

# Os Isotope Systematics in the Canary Islands and Madeira: Lithospheric Contamination and Mantle Plume Signatures

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Osmium concentrations and isotopic signatures were measured in 28 primarily Holocene basalts (22 of which have been analyzed for Sr–Nd–Pb isotope composition), two carbonatites and two mantle xenoliths from the Canary Islands, Selvagen Grande and Madeira in the eastern North Atlantic.  $^{187}\text{Os}/^{188}\text{Os}$  ratios in the basalts range from 0.129 to 0.183. The Os isotope systematics indicate that the basalts fall into three petrogenetic groups: (1) a ‘radiogenic’ group with high  $^{187}\text{Os}/^{188}\text{Os}$  from 0.152 to 0.183; (2) an ‘unradiogenic’ group with low  $^{187}\text{Os}/^{188}\text{Os}$  from 0.129 to 0.138; (3) an ‘intermediate’ group with  $^{187}\text{Os}/^{188}\text{Os}$  between 0.139 and 0.151. The Os isotope systematics of the radiogenic group samples are consistent with minor contamination of the basalts by marine sediment. All samples in the unradiogenic group contain mantle xenoliths, and the unradiogenic Os can be explained by bulk assimilation of  $\leq 5\%$  mantle peridotite in the form of disaggregated xenoliths. The radiogenic and unradiogenic groups are also characterized by higher  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  but lower  $^{143}\text{Nd}/^{144}\text{Nd}$  than samples with similar  $^{206}\text{Pb}/^{204}\text{Pb}$  from the intermediate group, which is interpreted to reflect interaction of plume magmas with the lithospheric mantle. The intermediate group samples are believed to represent the isotopic signature of the mantle plume. The Os isotopic composition of the Canary plume is among the most radiogenic found in ocean island basalts, comparable with the endmember HIMU islands Mangaia and Tubuaii, but at significantly lower  $^{206}\text{Pb}/^{204}\text{Pb}$ . The radiogenic Os and moderate  $^{206}\text{Pb}/^{204}\text{Pb}$  signature of the Canary plume is consistent with a plume which contains 25–35% of relatively young ( $\sim 1.2$  Ga) recycled oceanic crust. Variable degree of mixing of the Canary Island plume source with shallow depleted asthenosphere containing

a component of Paleozoic oceanic crust produces the limited range in Os isotopic signatures observed in the Madeira and Canary Island basalts despite a large range in  $^{206}\text{Pb}/^{204}\text{Pb}$  isotopic composition.

KEY WORDS: Canary Islands; crustal contamination; lithospheric mantle; ocean island basalts; Os isotopes

## INTRODUCTION

The compositions of mantle sources are commonly inferred from the isotopic signatures of basalts erupted at the Earth’s surface. To extrapolate from the composition of a basalt to that of the mantle source from which it was generated, the nature of interactions between the melt and overlying lithosphere must be understood in detail. However, it is often difficult to distinguish conclusively between enriched components in the plume and those incorporated by plume melts in the lithosphere. The Os isotope system is a powerful tracer for investigating both the processes which affect plume melts during ascent through the overlying lithosphere, as well as the nature of recycled components in mantle plume sources.

Distinguishing between contamination of basaltic melts in the crust vs the lithospheric mantle can be difficult,

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as mantle metasomatic processes can produce Sr, Nd and Pb isotopic signatures in the lithospheric mantle that are similar to those of crustal material. In contrast, the Os isotope signatures of the lithospheric mantle and crust are distinct from one another. The lithospheric mantle generally preserves unradiogenic Os signatures caused by initial Re depletion, because of the relative insensitivity of the Os isotope system to overprinting by mantle metasomatic processes (Walker *et al.*, 1989; Pearson *et al.*, 1995*b*), whereas crustal material tends to be very radiogenic in Os because of the high Re/Os ratios generated during crust formation. Thus, very different Os isotope signatures might be imparted to plume melts depending on the nature of the lithospheric contaminant.

The very radiogenic nature of crustal material relative to residual mantle also allows the Os isotope system to be a useful tracer of recycling of crustal material back into the deep mantle. Because Os concentrations in the mantle are much greater than those in most crustal material, the Os isotope system is sensitive only to a fairly large percentage of recycled crustal material in a mantle source. In contrast, even minute amounts of crustal recycling, especially of sediments, can overwhelm the signatures of highly incompatible element isotope systems such as Sr, Nd and Pb. The Os isotope system therefore provides important evidence as to the percentage of recycled oceanic crust which might contribute to mantle plumes, provided that lithospheric contamination signatures can be eliminated.

Because Os is compatible during melting of the mantle, the Os concentrations of basaltic melts are typically extremely low, which enhances the utility of Os as a tracer of melt–lithosphere interactions. However, the ease with which basaltic melts may become contaminated during ascent through the lithosphere makes the interpretation of Os isotope systematics in ocean island basalts rather complex. To utilize the Os isotope system as a mantle tracer, it is necessary to filter out signatures superimposed on plume melts by the various high-level contamination processes. This requires detailed studies of individual ocean islands and island chains, where systematic variations in Os isotope signatures can be discerned and combined with other isotope systems such as Sr, Nd and Pb.

The location of the Canary Islands, Selvagen Islands and Madeira close to the African continent on old (>130 Ma) thick lithosphere with up to 10 km sediment cover makes these island chains particularly appropriate for an investigation of the effects of melt–lithosphere interaction on the Os isotope system. In this paper we report Os concentrations and isotope ratios for a suite of 28 primarily Holocene basalts from Madeira, Selvagen Grande and all of the Canary Islands (Hiero, La Palma, Gomera, Tenerife, Gran Canaria, Fuerteventura, Lanzarote), as well as two carbonatites from Fuerteventura and two

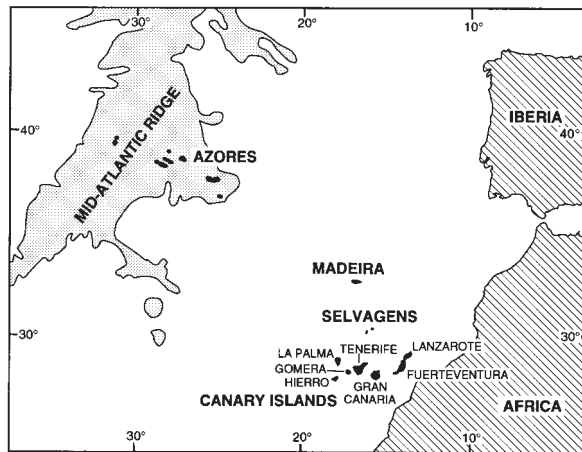
peridotites from Lanzarote. This study concentrates on the Canary Islands but includes a few samples from Madeira and Selvagen Grande, which help constrain the processes occurring in the Canary Islands. In particular, Sr–Nd–Pb isotope systematics indicate that the Canary Islands and Madeira may share a common low  $^{206}\text{Pb}/^{204}\text{Pb}$  mantle endmember (Hoernle *et al.*, in preparation, a); we therefore consider these islands together in this study. We integrate the Os data with Sr–Nd–Pb isotope data on the same samples to evaluate the role of lithospheric contamination and in particular to distinguish between crustal and lithospheric mantle contamination, and to recognize recycled components in the mantle plume sources.

## GEOLOGIC AND GEOCHEMICAL SETTING

The Canary Islands comprise a chain of seven islands located off the northwest coast of Africa (Fig. 1). The origin of the island chain is thought to be hotspot related (Morgan, 1981), consistent with the geochemistry of the volcanic rocks and the east to west age progression in both the subaerial (from >20 to 1 Ma) and uplifted submarine complexes [25–70 to 4 Ma; see review by Hoernle & Schmincke (1993)]. Each of the Canary Islands has been active in the Holocene, except Gomera, where there has been no Quaternary activity; a 4 Ma sample is therefore taken to represent this island. Historic activity has occurred on four of the islands (Hiero, La Palma, Tenerife, Lanzarote), which span the entire Canary chain. Samples from Selvagen Grande and Madeira are believed to be <100 000 years in age.

Crustal ages beneath the Canary Islands are ~150–175 Ma based on the location of the M25 magnetic anomaly (156 Ma) between the westernmost islands of Hierro and La Palma and the S1 anomaly (~175 Ma) between the easternmost islands and Africa (Roeser, 1982; Klitgord & Schouten, 1986; Roest *et al.*, 1992). The nature of the lithosphere beneath the Canary Islands (continental vs oceanic) has been the subject of a long-standing controversy. However, seismic refraction data (e.g. Bossard & Macfarlane, 1970; Banda *et al.*, 1981) and the occurrence of mid-ocean ridge basalt (MORB)-like gabbros on Lanzarote, Gran Canaria and La Palma (Hoernle, 1998; Schmincke *et al.*, 1999; and references therein) strongly argue for the presence of oceanic crust beneath all of the Canary Islands. The seismic refraction studies further indicate that a sediment cover of 5–10 km in thickness may underlie the easternmost islands.

Late Pleistocene and Holocene basalts from the Canary Islands are isotopically heterogeneous in Sr, Nd and Pb isotope ratios (Hoernle *et al.*, in preparation, a; in preparation, b). Basanites and alkali basalts with  $\text{SiO}_2$



**Fig. 1.** Map of the eastern North Atlantic Ocean basin between 25° and 45°N, showing the location of the Canary Islands, Selvagen Islands and Madeira. Six of the seven Canary Islands have had Holocene volcanism and are represented in this study; one 4 Ma sample from Gomera is also included in this study, as are Late Pleistocene (<100 ka) samples from Selvagen Grande and Madeira.

$\leq 46$  wt % and MgO > 8 wt % occur on all studied islands and display binary mixing trends on Sr–Nd–Pb isotope correlation diagrams, which could be explained by mixing of two components: (1) the low seismic velocity component (LVC) of Hoernle *et al.* (1995), a HIMU-type plume component (radiogenic  $^{206}\text{Pb}/^{204}\text{Pb}$ ; Zindler & Hart, 1986) found throughout the eastern Atlantic, western Mediterranean and Europe; (2) an asthenospheric component characterized by Holocene Madeira basalts, with HIMU trace element characteristics but MORB-like Sr–Nd–Pb isotopic ratios, interpreted as reflecting oceanic crust subducted in this region during the Paleozoic (Hoernle *et al.*, in preparation, b). Evidence for the location of this component in the asthenosphere comes from studies of Jurassic ocean crust samples from Gran Canaria, some of which have HIMU-like trace element characteristics (Hoernle, 1998). Alkali basalts and tholeiites with  $\text{SiO}_2 > 46$  wt % occur only on the two easternmost Canary Islands of Lanzarote and Fuerteventura. These high- $\text{SiO}_2$  basalts generally have higher  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\Delta 8/4$  [or  $^{208}\text{Pb}/^{204}\text{Pb}$  for a given  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio relative to the Northern Hemisphere Reference Line (NHRL); Hart, 1984] but lower  $^{143}\text{Nd}/^{144}\text{Nd}$  than low- $\text{SiO}_2$  basalts from the same islands and even from the same eruption (e.g. 1730–1736 eruption on Lanzarote zoned from basanite to tholeiite), providing evidence for a third, enriched mantle (EMI; Zindler & Hart, 1986) component. The isotopic signatures of these basalts are attributed to contamination within the lithosphere.

