd addition at constant Hf. The magnitude of the anomalies can then be used to correct the subduction-modified lavas for added Nd and allow them to be plotted on the Hf–Nd discriminant diagram. The results show that the Kermadec arc, the Valu Fa Ridge and perhaps the Southern Tonga arc (Ata) together with the South and North Vanuatu arcs have 'Pacific' affinities while the remainder of the Tonga arc has 'Indian affinities'. Central Vanuatu likely has both affinities, indicative of traversing a mantle domain boundary.

3. The distribution of lavas of 'Pacific' characteristics in time and space indicates that mantle of 'Pacific' provenance dominated the early history of the Western Pacific and may be present today throughout the SW Pacific from the Australian–Antarctic Discordance to the southern part of the study area. However, the data presented in this paper demonstrate that the mantle of 'Indian' provenance in the SW Pacific can be explained by melt extraction from SOPITA mantle that has flowed into the region following the detachment of the Pacific plate and the removal of the barrier to flow at the now-extinct Vitiaz trench. Reversal of the polarity of the Vanuatu subduction zone accompanied by trench retreat and back-arc extension then provides the pressure gradient that drives SOPITA mantle into the North Fiji Basin. Rifting of the Miocene Tonga arc subsequently allows 'Indian' mantle into the Lau Basin. Finally, tearing of the plate in the north allows 'Indian' mantle to flow into the North Tonga region.
4. Geochemical sections from the Samoan chain into the back-arc basins indicate that the scale of the gradation from plume to 'Indian' MORB mantle is variable but in the order of 200 km. To a first approximation these gradients can be explained by mixing between Samoan plume-influenced and Indian MORB mantle or by progressive depletion of the Samoan end-member or by a combination of the two. However, there is no evidence that an Indian MORB reservoir predated the inflow of SOPITA mantle. Thus we believe that the MORB in the Lau and North Fiji Basins formed by progressive depletion of SOPITA mantle as it lost small melt fractions due to decompression.

Acknowledgements

We are grateful to Sarah Acland, Kai Hirose, Dave Peate, Dave Tappin, Simon Turner and Sergei Vysotsky for collaborations on SW Pacific geochemistry that have helped in providing samples and data for this paper. Geochemical analyses were supported by Joint Infrastructure Grant NER/H/S/2000/00862 and Research Grant GR9/1260A to JAP. Iain McDonald provided assistance with the trace element analyses. We thank Rick Carlson for editing the manuscript, and Janet Hergt and an anonymous referee for their constructive comments.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2007.05.023.

References

Acland, A.S., 1996. Magma genesis in the northern Lau Basin, S.W. Pacific. PhD thesis (University of Durham, UK), 260 pp.
Auzende, J.-M., Pelletier, B., Eissen, J.-Ph., 1995. The North Fiji Basin: geology, structure and geodynamic evolution. In: Taylor, B. (Ed.), Backarc Basins: Tectonics and Magmatism. Plenum Press, N.Y., pp. 177–235.
Barry, T.L., Pearce, J.A., Leat, P.T., Millar, I.L., 2006. Hf isotope evidence for selective mobility of high-field-strength-elements in a subduction setting: South Sandwich Islands. Earth Planet. Sci. Lett. 252, 223–244.
Boespflug, X., Dosso, L., Bougault, H., Joron, J.-L., 1990. Trace element and isotopic (Sr, Nd) geochemistry of volcanic rocks from the Lau Basin. Geol. Jahrb. D92, 503–516.
Crawford, A.J., Briqueu, L., Laporte, C., Hasenaka, T., 1995. Coexistence of Indian and Pacific oceanic upper mantle reservoirs beneath the Central New Hebrides island arc. AGU Geophys. Monogr. 88, 199–217.
Douglass, J., Schilling, J.-G., Fontignie, D., 1999. Plume–ridge interactions of the Discovery and Shona mantle plumes with the southern mid-Atlantic Ridge (40°–55°S). J. Geophys. Res. 104, 2941–2962.
Dunkley, P.N., 1983. Volcanism and the evolution of the Ensimatic Solomon Islands Arc. In: Shimozuru, D., Yokoyama, I. (Eds.), Arc Volcanism: Physics and Tectonics. Terra Scientific Publishing Company, Tokyo, pp. 225–241.
Eissen, J.-P., Nohara, M., Cotton, J., Hirose, K., 1994. North Fiji Basin basalts and their magma sources: Part I. Incompatible element constraints. Mar. Geol. 116, 153–178.
Ewart, A., Hawkesworth, C.J., 1987. The Pleistocene–Recent Tonga–Kermadec arc lavas: interpretation of a new isotopic and rare earth data in terms of a depleted mantle source model. J. Petrol. 28, 495–530.
Ewart, A., Collerson, K.D., Regelous, M., Wendt, J.I., Niu, Y., 1998. Geochemical evolution within the Tonga–Kermadec–Lau-arc–back-arc systems: the role of varying mantle wedge composition in space and time. J. Petrol. 39, 331–368.
Gaina, C., Muller, R.D., 2000. Absolute plate motion, mantle flow, and volcanism at the boundary between the Pacific and Indian oceanic mantle domains since 90 Ma. AGU Geophys. Monogr. 121, 189–210.
Giardini, D., Woodhouse, J.H., 1986. Horizontal shear flow in the mantle beneath the Tonga arc. Nature 319, 551–555.
Gill, J., Whelan, P., 1989. Postsubduction ocean island alkali basalts in Fiji. J. Geophys. Res. 94, 4579–4588.