## ANALYTICAL TECHNIQUES

Holocene samples from the Canary Islands were collected with Os isotopic analysis in mind. Care was taken to limit exposure of the samples to metal, in order to minimize potential Re and Os processing blanks. Also, all sampled units were carefully inspected, over regions of more than 100 m in some cases, to identify the freshest portions of the volcanic unit and to avoid xenolithic material. The presence, type and abundance of xenoliths was carefully noted. Fresh sample chips of a size appropriate for the shatter box were carefully hand-picked by the authors to avoid any areas showing signs of alteration and to insure that the sample chips were free of any obvious xenolith debris. Sample chips were then ground to a flour in an agate shatter box. Most samples were digested by the Carius tube method; a few samples were dissolved by an acid digestion technique, which has been described in detail elsewhere (Walker, 1988; Shirey & Walker, 1995). In the Carius tube technique (Shirey & Walker, 1995), 2–3 g of sample powder are dissolved in concentrated aqua regia in a sealed glass tube by heating in an oven for 24–48 h at 200–250°C. This method is more effective than the Teflon vessel digestion technique for equilibrating spike and sample Os, and for extracting Os from sulfides, metals and spinels. Os concentrations measured in alkali basalts tend to be somewhat higher when samples are digested in Carius tubes compared with Teflon vessel digestions, but Os isotopic compositions in young samples are identical (Shirey & Walker, 1995). Total processing blanks are  $\sim 2$  pg with  $^{187}\text{Os}/^{188}\text{Os}$  of  $0.17 \pm 0.02$ . Procedures for Re separations using anion exchange columns with AG1-X8 resin have been described elsewhere (Pearson *et al.*, 1995b). Re blanks ranged from 5 to 20 pg, and averaged 12 pg.

Re and Os isotope ratios were measured as the negative oxides  $\text{ReO}_4^-$  and  $\text{OsO}_3^-$  following existing techniques (Creaser *et al.*, 1991). The procedures for measuring Re and Os at DTM have been described in detail by Pearson *et al.* (1995b). In-run precision was generally better than 0.5% for  $^{187}\text{Re}/^{185}\text{Re}$  ratios and, with a few exceptions, between 0.16% and 1.5% for  $^{187}\text{Os}/^{188}\text{Os}$  ratios. The small amount of sample Os and correspondingly small Os signal sizes produced in-run precisions for samples that were sometimes greater than the 0.2%  $2\sigma$  external reproducibility obtained on standards. Replicate measurements of Os concentration agreed within 2% to 29%. This level of reproducibility of Os concentration is not unexpected given the small sample sizes (mostly 2–3 g) and the very low Os concentrations. The Os is presumably hosted in trace phases and may therefore not be homogeneously distributed throughout the sample. Indeed, if we calculate the expected reproducibility of Os concentration measurements for 2 g samples, based

on the ~5% worst-case reproducibility found in replicates of 50 g fusion samples (Hauri & Hart, 1993) and using the sampling error estimates of Kleeman (1967), we would estimate worst-case reproducibility for Os concentration of ~100%. Such reproducibility is consistent with what we observe in the Canaries data set as well as a similar data set on samples from the Azores (Widom & Shirey, 1996). Replicate analyses of the Os isotope ratios all agree within 0.5–1.6% (Table 1).

## RESULTS

The basalts analyzed in this study range from tholeiite to alkali basalt to basanite. All samples are fairly mafic with MgO = 8–15 wt % and Ni = 113–437 ppm. Os concentrations range from 7 to 278 pg/g (Table 1 and Fig. 2), and display a positive correlation with both MgO and Ni content. Re concentrations in 13 basalts from six of the Canary Islands range from 41 to 705 pg/g, but do not vary systematically with MgO or Ni. Re/Os ratios, however, are negatively correlated with Os concentration, because of the relatively large variation in Os abundances.  $^{187}\text{Os}/^{188}\text{Os}$  isotope ratios in basalts from the Canary Islands, Selvagen Grande and Madeira span a large range from 0.129 to 0.183 (Table 1). The Os isotope ratios do not seem to vary systematically between islands, but rather large variations occur within most of the islands. An extreme case of the large intra-island variations in Os isotope signature is exemplified by the island of Lanzarote, which exhibits the full range of Os isotope ratios found in the Canary archipelago as a whole.

The Os isotope signatures in the Canary Islands, Selvagen Islands and Madeira exhibit a complex relationship with Os concentration (Fig. 2). Samples with low Os concentration exhibit a large range in  $^{187}\text{Os}/^{188}\text{Os}$  and display the most radiogenic values, a relationship that has been observed in other cases including St Helena (Reisberg *et al.*, 1993), the Azores archipelago (Widom & Shirey, 1996) and La Palma (Marcantonio *et al.*, 1995). For high Os concentration samples, however, the relationship between  $^{187}\text{Os}/^{188}\text{Os}$  and Os concentration in the Canary Islands differs from that of St Helena and the Azores. In the latter islands, the high Os concentration samples yield a relatively narrow range in  $^{187}\text{Os}/^{188}\text{Os}$  despite large ranges in Os concentration, whereas the high concentration samples in the Canary Islands are variable in  $^{187}\text{Os}/^{188}\text{Os}$ , and extend to relatively unradiogenic Os isotope signatures (Fig. 2).

In detail, the Os isotope systematics of the Canary Islands, Selvagen Islands and Madeira samples allow a simple division into three sample groups. One group, the 'radiogenic' group, includes the nine most radiogenic samples ( $^{187}\text{Os}/^{188}\text{Os} = 0.152\text{--}0.183$ ), all of which have Os concentrations <52 pg/g and  $^{187}\text{Os}/^{188}\text{Os}$  more

radiogenic than any samples with high Os abundances (>52 pg/g Os). The second group, or 'unradiogenic' group, consists of the six basalt samples which come from mantle xenolith-bearing lava flows and contain xenocrystic olivine from mantle peridotite (D. Graham, unpublished data, 1998). These basalts have the least radiogenic Os isotope ratios, ranging in  $^{187}\text{Os}/^{188}\text{Os}$  from 0.129 to 0.138. The third group, or 'intermediate group' consists of the remaining 13 samples, which have a relatively limited range in  $^{187}\text{Os}/^{188}\text{Os}$  from 0.139 to 0.151 despite an almost 20-fold variation in Os concentration from 12 to 232 pg/g (Fig. 2). This is approximately the same range of  $^{187}\text{Os}/^{188}\text{Os}$  as found previously in 0.8–1.6 Ma basalts from the island of La Palma (0.136–0.150; Marcantonio *et al.*, 1995). In the following discussion we consider the implications of these variable Os isotopic signatures regarding the composition of the Canary Island plume and potential melt–lithosphere interactions.

## DISCUSSION

### Os isotopic composition of the Canary Island plume

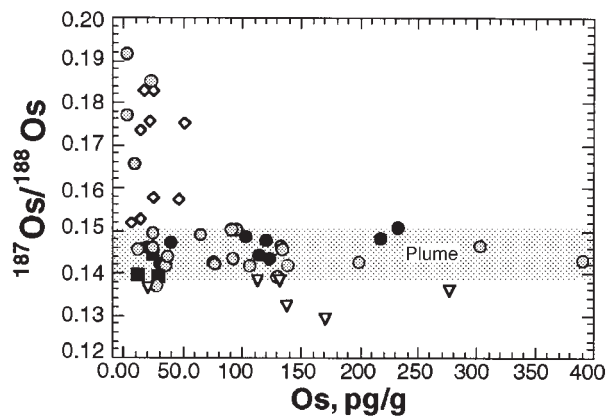
Detailed Os isotope studies of basalts from individual ocean islands have generally shown that low Os concentration basalts (<30–50 ppt) have highly variable Os isotope signatures extending to very radiogenic values, whereas higher Os abundance basalts display limited variability and have the least radiogenic Os signatures (Reisberg *et al.*, 1993; Martin *et al.*, 1994; Marcantonio *et al.*, 1995; Widom & Shirey, 1996; Widom, 1997). In these cases, the high Os concentration basalts have been interpreted as representing the Os isotopic signature of the respective mantle plume, and the radiogenic Os isotope signatures of the low Os concentration basalts have been attributed to crustal contamination of plume-derived basalts (Reisberg *et al.*, 1993; Martin *et al.*, 1994; Marcantonio *et al.*, 1995; Widom & Shirey, 1996; Widom, 1997). In the case of the Canary Islands basalts, where high Os concentration samples (>52 ppt) exhibit relatively variable Os isotopic signatures characteristic of both the intermediate and unradiogenic groups, determining the Os isotopic composition of the plume is more complex.

Conventional wisdom based on incompatible element isotope ratios would lead to the conclusion that the unradiogenic, mantle xenolith-bearing group have suffered the least shallow-level contamination and therefore are the most likely to represent the isotopic composition of the mantle plume from which they were derived. However, this is not necessarily an appropriate inference for a compatible element such as Os. In the case of Os, the relative mass-balance dictates that basalts might easily become contaminated during ascent through

Table 1: Sr–Nd–Pb–Os isotope and other relevant data for samples from the Canary Islands, Selvagen Grande and Madeira

Sample	Age (years)	Rock type	MgO (%)	Ni (ppm)	Os (ppt)	Re (ppt)	$^{187}\text{Re}/^{188}\text{Os}$	$^{187}\text{Os}/^{188}\text{Os}$	Digestion
<i>Canary Islands</i>									
Fuerteventura EF1	Prehistoric	Basanite	11.6	286	73.0	115	7.57	0.1438(7)	CT
<i>EF1</i>					76.1			0.1415(18)	CT
EF5	Holocene	Basanite	13.6	395	131.7			0.1379(4)	CT
EF6	Holocene	Tholeiite	8.4	187	15.5			0.1731(47)	CT
<i>EF6</i>									
EF7	85 ka?	Basanite	10.8	260	22.4	73	15.7	0.1755(11)	CT
EF12	Holocene	Tholeiite	9.6	264	17.9			0.1827(16)	CT
68/SC/72	30 Ma	Carbonatite			14.5			0.6138(103)	AD/CT
F/75/153	60 Ma	Carbonatite			4.7			0.4554(184)	AD/CT
Gran Canaria EGC1	Holocene?	Basanite	14.6	371	40.1			0.1473(11)	CT
EGC6	3075	Basanite	10.3	189	20.8			0.1362(10)	CT
EGC8	50 ka?	Basanite	11.2	234	7.5			0.1513(12)	CT
Hierro EH4	2900	Basanite	11.0	323	119.7	327	13.1	0.1475(10)	CT
<i>EH4</i>									
EH8	1793	Basanite	14.5	404	216.9			0.1481(14)	CT
<i>EH8</i>									
EH11	Prehistoric	Basanite	11.9	312	114.3	173	7.28	0.1443(7)	CT
Lanzarote EL1	1824	Basanite	12.9	346	113.2			0.1377(18)	CT
<i>EL1</i>									
EL5	1731	Alk Bas	11.0	314	137.9	155	5.4	0.1320(10)	CT
EL8	April 1736	Tholeiite	9.5	279	25.4	114	21.6	0.1574(25)	CT
EL10	Sept. 1730	Basanite	14.3	437	170.9	168	4.73	0.1288(7)	CT
EL17	Prehistoric	Alk Bas	10.2	255	25.3	41	7.79	0.1826(31)	CT
ELX1	1730–1736	Harzburgite			1293.2	40	0.149	0.1230(2)	CT
ELX2	1730–1736	Harzburgite			8029.7	203	0.122	0.1274(2)	CT
La Palma LP71-7L	1971	Basanite	8.2	121	14.5			0.1524(7)	AD
<i>LP71-7L</i>			8.2	109					
LP26192-5	1712?	Basanite	12.1	299	103.1	206	9.61	0.1487(8)	CT
<i>LP26192-5</i>			12.0	282					
ELP1	1470–1492	Basanite	7.6	113	18.3			0.1454(8)	AD
<i>ELP1</i>					21.4			0.1462(43)	CT
ELP4	Holocene?	Basanite	10.7	244	51.2	705	66.2	0.1741(7)	CT
<i>ELP4</i>					52.5			0.1755(26)	CT
ELP7	Holocene	Basanite	9.3	168	30.8			0.1420(11)	CT
Tenerife ET6	1705	Basanite	9.3	188	123.2	397	15.5	0.1433(7)	CT
<i>ET6</i>			9.3	187					
ET8	Holocene?	Alk Bas	8.0	224	39.9	397	47.8	0.1570(12)	
<i>ET8</i>			8.0	213	53.3				
Gomera EG15b	4.4 Ma	Basanite	14.8	377	231.7	352	7.30	0.1509(2)	CT
Madeira M191292-5	Holocene?	Basanite	11.8	235	12.3			0.1395(26)	CT
M191292-6	Holocene?	Basanite	13.6	295	24.6			0.1444(19)	CT
M191292-8	Holocene?	Basanite	14.8	369	29.5			0.1390(7)	CT
Selvagen Grande SG10	<100 ka	Alk Bas	10.3	332	277.8	229	3.96	0.1359(2)	CT

Replicate analyses are included with sample names in italics. Sample digestion methods for Os isotope analyses are designated as AD for acid digestion and CT for Carius tube digestion. Age corrections for Os isotopes are negligible because of the young ages of the basalts for all but sample EG15b (measured  $^{187}\text{Os}/^{188}\text{Os} = 0.1515 \pm 2$ ; initial  $^{187}\text{Os}/^{188}\text{Os}$  at 4.4 Ma =  $0.1509 \pm 2$ ). The errors for the ratios are reported as  $2\sigma$  in-run precision.



**Fig. 2.**  $^{187}\text{Os}/^{188}\text{Os}$  vs Os concentration for basalts from the Canary Islands, Selvagen Islands and Madeira. The samples from this study are displayed as three groups, including the radiogenic group ( $\diamond$ ), the unradiogenic group ( $\nabla$ ) and the intermediate group ( $\bullet$ , Canary Islands;  $\blacksquare$ , Madeira). The radiogenic group includes samples which have  $<52$  pg/g and have Os isotope signatures more radiogenic than any at higher Os concentrations. The unradiogenic group contains the samples with the least radiogenic Os and includes all samples that come from xenolith-bearing basalt flows. These samples also contain xenocrystic olivine from mantle peridotite (based on their forsterite and CaO contents; D. Graham, unpublished data, 1998). The intermediate group, which comprises the remaining samples, has a relatively limited range in  $^{187}\text{Os}/^{188}\text{Os}$  from 0.139 to 0.151 over a range in Os concentration from 12 to 232 pg/g. Also included are literature data for 0–1.6 Ma basalts from La Palma (Marcantonio *et al.*, 1995; gray circles), which extend the range in Os concentration of intermediate group samples to nearly 400 pg/g. The intermediate group is interpreted to represent the Os isotopic composition of the Canary Island plume, whereas the radiogenic and unradiogenic group samples are thought to be contaminated in the crust and lithospheric mantle, respectively.

the overlying lithospheric mantle, which has an Os concentration one to three orders of magnitude higher than most basaltic magmas. This, however, applies only to bulk assimilation of lithospheric mantle material, as melts of the lithosphere induced by the passing plume melts will have relatively low Os concentrations. It is thus not immediately clear whether the unradiogenic group or intermediate group samples should best represent the Os isotopic composition of the Canary Island mantle plume. The implications of both possibilities are considered below.

If it is assumed that the unradiogenic group basalts represent the Os isotopic composition of the Canary Island plume, then the intermediate group samples must be attributed to crustal contamination of initially less radiogenic magmas. Whatever the precise mechanism of contamination, the process must be able to explain the fact that the intermediate group samples from this study plus high Os abundance samples from La Palma (Marcantonio *et al.*, 1995) display a nearly 40-fold range in Os concentration from 12 to 390 ppt, yet range in  $^{187}\text{Os}/^{188}\text{Os}$  from only 0.139 to 0.151 (Fig. 2).

To produce such a limited range in Os isotopic composition by crustal contamination of magmas with initial Os isotopic compositions similar to those in the unradiogenic group would require a substantial variability in the percentages of assimilated crust, with the low Os concentration basalts always affected by less crustal contamination than the high Os concentration samples. For example, if the least radiogenic sample in the unradiogenic group (EL10 with  $^{187}\text{Os}/^{188}\text{Os} = 0.1288$ ) is considered to represent the mantle plume composition, and all of the intermediate group samples are derived by contamination of plume melts with a given radiogenic crust or sediment (we assume bulk assimilation of sediment with  $^{187}\text{Os}/^{188}\text{Os} = 1.2$ , Os = 0.1 pg/g for the purpose of this example), then sample ELP1 (12 pg/g Os), sample EH11 (114 pg/g Os), and the 390 pg/g sample from La Palma (Marcantonio *et al.*, 1995), must have assimilated 2%, 14% and 35% sediment, respectively. In this scenario, the amount of sediment assimilated would vary among these samples by nearly 20-fold, yet each mixture must result in essentially the same  $^{187}\text{Os}/^{188}\text{Os}$  signature. We consider this to be an unlikely scenario.

An alternative explanation to consider for the narrow range in  $^{187}\text{Os}/^{188}\text{Os}$  over a large range in Os concentration in the intermediate group samples is the accumulation of variable amounts of Os-rich olivine into initially low Os concentration melts. However, this explanation suffers from several problems. First, there is no clear correlation between the modal olivine content of the basalts and the Os concentrations among the intermediate group samples. Second, it cannot easily explain the limited variability of  $^{187}\text{Os}/^{188}\text{Os}$ , because there is no reason that all accumulated olivine should have the same Os isotopic ratio. Because the Os isotopic signature of the accumulated olivine would have to have been acquired by crystallization of crustally contaminated magmas to produce the elevated Os isotopic signatures (relative to the unradiogenic group samples), this scenario would require that all of the olivine crystallized from contaminated magmas with the same Os isotopic signature. This is clearly an unlikely scenario given the fact that low-Os, crustally contaminated magmas normally display extremely large ranges in Os isotopic signature (Fig. 2 and Reisberg *et al.*, 1993; Martin *et al.*, 1994; Marcantonio *et al.*, 1995; Widom & Shirey, 1996; Widom, 1997).

Given the above difficulties in explaining the narrow range in  $^{187}\text{Os}/^{188}\text{Os}$  over a large range in Os concentration in the intermediate group samples by crustal contamination of melts initially with Os isotopic signatures characteristic of the unradiogenic group samples, we consider it more likely that the intermediate group samples are the ones that most closely represent the Os isotopic composition of the Canary Islands mantle plume.

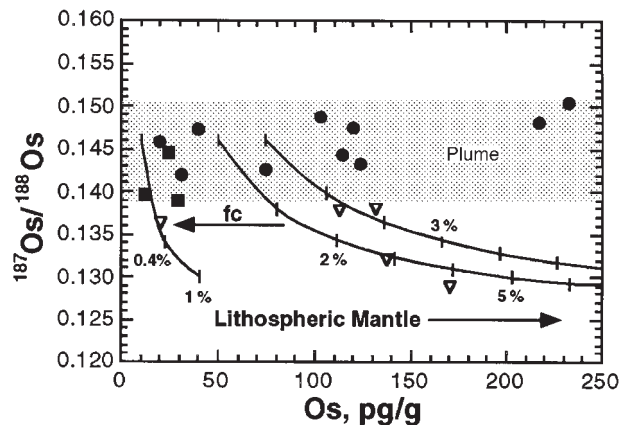
For clarity, this sample group will be referred to henceforth as the 'plume group'.

### Contamination of magmas by the lithospheric mantle

#### *Os isotope evidence*

If the unradiogenic group basalts are ultimately derived from plume melts with more radiogenic Os signatures, then these basalts must have interacted in some fashion with a reservoir that is relatively unradiogenic in Os. The lithospheric mantle is the only reservoir with which the Canary Island plume melts might have come in contact that is known to have an appropriate unradiogenic Os isotopic signature. Abyssal peridotites range in  $^{187}\text{Os}/^{188}\text{Os}$  from 0.122 to 0.127 (Luck & Allègre, 1992; Snow & Reisberg, 1995a, 1995b), and data from 11 Canary Island mantle xenoliths show a similar range (this study and E. Widom & E. R. Neumann, unpublished data, 1998). Because the Os concentration of mantle peridotite is typically 1–3 orders of magnitude higher than basaltic melts, minor amounts of bulk assimilation of lithospheric mantle could greatly alter the Os isotope signatures of ascending basaltic magmas.