Haase, K.M., Worthington, T.J., Stoffers, P., Garbe-Schönberg, Wright, I., 2002. Mantle dynamics, element recycling and magma genesis beneath the Kermadec arc–Havre Trough. Geochem. Geophys. Geosyst. 3. doi:10.1029/2002GC000335.

Hart, S.R., Coetzee, M., Workman, R.K., Blusztajn, J., Johnson, K.T.M., Sinton, J.M., Steinberger, B., Hawkins, J.W., 2005. Genesis of the Western Samoa seamount province: age, geochemical fingerprint and tectonics. Earth Planet. Sci. Lett. 227, 37–56.

Hergt, J.M., Hawkesworth, C.J., 1994. Pb, Sr and Nd isotopic evolution of the Lau Basin: implications for mantle dynamics during back-arc opening. In: Hawkins, J.W., Parson, L.M., Allan, J.F. (Eds.), Proc. ODP Sci. Res., vol. 135, pp. 505–517.

Hickey-Vargas, R., Hergt, J.M., Spadea, P., 1995. The Indian Ocean type isotopic signature in western Pacific marginal basins: origin and significance. In: Taylor, B., Natland, J. (Eds.), Active Margins and Marginal Basins of the Western Pacific. AGU Geophysical Monograph, vol. 88, pp. 175–197.

Kamenetsky, V.S., Maas, R., 2002. Mantle-melt evolution (dynamic source) in the origin of a single MORB suite: a perspective from magnesian glasses of Macquarie Island. J. Petrol. 43, 1909–1922.

Kellogg, L.H., Turcotte, D.L., 1990. Mixing and the distribution of heterogeneities in a chaotically convecting mantle. J. Geophys. Res. 95, 421–432.

Kempton, P.D., 1995. Common Pb chemical procedures for silicate rocks and minerals, methods of data correction and an assessment of data quality at the NERC Isotope Geosciences Laboratory. NIGL Report Series 78 26 pp.

Kempton, P.D., Nowell, G.M., Fitton, J.G., Saunders, A.D., Taylor, R.N., 2000. The Iceland plume in space and time: a Sr–Nd–Pb–Hf study of the North Atlantic rifted margin. Earth Planet. Sci. Lett. 177, 255–271.

Kempton, P.D., Pearce, J.A., Barry, T.L., Fitton, J.G., Langmuir, C., Christie, D.M., 2002. Sr–Nd–Pb–Hf isotope results from ODP Leg 187: evidence for mantle dynamics of the Australian–Antarctic Discordance and origin of the Indian MORB source. Geochem. Geophys. Geosyst. doi:10.1029/2002GC000320.

Kincaid, C., Hall, P.S., 2003. Role of back-arc spreading in circulation and melting at subduction zones. J. Geophys. Res. 108 2001JB001174.

Lagabrielle, Y., Goslin, J., Martin, H., Thirot, J.-L., Auzende, J.-M., 1997. Multiple active spreading centres in the hot North Fiji Basin (Southwest Pacific): a possible model for Archaean seafloor dynamics. Earth Planet. Sci. Lett. 149, 1–13.

Lanyon, R., Varne, R., Crawford, A.J., 1993. Tasmanian Tertiary basalts, the Balleny plume, and opening of the Tasman Sea (Southwest Pacific Ocean). Geology 21, 555–558.

Lassiter, J.C., Blichert-Toft, J., Hauri, E.H., Barsczus, H.G., 2004. Isotope and trace element variations in lavas from Raivavae and Rapa, Cook–Austral islands: constraints on the nature of HIMU- and EM-mantle and the origin of mid-plate volcanism in French Polynesia. Chem. Geol. 202, 115–138.

Loock, G., McDonough, W.F., Goldstein, S.L., Hofmann, A.W., 1990. Isotopic compositions of volcanic glasses from the Lau basin. Mar. Min. 9, 235–245.