We emphasize that all samples within the unradiogenic Os group came from lava flows containing mantle xenoliths. Although all samples were carefully taken and then hand-picked to avoid obvious xenolith debris, microprobe analyses of the olivine crystals in the unradiogenic group samples showed that the olivines were xenocrysts from mantle peridotite, on the basis of their high forsterite (>86) and low CaO (<0.15 wt %) contents (D. Graham, unpublished data). Oxygen isotope analyses of olivines from these samples yielded values within the range found in mantle peridotite xenoliths from the Canary Islands but distinct from most Canary Island olivine phenocrysts (Wiechert *et al.*, 1997; in preparation), providing additional evidence for a lithospheric mantle origin of these olivines. Figure 3 shows that bulk assimilation of  $\leq 5\%$  average oceanic lithospheric mantle by typical plume group basalts with 50–75 pg/g Os can account for the relatively low  $^{187}\text{Os}/^{188}\text{Os}$  ratios in most of the unradiogenic group samples. Because the incorporation of bulk mantle significantly increases the Os concentration in the basaltic melt, a melt with a low initial Os concentration is required to explain the unradiogenic sample with 21 pg/g Os by this mechanism. If the melt initially contained about 10 pg/g Os, bulk assimilation of 0.3% mantle would produce an appropriately decreased Os isotopic signature and increase the Os concentration to only 20 pg/g. Alternatively, it is possible that a higher Os concentration melt assimilated 1–2% lithospheric mantle, but underwent a subsequent decrease in Os



**Fig. 3.**  $^{187}\text{Os}/^{188}\text{Os}$  vs Os for plume group and unradiogenic group basalts from the Canary Islands and Madeira. Mixing curves illustrate the effect of bulk assimilation of oceanic lithospheric mantle by typical plume group basalts with  $^{187}\text{Os}/^{188}\text{Os} = 0.146$  and Os concentrations of 10, 50 and 75 pg/g. The mantle endmember has Os = 3.1 ng/g and  $^{187}\text{Os}/^{188}\text{Os} = 0.125$ , the average isotopic composition of the two mantle xenoliths from Lanzarote (this study). This is also the average Os isotopic signature for abyssal peridotites (Snow & Reisberg, 1995a, 1995b). Assimilation of  $\leq 5\%$  lithospheric mantle in the form of disaggregated mantle xenoliths can explain the relatively unradiogenic Os isotope signatures in the mantle xenolith-bearing basalts. The low Os concentration xenolith-bearing sample may have been produced by contamination of a low Os concentration basalt or by fractional crystallization (fc) of an Os-bearing phase subsequent to contamination. Symbols as in Fig. 2.

concentration by fractional crystallization before eruption.

The model of bulk assimilation depicted in Fig. 3 would apply equally to assimilation by bulk melting of lithospheric mantle or entrainment of mantle xenolith fragments. Bulk melting of the lithosphere is unlikely, on the basis of thermal constraints. On the other hand, the modal contents of olivine in the thin sections are consistent with up to 5% bulk incorporation of xenocrysts from mantle peridotite. Assimilation of Os-rich phases of mantle xenoliths (sulfides or olivine with sulfide inclusions) by plume melts can strongly influence the Os isotopic composition of the magma. In conclusion, despite careful hand-picking to remove as much xenolith debris as possible, the unradiogenic Os group samples reflect the presence of small amounts ( $\leq 5$  wt %) of disaggregated xenolith material in these samples. These findings demonstrate the danger of bulk analyses of olivine-bearing basalts, in particular those from flows that contain mantle xenoliths. We therefore emphasize the need to carefully inspect sampled units for xenolithic material in the field, and the importance of determining whether crystals are phenocrystic or xenocrystic prior to Os isotope studies of basalts.

*Effect on Pb, Nd and Sr isotope signatures*

The Sr, Nd and Pb isotope data for the Canary Islands and Madeira basalts are shown in Fig. 4. It should be noted that the plume group samples, defined on the basis of their Os isotopic signatures, produce well-defined trends in Sr–Nd–Pb isotope space which are consistent with two-component mixing involving the LVC (low velocity composition—a HIMU-like plume component reflecting the composition of the low seismic velocity sublithospheric mantle; Hoernle *et al.*, 1995) and a relatively low  $^{206}\text{Pb}/^{204}\text{Pb}$  component characterized by the Madeira samples. The origins of these mixing components are discussed in subsequent sections.

An additional observation from Fig. 4 is that the majority of the unradiogenic and radiogenic Os group samples fall outside the two-component mixing trends defined by the plume group samples. These outlying samples provide evidence for a third mixing component with an EM-type signature characterized by elevated  $^{87}\text{Sr}/^{86}\text{Sr}$ , low  $^{143}\text{Nd}/^{144}\text{Nd}$  and slightly higher  $\Delta 8/4$  isotope signatures relative to the plume group samples. The fact that these Sr–Nd–Pb signatures are restricted to samples from the radiogenic and unradiogenic Os groups, which have been contaminated in the crust (see below) and lithospheric mantle, respectively, provides strong evidence that the EM signature is derived from the lithosphere and not a heterogeneous mantle plume source. If the EM component were part of the mantle plume source, some plume group samples should exhibit the anomalous Sr–Nd–Pb characteristics. In contrast, some of the samples recording Os isotopic contamination in the lithosphere have maintained plume-like Sr–Nd–Pb signatures, which indicates that the Os isotope system is generally more sensitive than Sr, Nd, and Pb isotopes to the operating lithospheric contamination processes.

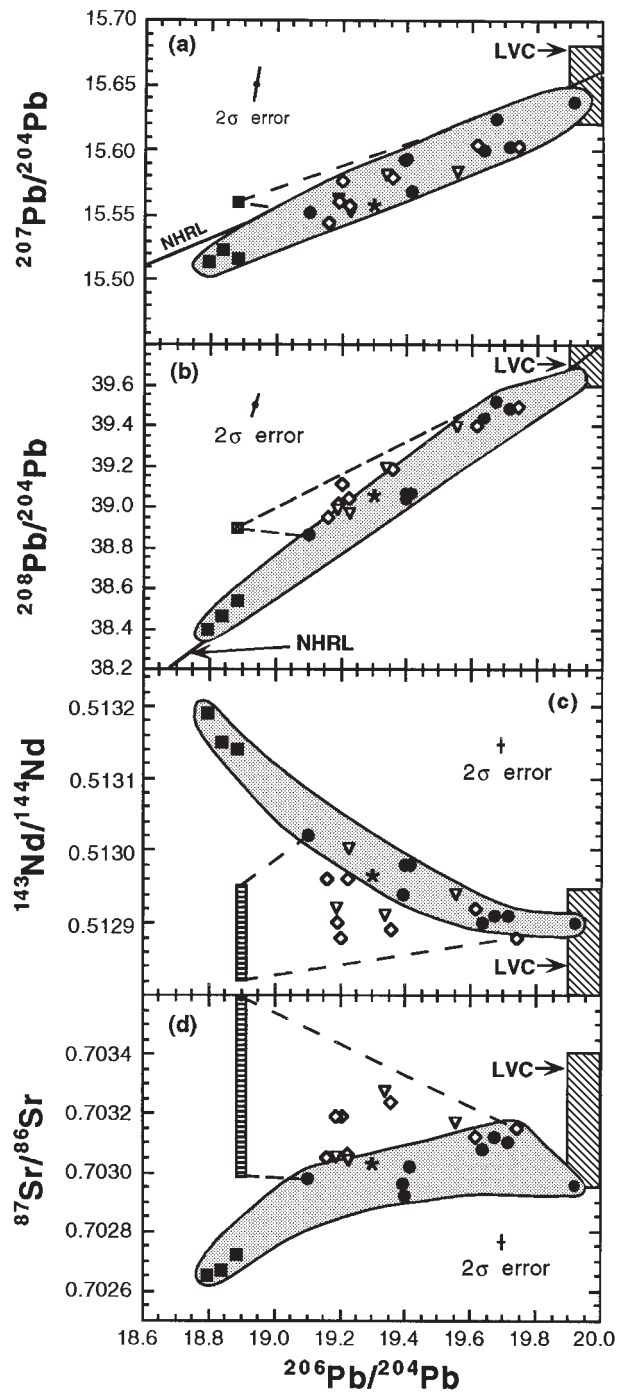
Given the Os isotopic evidence for the unradiogenic group samples having experienced contamination by the lithospheric mantle, it is important to evaluate the possibility that the enriched Sr, Nd and Pb isotopic compositions relative to the plume group were also inherited from the lithospheric mantle. This interpretation is supported by previous studies of volcanic rocks from the eastern islands of Fuerteventura and Gran Canaria that, on the basis of experimental phase equilibria arguments, attributed enriched Sr–Nd–Pb isotopic signatures in alkali basalts and tholeiites compared with basanites and nephelinites to contamination of plume-derived melts within the lithospheric mantle (Hoernle & Tilton, 1991; Hoernle *et al.*, 1991). In particular, the Holocene volcanic rocks may share the same EMI-type component as Pliocene volcanic rocks from Gran Canaria ( $^{87}\text{Sr}/^{86}\text{Sr} > 0.7033$ ,  $^{143}\text{Nd}/^{144}\text{Nd} < 0.51275$ ,  $^{206}\text{Pb}/^{204}\text{Pb} < 18.8$ ,  $\Delta 8/4 \geq 60$ ,  $\Delta 7/4 \leq 0$ ). This component is observed not only in relatively evolved samples from

Gran Canaria (Hoernle *et al.*, 1991), but also in several mafic basanites (*mg*-number = 66–68) with oxygen isotope compositions within the range found in mantle xenoliths from the Canary Islands (Wiechert *et al.*, in preparation), which further supports a mantle origin for this component (Hoernle, 1998).

Although only few data are available at present, the existence of enriched mantle lithosphere beneath the eastern Canary Islands is supported by studies of mantle xenoliths from Lanzarote. Spinel harzburgite and dunite xenoliths from Lanzarote display enrichments in many incompatible trace elements and have  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7030\text{--}0.7036$  and  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51286\text{--}0.51295$  (Vance *et al.*, 1989; Siena *et al.*, 1991). In particular, a dunite xenolith from the same eruptive center (Pico de Partido) as sample EL5, which belongs to the unradiogenic Os group, has  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7033$  and  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51286$ . Only one harzburgite from Lanzarote has been analyzed for Pb isotopes and has  $^{206}\text{Pb}/^{204}\text{Pb} = 18.9$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.56$  and  $^{208}\text{Pb}/^{204}\text{Pb} = 38.9$  (Zartman & Tera, 1973). Despite the paucity of data from mantle xenoliths, the range in Sr and Nd isotope ratios in the xenoliths from Lanzarote overlap and extend to more enriched compositions than those in the basalts from Lanzarote including the Holocene unradiogenic Os group samples (Fig. 4).