Malahoff, A., Hammond, S.R., Naughton, J.J., Keeling, D.L., Richmond, R.N., 1982. Geophysical evidence for post-Miocene rotation of the island of Viti Levu, Fiji, and its relationship to the tectonic development of the North Fiji Basin. Earth Planet. Sci. Lett. 57, 398–414.

McCulloch, M.T., Gamble, J.A., 1991. Geochemical and geodynamic constraints on subduction zone magmatism. Earth Planet. Sci. Lett. 102, 358–374.

Münker, C., Worner, G., Yogodzinski, G., Churikova, T., 2004. Behaviour of high field strength elements in subduction zones: constraints from Kamchatka–Aleutian arc lavas. Earth Planet. Sci. Lett. 224, 275–293.

Niu, Y., Collerson, K.D., Batiza, R., Wendt, I.J., Regelous, M., 1999. The origin of E-type MORB at ridges far from mantle plumes: the East Pacific Rise at 11°20′N. J. Geophys. Res. 104, 7067–7087.

Nohara, M., Hirose, K., Eissen, J.-P., Urabe, T., Joshima, M., 1994. The North Fiji Basin basalts and their magma sources: Part II. Sr–Nd isotope and trace element constraints. Mar. Geol. 116, 179–195.

Nowell, G.M., Kempton, P.D., Fitton, J.G., Saunders, A.D., Taylor, R., 1998. High-precision Hf isotope measurements of MORB and OIB by thermal ionization mass spectrometry: insights into the depleted mantle. Chem. Geol. 149, 211–233.

Panter, K.S., Blusztajn, J., Hart, S.R., Kyle, P.R., Esser, R., McIntosh, W.C., 2004. The origin of HIMU in the SW Pacific: evidence from intraplate volcanism in southern New Zealand and Subantarctic islands. J. Petrol. 45. doi:10.1093/petrology/eg1024.

Parson, L.M., Hawkins, J.W., 1994. Two-stage ridge propagation and the geological history of the Lau backarc basin. In: Hawkins, J.W., Parson, L.M., Allan, J.F. (Eds.), Proc. ODP Sci. Res., vol. 135. Washington, US Government Printing Office, Washington D.C., pp. 819–882.

Parson, L.M., Tiffin, D.L., 1993. The northern Lau Basin: diffuse backarc extension at the leading edge of the Indo-Australian Plate. Geo-Mar. Lett. 13, 107–115.

Parson, L.M., Pearce, J.A., Murton, B.J., Hodkinson, B.J., 1990. RRS Charles Darwin Scientific Party, the role of ridge jumps and ridge propagation in the tectonic evolution of the Lau back-arc basin, SW Pacific. Geology 18, 470–473.

Patchett, P.J., Tatsumoto, M., 1980. Hafnium isotope variations in oceanic basalts. Geophys. Res. Lett. 7, 1077–1080.

Pearce, J.A., 2005. Mantle preconditioning by melt extraction during flow: theory and petrogenetic implications. J. Petrol. 46, 973–997.

Pearce, J.A., Ernewein, M., Bloomer, S.H., Parson, L., Murton, B.J., Johnson, L.E., 1995. Geochemistry of Lau Basin volcanic rocks: influence of ridge segmentation and arc proximity. Geol. Soc. London, Spec. Publ. 81, 53–75.

Pearce, J.A., Kempton, P.D., Nowell, G.M., Noble, S.R., 1999. Hf–Nd element and isotope perspective on the nature and provenance of mantle and subduction components in arc-basin systems: examples from the western Pacific. J. Petrol. 40, 1579–1611.

Peate, D.W., Pearce, J.A., Hawkesworth, C.J., Colley, H., Edwards, C. M.H., Hirose, K., 1997. Geochemical variations in Vanuatu arc lavas: the role of subducted material and a variable mantle wedge composition. J. Petrol. 38, 1331–1358.

Peate, D.W., Kokfelt, T.F., Hawkesworth, C.J., van Calsteren, P., Hergt, J.M., Pearce, J.A., 2001. ^{238}U–^{230}Th–^{226}Ra disequilibrium in Lau Basin glasses: the role of subduction-related fluids during melt generation in back-arc basins. J. Petrol. 42, 1449–1470.

Pelletier, B., Calmant, S., Pillet, R., 1998. Current tectonics of the Tonga–New Hebrides region. Earth Planet. Sci. Lett. 164, 263–276.

Phipps Morgan, J., 1999. Isotope topology of individual hotspot basalt arrays: mixing curves or melt extraction trajectories. Geochem. Geophys. Geosyst. 1 1999GC000004.