Even though the mantle xenoliths from the eastern Canary Islands could qualitatively serve as the enriched (EMI-type) endmember for the radiogenic and unradiogenic Os groups, excessively large amounts of bulk lithosphere assimilation would be required to produce the observed Sr, Nd and Pb isotope variations, because of the relatively low abundances of these elements in the lithospheric mantle. We envisage two possible solutions to this problem. First, studies of mantle xenoliths from the eastern islands attribute the enrichment to relatively recent infiltration of the lithosphere by Fe–Ti-rich silicate melts and  $\text{CO}_2$ -rich fluids associated with plume activity (Vance *et al.*, 1989; Siena *et al.*, 1991; Neumann *et al.*, 1995). Carbonate-rich veins (Frezotti *et al.*, 1994) and pockets of silicic glass attributed to mantle–melt reactions at 8–12 kbar (Neumann & Wulff-Pedersen, 1997) have been reported in spinel harzburgite and lherzolite xenoliths from the Canary Islands. Assimilation of small amounts of partial melts of such enriched material (e.g. concentrated in veins or melt pockets) could have a major effect on the Sr–Nd–Pb isotopic composition of the plume melts. Metasomatism by plume melts, however, has not significantly affected the Os isotopic composition of the Canary oceanic lithospheric mantle (E. Widom & E. R. Neumann, unpublished data, 1998), and in any case assimilation of small degree melts would not be expected to significantly affect a compatible element isotope system such as Os. Therefore, assimilation of melts of the metasomatic veins or pockets could produce the observed





**Fig. 4.**  $^{206}\text{Pb}/^{204}\text{Pb}$  vs (a)  $^{207}\text{Pb}/^{204}\text{Pb}$ , (b)  $^{208}\text{Pb}/^{204}\text{Pb}$ , (c)  $^{143}\text{Nd}/^{144}\text{Nd}$  and (d)  $^{87}\text{Sr}/^{86}\text{Sr}$  for Canary Island and Madeira basalts (Hoernle *et al.*, in preparation, a and b). The intermediate (or plume) group basalts fall along two-component mixing trends consistent with mixing between the HIMU-like LVC source (Hoernle *et al.*, 1995) and a source with MORB-like Sr–Nd–Pb isotopic signatures but HIMU-like trace element composition, which is interpreted to contain a recycled Paleozoic oceanic crustal component (Hoernle *et al.*, in preparation, b). The unradiogenic and radiogenic Os group samples have similar  $^{207}\text{Pb}/^{204}\text{Pb}$  but extend to higher  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\Delta 8/4$  and lower  $^{143}\text{Nd}/^{144}\text{Nd}$  at a given  $^{206}\text{Pb}/^{204}\text{Pb}$  compared with the plume group samples. Mantle xenoliths from Lanzarote (Zartman & Tera, 1973; Vance *et al.*, 1989; Siena *et al.*, 1991) denoted by shaded box in (a) and (b) and shaded bar in (c) and (d) show that the lithosphere contains enriched mantle (EM) more extreme in Sr–Nd–Pb isotopic composition than the unradiogenic and radiogenic Os group basalts. Symbols as in Fig. 2 (refer to the caption to Fig. 5 for an explanation of the asterisks).

enriched Sr, Nd and Pb isotope signatures without inducing radiogenic or unradiogenic Os isotopic signatures. Both the mineral and major element chemistry (Neumann *et al.*, 1995), and the  $^{187}\text{Os}/^{188}\text{Os}$  ratios measured in Canary mantle xenoliths (this study and E. Widom & Neumann, unpublished data), which are within the range of Os isotope ratios found in abyssal peridotites, are consistent with an oceanic origin for at least some of the enriched lithospheric material beneath the eastern islands.

Alternatively, more strongly enriched mantle may exist beneath the Canary Islands than that observed so far in the few analyzed xenoliths. Recently it has been shown that blocks of continental crust stranded during continental break-up occur in the Atlantic ocean basin as far as 250 km west of the Iberian Peninsula (Whitmarsh & Party, 1998). Assimilation of such enriched subcontinental lithospheric mantle, if it occurs beneath the Canary Islands, could therefore also produce the enriched Sr, Nd and Pb isotopic signatures observed in the unradiogenic group Os samples. Furthermore, as observed in samples of the Canaries oceanic lithospheric mantle, ancient subcontinental lithospheric mantle is typically characterized by unradiogenic Os isotope signatures despite extensive metasomatism resulting in enriched Sr, Nd and Pb isotope signatures (Walker *et al.*, 1989; Pearson *et al.*, 1995a, 1995b). If sufficiently enriched mantle exists beneath the Canary Islands, then smaller amounts of bulk assimilation might explain the observed EMI signatures in the unradiogenic Os group samples. For example, it has been proposed that blocks or rafts of subcontinental lithospheric mantle, delaminated or detached during the rifting of Pangaea, may have been incorporated into the oceanic mantle and could provide a source for some EM-type oceanic basalts (Hawkesworth *et al.*, 1984). EMI signatures significantly more extreme than those measured in the Canaries mantle xenoliths have been found in MORB near the Oceanographer Transform of the Mid-Atlantic Ridge (35°N; Shirey *et al.*, 1987), in basalts from Tristan da Cunha in the South Atlantic (Le Roex *et al.*, 1990), and in Kerguelen Plateau basalts in the southern Indian Ocean (Mahoney *et al.*, 1995); these EMI signatures have all been attributed to detached fragments of old subcontinental lithospheric mantle, by Shirey *et al.* (1987), Hawkesworth *et al.* (1984) and Mahoney *et al.* (1995), respectively. Furthermore, unradiogenic Os isotope signatures in peridotite xenoliths from the Kerguelen Islands provide strong evidence for the existence of subcontinental lithospheric mantle beneath the Kerguelen Plateau (Hassler & Shimizu, 1998). Fragments of enriched subcontinental lithospheric mantle might similarly have been incorporated within the lithospheric mantle beneath the eastern Canary Islands during the initial stages of continental rifting and seafloor spreading (Hoernle *et al.*, 1991).

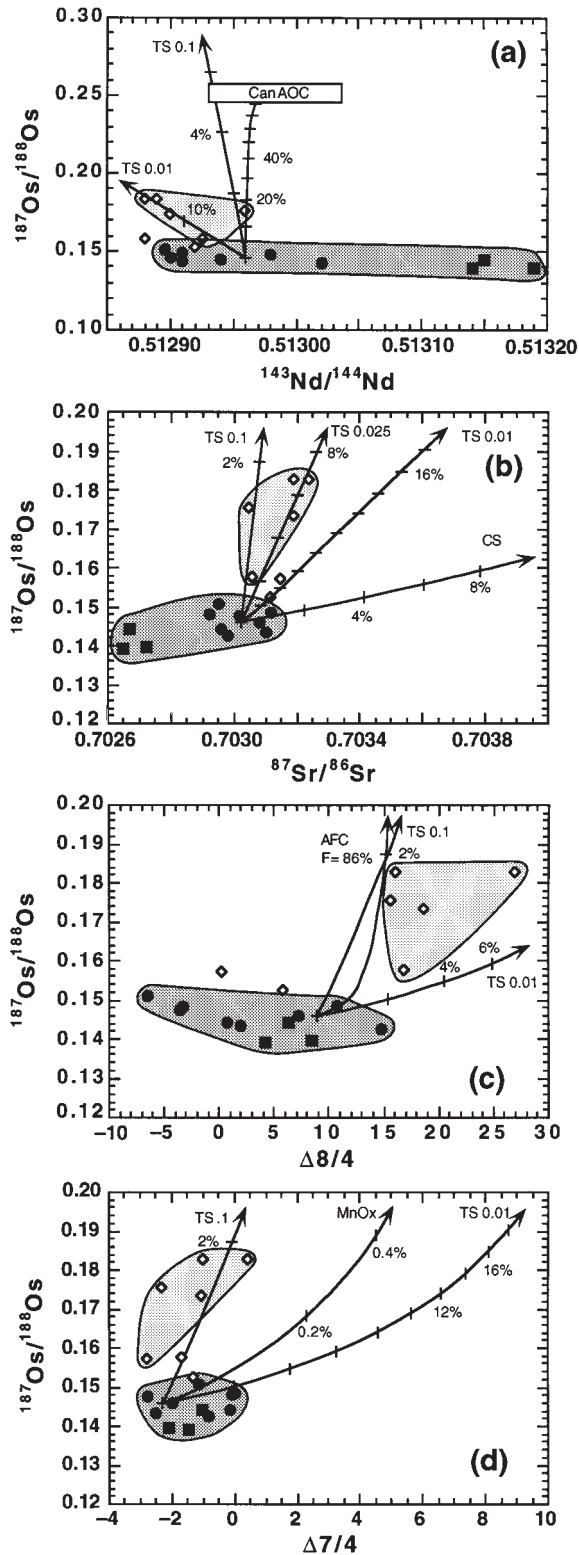
It is clear that additional studies of mantle xenoliths are needed to constrain the composition of the shallow mantle beneath the Canary Islands and to test between the aforementioned hypotheses. Nevertheless, regardless of the precise origin of the Canary Island lithospheric mantle, it clearly has appropriate isotopic signatures to qualitatively explain the unradiogenic Os and Nd, radiogenic Sr, and high  $\Delta 8/4$  in the xenolith-bearing samples (Fig. 4).

### Crustal contamination

The highly variable and often radiogenic Os isotope signatures found in the low Os concentration basalts are indicative of crustal contamination. There are a number of possible crustal sources containing radiogenic Os with which magmas might interact during ascent, including altered Jurassic oceanic crust, sediment, and the basalts and differentiates of the volcanic edifices through which the basalts are erupted. However, distinguishing between these contaminants is not straightforward using only Os isotope data. Nevertheless, we can place additional constraints on possible crustal components affecting the Os isotopic composition with Sr–Nd–Pb isotope data.

The old oceanic crust beneath the Canary Islands might be considered a likely source of contamination of the Canary Island basalts. The oceanic crust beneath the Canary Islands is dated at ~150–175 Ma and is therefore expected to have very radiogenic  $^{187}\text{Os}/^{188}\text{Os}$  ratios. Assuming that the oceanic crust has an average  $^{187}\text{Re}/^{188}\text{Os}$  of 50 (corresponding to average MORB basalts with Os concentrations of about 50 pg/g), the  $^{187}\text{Os}/^{188}\text{Os}$  of this crust would be ~0.257. Although ~20% assimilation of such crust could have produced the observed radiogenic Os isotope signatures in some Canary Island basalts, it cannot explain the decrease in  $^{143}\text{Nd}/^{144}\text{Nd}$  isotope ratio observed in most radiogenic group samples. The relatively high  $^{143}\text{Nd}/^{144}\text{Nd}$  values of the altered oceanic crust beneath Gran Canaria (Hoernle, 1998) relative to most of the radiogenic Os group samples preclude the Jurassic oceanic crust as a significant contaminant (Fig. 5a). This is consistent with the observation that the contaminated basalts from the Canary Islands are no more radiogenic in Os than crustally contaminated basalts from the Azores (Widom & Shirey, 1996) and St Helena (Reisberg *et al.*, 1993), which lie on very young oceanic crust. These observations indicate that oceanic crust is in general not the primary contaminant affecting the Os isotope signatures of ocean island basalts (Reisberg *et al.*, 1993; Widom, 1997).

The Canary Islands are underlain by a thick sediment pile that also provides a potential source of radiogenic Os. The two easternmost islands in particular may be underlain by as much as 10 km of sediment, which



includes limestones and terrigenous shales, siltstones and sandstones (Stillman *et al.*, 1975). The effects of sediment contamination can be modeled using Sr, Nd, Pb isotope data for local Miocene to Cretaceous sediment from DSDP site 397, which lies ~100 km SE of Gran Canaria, and sediment xenoliths in Gran Canaria mafic volcanic rocks (Hoernle *et al.*, 1991; Hoernle, 1998), and assuming Os isotope signatures characteristic of terrigenous and carbonate-rich sediments (Esser & Turekian, 1993; Peucker-Ehrenbrink *et al.*, 1995).

The Pb isotope data place major constraints on the amount of possible sediment assimilation. Although the radiogenic Os group samples generally have slightly higher  $\Delta 8/4$  than the plume group, there is almost no difference in the  $\Delta 7/4$  between the groups (Figs 4a and b and 5c and d). In fact, all Holocene samples analyzed to date (>40) fall on or below the Northern Hemisphere Reference Line (i.e. have  $\Delta 7/4 \leq 0$ ) on the  $^{207}\text{Pb}/^{204}\text{Pb}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram (Hoernle *et al.*, in preparation, a). Assuming assimilation of bulk sediment from the Canary

**Fig. 5.** Plots of  $^{187}\text{Os}/^{188}\text{Os}$  vs (a)  $^{143}\text{Nd}/^{144}\text{Nd}$ , (b)  $^{87}\text{Sr}/^{86}\text{Sr}$  and (c)  $\Delta 8/4$ , the difference between sample  $^{206}\text{Pb}/^{204}\text{Pb}$  and Northern Hemisphere Reference Line (NHRL) for a given  $^{206}\text{Pb}/^{204}\text{Pb}$  (Hart, 1984), and (d)  $\Delta 7/4$  (the difference between sample  $^{207}\text{Pb}/^{204}\text{Pb}$  and NHRL for a given  $^{206}\text{Pb}/^{204}\text{Pb}$ ). Mixing curves represent contamination of plume-group basalts by assimilation of average local Jurassic altered oceanic crust (AOC; Hoernle, 1998), average local terrigenous sediment (TS; Hoernle *et al.*, 1991; Hoernle, 1998), average carbonate-rich sediment (CS; Hoernle *et al.*, 1991; Hoernle, 1998), and manganese oxide (MnOx; Ben Othman *et al.*, 1989; Pegram *et al.*, 1992; Ravizza, 1993; Ravizza & Esser, 1993), with  $^{187}\text{Os}/^{188}\text{Os}$  assumed to be equal to >70 Ma seawater (Peucker-Ehrenbrink *et al.*, 1995). Compositions of the mixing endmembers are as follows. Plume basalt: Os = 0.05 ng/g,  $^{187}\text{Os}/^{188}\text{Os}$  = 0.146, Nd = 50  $\mu\text{g/g}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$  = 0.51296, Sr = 750  $\mu\text{g/g}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$  = 0.703025, Pb = 2.5  $\mu\text{g/g}$ ,  $\Delta 8/4$  = 8.93,  $\Delta 7/4$  = -2.3; AOC: Os = 0.100 ng/g,  $^{187}\text{Os}/^{188}\text{Os}$  = 0.257, Nd = 7.3  $\mu\text{g/g}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$  = 0.51298; CS: Os = 0.010 ng/g,  $^{187}\text{Os}/^{188}\text{Os}$  = 0.931, Sr = 1190  $\mu\text{g/g}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$  = 0.7093; TS: Os = 0.01, 0.025 or 0.10 ng/g (denoted as TS .01, etc.),  $^{187}\text{Os}/^{188}\text{Os}$  = 1.2, Nd = 24  $\mu\text{g/g}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$  = 0.51200, Sr = 179  $\mu\text{g/g}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$  = 0.7147, Pb = 16.9  $\mu\text{g/g}$ ,  $\Delta 8/4$  = 61.62,  $\Delta 7/4$  = 16.16; MnOx: Os = 1.0 ng/g,  $^{187}\text{Os}/^{188}\text{Os}$  = 0.722, Pb = 655  $\mu\text{g/g}$ ,  $\Delta 8/4$  = 46,  $\Delta 7/4$  = 11. The starting plume basalt composition was chosen to represent that of an average eastern-group island magma with  $^{206}\text{Pb}/^{204}\text{Pb}$  = 19.3, and appropriate respective  $^{207}\text{Pb}/^{204}\text{Pb}$ ,  $^{208}\text{Pb}/^{204}\text{Pb}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  compositions given the plume group mixing trends in Fig. 4. It should be noted that the starting plume composition (marked by asterisks in Fig. 4) is such that the amount of assimilated sediment required to produce the EMI signatures in the radiogenic Os group samples from the eastern-group islands (light gray shaded fields) is minimized. The AOC field represents the range of values found in Gran Canaria Jurassic oceanic crust (Hoernle, 1998), and assuming an age of 160 Ma and  $^{187}\text{Re}/^{188}\text{Os}$  = 50. Compositions of local sediment from Hoernle *et al.* (1991). Tick marks indicate percentage of assimilated material, except for AFC (assimilation-fractional crystallization) curves where  $F$  denotes the amount of liquid remaining. AFC curve (c) calculated with  $D_{\text{Os}} = 20$ ,  $D_{\text{Sr,Pb}} = 0.01$ , and  $r$  (ratio of mass assimilated to mass crystallized) = 0.1 (DePaolo, 1981). In (a), (b) and (d) the AFC curves for sediment with 10 pg/g Os are essentially indistinguishable from the bulk mixing curves for 100 pg/g Os terrigenous sediment. Symbols as in Fig. 2.

region [ $Pb = 12.2$  ppm,  $^{206}Pb/^{204}Pb = 18.97$ ,  $^{207}Pb/^{204}Pb = 15.71$ ,  $^{208}Pb/^{204}Pb = 39.16$ ;  $n = 7$ , samples range from carbonate rich to silicate rich (Hoernle *et al.*, 1991; Hoernle, 1998)], and including the analytical error on the Pb isotope ratios based on replicate analyses, a maximum of 2% sediment assimilation is allowed. Although the variation in Os isotope ratio between the radiogenic Os and plume groups can be explained by <2% sediment assimilation with either the involvement of AFC processes or assimilation of a relatively high Os concentration sediment (100 pg/g, Fig. 5), it is clear that neither the Os vs Nd nor Os vs Sr isotope data trends can be explained by such small amounts of sediment assimilation (Fig. 5a and b). Significant shifts to low  $^{143}Nd/^{144}Nd$  can be produced only by assimilation of relatively large amounts ( $\geq 15\%$ ) of sediment with very low Os concentration (10 pg/g; Fig. 5a). Although such low Os concentrations are within the observed range in Os concentration in sediments (Esser & Turekian, 1993), the large amounts of sediment assimilation are clearly unrealistic based on the Pb isotope data. We note that the 8% sediment assimilation proposed by Thirlwall *et al.* (1997) for a Miocene tholeiite with low incompatible element abundances resulted in an increase in  $\Delta 7/4$  of +10, three times the range observed in our Holocene data set (Fig. 5d). The Sr–Os isotope relationships indicate that any sediment contaminant must be largely terrigenous; the high Sr concentration of the more carbonate-rich sediment from DSDP site 397 would produce a shift to radiogenic Sr that is far higher than observed before causing any significant shift to radiogenic Os (Fig. 5b). AFC processes (for a given Os concentration in the sediment) would produce significantly more vertical mixing curves on these diagrams, because of the compatible behavior of Os. Therefore, it will be difficult to produce significant shifts in Sr and Nd isotope ratios and  $\Delta 8/4$  by AFC without inducing Os isotope signatures much more radiogenic than observed. An example of the effect of AFC is shown in Fig. 5c using  $D_{Os} = 20$  (Hart & Ravizza, 1996),  $D_{Sr,Pb} = 0.01$ , and  $r = 0.1$ . In Fig. 5a, b and d, the AFC curves for sediment with 10 pg/g Os are essentially indistinguishable from the bulk mixing curves for 100 pg/g Os terrigenous sediment.

Rocks making up the volcanic edifice through which magmas ascend are also possible sources of contamination. The volcanic edifices, however, are substantially younger than the oceanic crust beneath the Canary Islands and thus would be expected to be significantly less radiogenic than the Jurassic oceanic crust. Also, these rocks are likely to have similar Sr–Nd–Pb isotopic compositions to the Holocene plume magmas (Hoernle & Tilton, 1991). The oldest rocks in the Canary Islands, from the basal complex of Fuerteventura, may be as old as 30–80 Ma (Le Bas *et al.*, 1986). Following the calculations used above for Jurassic oceanic crust,

the  $^{187}Os/^{188}Os$  signature of the oldest edifice basalts would be  $\sim 0.19$ . This is only slightly more radiogenic than some of the radiogenic Os group samples at 0.183 (e.g. samples EF12 and EL17), and thus 85% assimilation of even the oldest basaltic edifice material would be required to produce the radiogenic signatures in these Holocene Canary Island basalts. Although this cannot be categorically ruled out, such large amounts of bulk assimilation are rather unlikely, on the basis of thermal arguments. It is possible that Mn-oxide coatings on subaqueous basalts in the volcanic pile could contribute significant radiogenic Os because of their radiogenic Os signatures and very high Os concentrations ( $\sim 1$  ng/g; Luck & Turekian, 1983; Palmer & Turekian, 1986; Esser & Turekian, 1988; Palmer *et al.*, 1988; Reisberg *et al.*, 1993). However, a minimum of 0.3–0.4% Mn-oxide assimilation is required to produce the most radiogenic Os isotopic signatures found in the Canary Island basalts. This is clearly inconsistent with the measured MnO contents in these Canary volcanic rocks, which range from 0.14 to 0.22. Furthermore, there is no correlation between  $^{187}Os/^{188}Os$  and MnO, as would be expected if Mn-oxide assimilation were the major source of the increase in  $^{187}Os/^{188}Os$ . All samples within the radiogenic Os group have MnO < 0.19. Also, because of the very high Pb contents found in Mn-oxide nodules (Ben Othman *et al.*, 1989), even such a minor amount of assimilation would be expected to have a significant effect on the Pb isotopic composition of the contaminated basalt, producing both  $\Delta 8/4$  and  $\Delta 7/4$  values that are far higher than observed in the Canary Island radiogenic Os group basalts (Fig. 5d).

Evolved differentiates in the volcanic pile are also unlikely contaminants, given their expected very low Os concentrations and the evidence that at some point during differentiation Re/Os ratios cease to increase, and perhaps even start to decrease (Walker *et al.*, 1991; Johnson *et al.*, 1995). Another possible contaminant in the volcanic edifice is carbonatite, which is exposed in the basal complex of Fuerteventura (Hoernle & Tilton, 1991). To address this possibility, we analyzed two carbonatites from the >20 Ma basal complex of Fuerteventura. Although both have extremely radiogenic Os ( $^{187}Os/^{188}Os = 0.614$  and  $0.455$ ), the Os concentrations are very low (14.5 ppt and 4.7 ppt, respectively), severely limiting their effectiveness as contaminants. Mixing calculations demonstrate that as much as 20% carbonatite assimilation would be required to produce the range in radiogenic Os signatures in the Canary basalts. Such a large amount of carbonatite contamination is clearly prohibited, on the basis of major element (e.g. CaO) and trace element (e.g. Sr and the LREE) considerations (Hoernle & Tilton, 1991; unpublished data, 1991).