Phipps Morgan, J., Morgan, W.J., 1999. Two-stage melting and the geochemical evolution of the mantle: a recipe for mantle plum-pudding. Earth Planet. Sci. Lett. 170, 215–239.

Phipps Morgan, J., Morgan, W.J., Zhang, Y.-S., Smith, W.H.F., 1995. Observational hints for a plume-fed sub-oceanic asthenosphere and its role in mantle convection. J. Geophys. Res. 100, 12753–12768.

Poreda, R.J., Craig, H., 1992. He and Sr isotopes in the Lau Basin mantle: depleted and primitive mantle components. Earth Planet. Sci. Lett. 113, 487–493.

Price, R.C., Maillet, P., McDougall, I., Dupont, J., 1991. The geochemistry of basalts from the Wallis Islands, Northern Melanesian Borderland: evidence for a lithospheric origin for Samoan-type basaltic magmas? J. Volcanol. Geotherm. Res. 45, 267–288.

Royse, K.R., Kempton, P.D., Darbyshire, D.P.F., 1998. Procedure for the analysis of rubidium–strontium and samarium–neodymium isotopes at the NERC Isotope Geosciences Laboratory. NIGL Report Series 121 28 pp..

Salters, V.J.M., White, W.M., 1998. Hf isotope constraints on mantle evolution. Chem. Geol. 145, 447–460.

Salters, V.J., Hart, S.R., Blichert-Toft, J., 2002. Hafnium–neodymium isotope systematics of ocean island basalts. Eos, Trans. - Am. Geophys. Union 83 (47) Fall Meet. Suppl., Abstract V61D-08.

Schellart, W.P., Lister, G.S., Toy, V.G., 2006. A Late Cretaceous and Cenozoic reconstruction of the Southwest Pacific region: tectonics controlled by subduction and slab rollback processes. Earth Sci. Rev. 76, 191–233.

Schilling, J.-G., 1969. Afar mantle plume: rare earth evidence. Nat. Phys. Sci. 242, 565–571.

Smith, G.P., Wiens, D.A., Fischer, K.M., Dorman, L.M., Webb, S.C., Hildebrand, J.A., 2001. A complex pattern of mantle flow in the Lau Backarc. Science 292, 713–716.

Sobolev, A.V., Dimitriev, L.V., 1994. Petrology and geochemistry of boninites from the north termination of the Tonga Trench: constraints on the generation conditions of primary high-Ca boninite magmas. J. Petrol. 35, 1183–1211.

Staudigel, H., Park, K.-H., Pringle, M., Rubenstone, J.L., Smith, W.H.F., Zindler, A., 1991. The longevity of the South Pacific isotopic and thermal anomaly. Earth Planet. Sci. Lett. 102, 24–44.

Todt, W., Cliff, R.A., Hanser, A., Hofmann, A.W., 1996. Evaluation of a ^{202}Pb–^{205}Pb double spike for high-precision lead isotope analysis. In: Hart, S.R., Basu, A. (Eds.), Earth Processes: Reading the Isotope Code. Geophys. Monogr. Ser., vol. 95. AGU, Washington D.C., pp. 429–437.

Tollstrup, D.L., Gill, J.B., 2005. Hafnium systematics of the Mariana arc: evidence for sediment melt and residual phases. Geology 33, 737–740.

Turner, S., Hawkesworth, C., 1998. Using geochemistry to map mantle flow beneath the Lau Basin. Geology 26, 1019–1022.

Turner, S., Hawkesworth, C., Rogers, N., Bartlett, J., Worthington, T., Hergt, J., Pearce, J., Smith, I., 1997. ^{238}U–^{230}Th disequilibria, magma petrogenesis, and flux rates beneath the depleted Tonga–Kermadec island arc. Geochim. Cosmochim. Acta 61, 4855–4884.

Turner, S.P., Peate, D.W., Hawkesworth, C.J., Eggins, S.M., Crawford, A.J., 1999. Two mantle domains and the time scales of fluid transfer beneath the Vanuatu arc. Geology 27, 963–966.

Volpe, A.M., Macdougall, J.D., Hawkins, J.W., 1988. Lau Basin basalts (LBB): trace element and Sr–Nd isotopic evidence for heterogeneity in back-arc basin mantle. Earth Planet. Sci. Lett. 90, 174–186.

Woodhead, J.D., Hergt, J.M., Davidson, J.P., Eggins, S.M., 2001. Hafnium isotope evidence for 'conservative' element mobility during subduction processes. Earth Planet. Sci. Lett. 192, 331–346.

Zellmer, K.E., Taylor, B., 2001. A three-plate kinematic model for Lau Basin opening. Geochem. Geophys. Geosyst. 2 2000GC000106.