Despite clear evidence that oceanic crust underlies all of the Canary Islands (Hoernle, 1998; Schmincke *et al.*,

1999, and references therein), it cannot be ruled out that blocks of continental crust may underlie at least the eastern Canary Islands, because of their proximity to the African continent. The enriched Sr, Nd and  $\Delta 8/4$  but low  $\Delta 7/4$  isotope signatures of the radiogenic Os group samples are inconsistent with assimilation of upper continental crust or sediment, as discussed above. However, early Proterozoic or Archean lower continental crust could have an appropriate Sr–Nd–Pb isotopic composition to serve as the contaminant (Hoernle *et al.*, 1991) and could also cause the observed increases in  $^{187}\text{Os}/^{188}\text{Os}$  (Esperanca *et al.*, 1997). In particular, lower continental crust is typically characterized by significantly lower  $\Delta 7/4$  than upper continental crust or sediment (Rudnick & Goldstein, 1990), and therefore substantially more crustal assimilation could be accommodated to explain the shifts to high  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\Delta 8/4$  and low  $^{143}\text{Nd}/^{144}\text{Nd}$ , without concomitant shifts to positive  $\Delta 7/4$ . Although we find assimilation of lower continental crust to be an interesting possibility, to date there has been no direct evidence for the presence of continental material beneath the Canary Islands, e.g. its presence as xenoliths or its necessity to explain geophysical observations in the region.

The above discussion of the effects of crustal contamination on the Canary Island basalts indicates that assimilation of local altered Jurassic oceanic crust or local Canaries sediment could easily explain the observed radiogenic Os isotopic signatures; however, it is not possible to explain the observed shifts to enriched Sr, Nd and  $\Delta 8/4$  signatures by this mechanism without producing either (1) significant shifts to positive  $\Delta 7/4$ , which are not observed, or (2) Os isotopic signatures that are much more radiogenic than observed. Although assimilation of lower continental crust could possibly explain the observed variations in Sr–Nd–Pb–Os isotope ratios, no such material has been found in the Canary Islands to date. These problems, and the fact that the radiogenic group samples display a similar range in  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $\Delta 8/4$  to the mantle xenolith-bearing unradiogenic Os group samples, lead to the conclusion that the radiogenic Os group samples inherited their enriched Sr, Nd and Pb isotope signatures in the lithospheric mantle prior to crustal contamination, which affected only the Os isotope signatures. It is noted that the limited mantle xenolith data from the eastern Canary Islands are qualitatively consistent with the shifts in  $\Delta 8/4$ , Sr, and Nd isotope ratios and the absence of a shift to positive  $\Delta 7/4$  observed in the volcanic rocks (Fig. 4). The existence of these xenoliths illustrates that such material exists within the shallow mantle beneath the Canaries. Additional support for existence of enriched mantle beneath at least the eastern Canary Islands comes from the Pliocene volcanic rocks on Gran Canaria, as was discussed above.

In summary, the elevated Sr,  $\Delta 8/4$  and low Nd isotopic signatures are a common feature of both the radiogenic and unradiogenic Os group samples (Fig. 4), and are interpreted to reflect contamination within the shallow mantle. The differences in Os isotope signatures between these groups, however, provide evidence for two distinct contamination processes. The unradiogenic Os group samples reflect the presence of small amounts ( $\leq 4$  wt %) of disaggregated mantle xenoliths in these samples, whereas the low concentration, radiogenic Os group samples are attributable to interaction of melts with a radiogenic crustal contaminant during ascent. Contamination of magmas with crust or sediment containing significantly more than 10 pg/g Os could produce substantial increases in Os isotopic signature without large changes in the Sr, Nd and Pb isotopic signatures. For example,  $<2\%$  bulk assimilation of terrigenous sediment with 100 pg/g Os could produce the full range of observed radiogenic Os isotope signatures with only minor changes (largely within the analytical errors) in Sr, Nd and Pb (Fig. 5). If AFC processes are important, it is predicted that isotope ratios of elements such as Os with  $D \gg 1$  will show significant effects with much smaller percentages of assimilation, and with even less effect on the incompatible element isotope ratios. The radiogenic Os group samples are therefore believed to have attained their radiogenic Os isotope signatures by crustal contamination, but this contamination was not the primary mechanism that caused the enriched Sr, Nd and Pb isotope signatures. The latter were more probably imparted by contamination within shallow mantle sources, which did not affect the Os isotopic composition. The Os isotopes therefore record processes of both crustal and lithospheric mantle contamination, whereas only the lithospheric mantle contamination can be discerned in the Sr–Nd–Pb isotope systematics.

### Os isotope systematics in the Canary Island plume

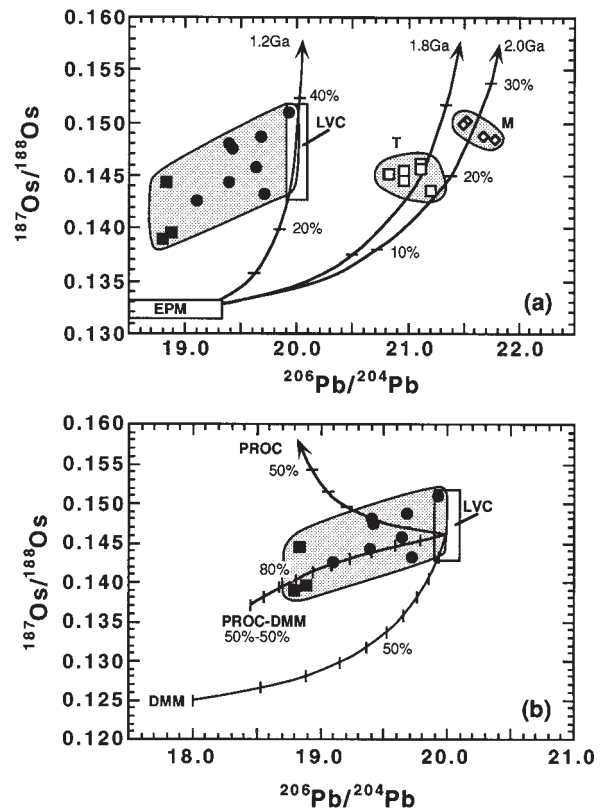
The plume group samples cover nearly the entire range in Pb isotopic composition ( $^{206}\text{Pb}/^{204}\text{Pb} = 18.8\text{--}19.9$ ) found in the Canary Islands and Madeira, with samples from Gomera and Tenerife having the most radiogenic Pb and samples from Madeira the least radiogenic Pb; the Sr–Nd–Pb isotopic composition of the Madeira basalts is consistent with their being the unradiogenic Pb end-member for the Canary Island basalts (Hoernle *et al.*, in preparation, a). On the  $^{207}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$  diagram (Fig. 4a), the plume group is parallel to but generally falls below the NHRL; whereas on the  $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$  diagram (Fig. 4b), the data are again parallel to but overlap or fall slightly above the NHRL. Plume group  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  show negative and

slightly positive correlations, respectively, with  $^{206}\text{Pb}/^{204}\text{Pb}$ . On all diagrams, the LVC plume component could serve as the endmember with radiogenic Pb and Sr and unradiogenic Nd (Hoernle *et al.*, 1995). The Madeira endmember has an Sr–Nd–Pb isotopic composition similar to average Atlantic N-MORB, yet as mentioned previously these samples have HIMU-like trace element compositions and therefore cannot come from a normal DMM source. Instead, it has been proposed that these melts come from subducted Paleozoic ocean crust, which at present resides in the asthenosphere (Hoernle *et al.*, in preparation, b).

The plume group basalts from the Canary Islands and Madeira display a limited range in  $^{187}\text{Os}/^{188}\text{Os}$  between 0.139 and 0.151. These values are significantly more radiogenic than those found in the depleted upper mantle (Snow & Reisberg, 1995a, 1995b; Meisel *et al.*, 1996) and are in fact among the most radiogenic values found in uncontaminated plume basalts, comparable with those of the endmember HIMU islands Mangaia, Tubuaii and Rurutu. Although the Canary Islands and the endmember HIMU basalts share Os isotope characteristics as well as some trace element characteristics such as high Ce/Pb ratios (Hoernle & Schmincke, 1993; Marcantonio *et al.*, 1995), the Canary Islands have distinctly less radiogenic Pb isotopic signatures than do the endmember HIMU islands.

#### Origin of radiogenic plume Os

The radiogenic Pb isotopic signatures of the endmember HIMU plumes are commonly attributed to a component of recycled oceanic crust in the plume source (Chase, 1981; Hofmann & White, 1982), and explanations for the radiogenic Os isotope signatures in these plumes have followed suit (Pegram & Allègre, 1992; Hauri & Hart, 1993; Reisberg *et al.*, 1993; Roy-Barman & Allègre, 1995). Indeed, the radiogenic Os and Pb isotopic signatures of these islands can be reproduced by incorporation of 20–25% of 1.8–2 Ga recycled oceanic crust with  $\mu = 20$  into FOZO-like enriched plume mantle (EPM; Fig. 6) with  $^{187}\text{Os}/^{188}\text{Os} \sim 0.130$ – $0.1325$  and  $^{206}\text{Pb}/^{204}\text{Pb} \sim 19.1$ . The endmember HIMU plume Os and Pb isotope signatures could alternatively be produced by recycling of slightly greater percentages of oceanic crust into depleted MORB mantle (DMM). However, even low  $^{206}\text{Pb}/^{204}\text{Pb}$  plumes have significantly more radiogenic  $^{187}\text{Os}/^{188}\text{Os}$  than DMM, and thus there is no evidence for the involvement of pure DMM in mantle plumes (Widom & Shirey, 1996; Widom, 1997; Shirey & Walker, 1998). The comparable radiogenic Os isotopic compositions of the Canary Island plume and the endmember HIMU islands suggests that the former may also be attributed to a component of recycled oceanic crust, despite the less radiogenic  $^{206}\text{Pb}/^{204}\text{Pb}$  signature (Marcantonio *et al.*, 1995).



**Fig. 6.** (a)  $^{187}\text{Os}/^{188}\text{Os}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$ , illustrating the composition of the Canary Islands and Madeira plume group samples (filled symbols as in Fig. 2) as well as the endmember HIMU islands Mangaia (M;  $\diamond$ ) and Tubuaii (T;  $\square$ ). Mixing curves depict mixing of FOZO-like enriched plume mantle (EPM) with 1.8 and 2 Ga recycled oceanic crust (ROC). The compositions of the mixing endmembers are as follows. EPM:  $^{206}\text{Pb}/^{204}\text{Pb} = 19.1$  (Hart *et al.*, 1992),  $^{187}\text{Os}/^{188}\text{Os} = 0.1325$  (Widom & Shirey, 1996), Pb = 30 ng/g, Os = 3.3 ng/g; ROC:  $\mu = 20$ , Pb = 250 ng/g, Os = 0.100 ng/g, and  $^{187}\text{Os}/^{188}\text{Os} = 1.61$  and 1.78 (assuming average  $^{187}\text{Re}/^{188}\text{Os} = 50$  and ages of 1.8 Ga and 2 Ga, respectively). It should be noted that EPM might have a range in  $^{206}\text{Pb}/^{204}\text{Pb}$  anywhere from  $\sim 18.5$  to 19.7 (Widom & Shirey, 1996; Shirey & Walker, 1998); we have picked an intermediate value for this model. The endmember HIMU islands are consistent with a plume containing 20–25% 1.8–2 Ga ROC with  $\mu = 20$ . The Canary Islands/LVC plume can be explained by 25–35% 1.2 Ga ROC with  $\mu = 20$ . Data for Mangaia and Tubuaii from Hauri & Hart (1993). (b)  $^{187}\text{Os}/^{188}\text{Os}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$  for the Canary Islands and Island plume group basalts. The  $^{187}\text{Os}/^{188}\text{Os}$  signature has a limited range from 0.139 to 0.151. The relatively limited range in Os cannot be explained by simple source mixing between the Canary Island plume/LVC and Paleozoic recycled oceanic crust (PROC), which would have very radiogenic Os despite its young age. Mixing between the Canary Island plume/LVC and DMM is also inconsistent with the Os isotope data, as this would produce a strong trend towards much less radiogenic Os isotope signatures than are observed. A possible explanation for the observed data trend is that the Canary Island plume/LVC is mixing with a shallow asthenospheric source which is itself a hybrid with  $\sim 50\%$  DMM and  $\sim 50\%$  Paleozoic recycled oceanic crust. The parameters used in the mixing models are as follows. Canary Islands/LVC plume (assumed to be a mixture of mantle with 30% 1.2 Ga recycled oceanic crust): Os = 2.325 ng/g,  $^{187}\text{Os}/^{188}\text{Os} = 0.146$ , Pb = 96 ng/g,  $^{206}\text{Pb}/^{204}\text{Pb} = 20$ ; DMM: Os = 3.3 ng/g,  $^{187}\text{Os}/^{188}\text{Os} = 0.125$ , Pb = 30 ng/g,  $^{206}\text{Pb}/^{204}\text{Pb} = 18.0$ ; PROC: Os = 0.100 ng/g,  $^{187}\text{Os}/^{188}\text{Os} = 0.62$ , Pb = 250 ng/g,  $^{206}\text{Pb}/^{204}\text{Pb} = 18.6$ ; 50%–50% mix of PROC and DMM: Os = 1.7 ng/g,  $^{187}\text{Os}/^{188}\text{Os} = 0.137$ , Pb = 140 ng/g,  $^{206}\text{Pb}/^{204}\text{Pb} = 18.45$ .

The lower  $^{206}\text{Pb}/^{204}\text{Pb}$  of the Canaries plume relative to endmember HIMU plumes could be explained by a 1.8–2 Ga recycled component with a lower  $\mu$  of  $\sim 16$ , or with a comparable  $\mu$  value if the age of the recycled crust is significantly younger ( $\sim 1.2$  Ga). Variable  $\mu$  values between individual recycled slabs might arise from compositional variability in the original fresh oceanic crust, variability in extent of alteration of the oceanic crust, and/or variability in the extent of subduction zone modification. With time, these compositional differences would produce distinct isotopic signatures in the recycled slabs (Marcantonio *et al.*, 1995). Another possible explanation for variable Pb isotope signatures in plumes with similar Os isotope signatures is that the Pb isotope signatures of plumes might be controlled by variable amounts of sediment subducted with the oceanic crust (Roy-Barman & Allègre, 1995). This model could explain the Os and Pb isotopic composition of the Canary Island plume (or LVC mantle source) if  $\sim 0.1\%$  ancient pelagic sediment is incorporated with 1.8–2 Ga subducted oceanic crust. However, the observation that negative  $\Delta 7/4$  OIB such as the Canary Islands has Ce/Pb and Nd/Pb higher than endmember HIMU OIB (Thirlwall, 1997) argues against this process; addition of sediment to an endmember HIMU source should, if anything, produce lower Ce/Pb and Nd/Pb ratios.

The most satisfactory model to explain the origin of mantle plumes such as the Canary plume, which have moderate  $^{206}\text{Pb}/^{204}\text{Pb}$ , negative  $\Delta 7/4$  and HIMU-like trace element signatures (e.g. high Ce/Pb), is that of recycling of relatively young oceanic crust (Thirlwall, 1997). Figure 6a illustrates that a mantle plume containing  $\sim 25\text{--}35\%$  of 1.2 Ga recycled oceanic crust could produce the  $^{187}\text{Os}/^{188}\text{Os}$ – $^{206}\text{Pb}/^{204}\text{Pb}$  isotopic signature of the Canary Island/LVC plume. These estimates are consistent with estimates of 18–35% recycled ocean crust in the Canary Island plume based on oxygen isotope data (Wiechert *et al.*, 1997). On the basis of this model, the similarity of the Os isotopic signature of the Canary Island/LVC plume and endmember HIMU OIB is a function of a slightly higher percentage in the plume of recycled oceanic crust with a lower  $^{187}\text{Os}/^{188}\text{Os}$  signature. The relative difference in the amount of recycled oceanic crust between LVC and endmember HIMU plumes (25–35% vs 20–30%, respectively), however, is small compared with the difference in the ages of the respective recycled slabs (1.2 Ga vs 1.8–2 Ga); this implies that as long as plume sources contain similar percentages of recycled oceanic crust, the effect on the Os isotopic signature will be relatively insensitive to the age of the slab. In contrast, the strongly hyperbolic nature of the Os–Pb mixing curves is such that the  $^{206}\text{Pb}/^{204}\text{Pb}$  signature of a plume is much more sensitive to the age of the recycled oceanic crust than to the amount of crust if in

excess of 10–20%. More speculative is the possibility that subduction zone processes have changed as a result of cooling of the mantle with time, from slab melting in the Archean to slab dewatering in the post-Archean (Vidal, 1992; Thirlwall, 1997). Slab melting may produce a subducted slab residue with a low Re/Os because of the incompatible behavior of Re and compatible behavior of Os during melting, whereas slab dewatering may produce a higher Re/Os residue because of mobility of Os in aqueous slab fluids (Brandon *et al.*, 1996). These processes may have operated to provide a higher Re/Os in younger subducted slabs, thus minimizing the differences in present-day  $^{187}\text{Os}/^{188}\text{Os}$  of variable age slab components of HIMU plumes.

#### *Implications for mixing processes*

The plume group basalts from the Canary Islands and Madeira display large variations in Pb isotope signatures which correlate with Sr and Nd isotopes (Fig. 4), and can be attributed predominantly to two-component mixing between the HIMU-like LVC component and a less enriched component with lower  $^{206}\text{Pb}/^{204}\text{Pb}$ . Mixing between the LVC plume and DMM, which could produce this negative trend, has been eliminated as a possibility because of the HIMU-like trace element systematics in the isotopically depleted Madeira basalts (Hoernle *et al.*, in preparation, b). Furthermore, it can be seen in Fig. 6b that plume–DMM source mixing would also be inconsistent with the relatively limited variation in Os isotope ratios in the Canary Island and Madeira basalts; this would result in Os isotope signatures significantly less radiogenic than those observed, because of the high Os/Pb of DMM relative to the LVC plume component, assuming 30% low Os/Pb recycled oceanic crust in LVC. Simple source mixing of the LVC plume and Paleozoic recycled oceanic crust is also inadequate to explain the Canary Islands–Madeira  $^{187}\text{Os}/^{188}\text{Os}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$  isotopic systematics, because the high Re/Os and thus very radiogenic  $^{187}\text{Os}/^{188}\text{Os}$  expected even in young subducted oceanic crust would cause a relatively steep negative trend in Fig. 6b, unlike the observed data. A possible explanation for the relatively limited variation in Os isotope ratios, but with a slightly negative  $^{187}\text{Os}/^{188}\text{Os}$ – $^{206}\text{Pb}/^{204}\text{Pb}$  trend, is mixing between the LVC plume and shallow upper mantle which is hybridized DMM and Paleozoic oceanic crust. Approximately 50% DMM–50% Paleozoic oceanic crust would produce a source with both a similar Pb/Os ratio and similar but slightly less radiogenic Os compared with the LVC plume, such that mixing between these sources would produce basalts with a relatively linear, slightly negative trend of  $^{187}\text{Os}/^{188}\text{Os}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ . The precise parameters of such mixing would be better constrained if  $^{187}\text{Os}/^{188}\text{Os}$  data for high Os concentration Madeira samples were available; the

low Os concentration of the Madeira samples provides only a maximum  $^{187}\text{Os}/^{188}\text{Os}$  value for the low  $^{206}\text{Pb}/^{204}\text{Pb}$  mixing component. However, the general model holds, as the high Os concentration Canary plume group samples alone provide evidence for a mixing process in which  $^{206}\text{Pb}/^{204}\text{Pb}$  varies with no clear increase or decrease in  $^{187}\text{Os}/^{188}\text{Os}$ .

## CONCLUSIONS

The Sr–Nd–Pb–Os isotope systematics in basalts from the Canary Islands and Madeira provide evidence for both the origin of the Canary Island plume sources as well as the complex interactions of plume melts with the overlying lithosphere. The Os isotope system preserves a record of both crustal and lithospheric mantle contamination in some Canary Island basalts. Radiogenic Os isotope signatures in low Os concentration basalts are attributed to assimilation of sediment by plume melts during ascent. Less than 2% assimilation of terrigenous sediment can produce the observed range of radiogenic Os isotopic signatures without significantly affecting the Sr, Nd, or Pb isotopic signatures, but minor contribution of radiogenic Os because of assimilation of Mn-oxide, carbonate sediment and altered oceanic crust is permissible. Relatively unradiogenic Os isotope signatures in the xenolith-bearing unradiogenic group basalts indicate bulk assimilation by plume melts of lithospheric mantle in the form of disaggregated mantle xenoliths. Correspondingly high Sr and  $\Delta 8/4$  and low Nd isotopic signatures in these samples indicate that assimilation of melts of the metasomatized lithospheric mantle has also occurred.

The Os isotope signature of the Canary Island plume (or LVC) is among the most radiogenic found in ocean islands to date, and is comparable with the signatures in the endmember HIMU islands of Mangaia, Tubuaii and Rurutu. The LVC plume, however, has distinctly less radiogenic Pb isotope signatures. The radiogenic Os isotopic signature and concomitant moderate Pb isotopic signature of the LVC plume is most consistent with a relatively young (1.2 Ga) recycled oceanic crustal component. Mixing between the Canary plume and depleted asthenospheric mantle which contains a component of young (Paleozoic) recycled oceanic crust explains the relatively limited range in Os isotope ratios of the plume group basalts despite a range in Sr, Nd and Pb isotopic signatures.

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