

# Ancient recycled mantle lithosphere in the Hawaiian plume: Osmium–Hafnium isotopic evidence from peridotite mantle xenoliths

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## Abstract

The Emperor Seamount–Hawaiian island chain is thought to originate from melting of a heterogeneous mantle plume, but the composition of the plume has always been inferred from the compositions of the erupted lavas. It has been suggested that recycled (*i.e.* previously subducted) basaltic oceanic crust (with or without sediments) is part of this plume and responsible for the enriched isotopic compositions of the Hawaiian lavas. Here we present the first combined Hf–Os isotopic study on peridotite mantle xenoliths from the island of O‘ahu, Hawai‘i. The clinopyroxene and spinel major element compositions overlap the global range of compositions of abyssal peridotites, suggesting that the O‘ahu peridotites are samples from the oceanic mantle and residues of variable degrees of melting. The peridotite xenoliths from Salt Lake Crater have both highly unradiogenic Os (down to  $^{187}\text{Os}/^{188}\text{Os}=0.1138$ ) and radiogenic Hf (up to  $\varepsilon_{\text{Hf}}=114$ ) isotopic compositions and minimum rhenium-depletion ages up to  $\sim 2$  Ga. Such extreme Hf and Os isotopic compositions are not observed in Hawaiian lavas and are far removed from the composition of the depleted mantle, as it is sampled by mid oceanic ridge basalts and abyssal peridotites. Importantly, both Hf and Os isotopic compositions correlate with degree of depletion, suggesting that they are related to an ancient melting event. In contrast, peridotites from the Pali and Kaau vents have Os and Hf isotope ratios consistent with an origin from the  $\sim 100$  Ma Pacific lithosphere that lies beneath the Hawaiian islands. We suggest that the Salt Lake Crater peridotites are fragments of an ancient ( $>2$  Ga) depleted and recycled mantle lithosphere that is part of the upwelling Hawaiian plume. Such depleted peridotites have higher solidus temperature than other more fertile mantle components, so that their contribution to the erupted lavas compositions is minor, if any. The recognition of such isotopically and compositionally depleted materials within the Hawaiian plume suggests that depleted components are more common in mantle plumes than previously realized.

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## 1. Introduction

Generation of basaltic oceanic crust at divergent plate boundaries (*i.e.* mid oceanic ridges) and recycling of the lithospheric plate back into the Earth's mantle *via* subduction at convergent plate boundaries play a principle role in the generation of long-lived chemical and isotopic heterogeneities in the mantle. Ocean island basalts (or OIB) are thought to represent the surface expression of localized mantle upwellings, or plumes, that originate perhaps as deep as the core–mantle boundary. The chemistry of OIB has thus been used to map the heterogeneities of the Earth's mantle and constrain the processes that can create these heterogeneities over time. Much of the trace element and isotopic variability observed in OIB has been attributed to mantle sources that contain various proportions of recycled oceanic basaltic crust, with or without sediments [1,2]. For example, the isotopically enriched endmember of the Hawaiian lavas, the Ko'olau lavas, has been argued to contain recycled oceanic crust [3–5], possibly with pelagic sediments [6] in their source. However, the subduction process requires that refractory components must be abundant in the mantle because a subducted oceanic plate will be volumetrically dominated by the depleted lithospheric mantle, the residue of the basaltic crust extraction. Some recent studies have proposed the presence of a depleted component in OIB in part because of new Hf [7,8] and Os [4,9] isotopic data. However, by their nature, depleted or refractory mantle components are difficult to study through examination of mantle-derived melts, both because such components contribute proportionately less melt than more fertile components, and because they are depleted in the incompatible elements (*e.g.* Sr–Nd–Pb–Hf) typically utilized to infer the nature and origin of the mantle sources of ocean island basalts.

In this study we take a new approach to investigate the presence and type of refractory material present in mantle plumes, with a detailed isotopic, trace and major element investigation of peridotite xenoliths from O'ahu, Hawai'i. Earlier studies have suggested that the O'ahu peridotites represent metasomatized fragments of the Pacific lithosphere that underlies the Hawaiian islands [10–13]. The combined Hf and Os isotope data presented in this study however, suggest that some peridotite xenoliths from the Salt Lake Crater vent cannot be fragments of the recent Pacific lithosphere, but instead represent ancient (1–2 Ga), recycled and depleted mantle lithosphere present within the upwelling Hawaiian plume.

## 2. Background information

### 2.1. The O'ahu mantle xenoliths

The O'ahu xenoliths are primarily dunites, spinel peridotites (harzburgites and lherzolites) and pyroxenites [10,14]. They are present within the alkalic post-erosional (or rejuvenated) stage Honolulu Volcanics (HV) lavas that mark the last stage of volcanism on the Ko'olau volcano [15]. Of all the xenolith-bearing vents on O'ahu only Pali, Kaau and Salt Lake Crater (SLC) carry peridotite xenoliths abundant or large enough for detailed isotope or trace element analyses [11–13,16–18].

The magnesian- and chromium-rich nature of the O'ahu peridotites [10] and the LREE depleted character of some Pali and Kaau peridotites [17] has been used to argue that these peridotites are mantle residues from the Pacific lithosphere. However, while thermobarometric calculations place the peridotites shallower than 60–70 km, their temperatures are hotter than a 100 Ma oceanic geotherm [10,19]. The high equilibration temperatures, the LREE enriched patterns of most SLC peridotites [13,17] and the near identical Sr–Nd isotopic compositions between peridotites and the host HV lavas [11–13] led to the suggestion that these peridotites represent pieces of the Pacific lithosphere that had experienced varying degrees of metasomatism and/or melt–mantle interaction in response to recent Hawaiian volcanism. However, Salters and Zindler [18] first reported highly radiogenic  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios in clinopyroxenes from the SLC peridotites (hereafter termed SLCP) and suggested that these xenoliths may not be parts of the 100 Ma Pacific lithosphere but residues of a much older melting event.

### 2.2. Os–Hf isotope systematics in peridotites

Osmium behaves as a compatible element during partial melting in the mantle, whereas Re is moderately incompatible [20,21]. As a result, melt depletion significantly lowers the Re/Os ratio of mantle peridotites, thereby retarding the ingrowth of  $^{187}\text{Os}$  from the decay of  $^{187}\text{Re}$ . In addition, because mantle peridotites have much higher Os concentrations than typical mantle-derived melts or fluids, Os-isotopes in peridotites are generally resistant to metasomatic effects (*c.f.*[22]). These features make the Re–Os system useful for evaluating the timing and extent of past melt extraction in mantle peridotites, including peridotites in which other isotopic systems (*e.g.* Sr–Nd–Pb) have been disturbed by recent metasomatism.

Clinopyroxene (cpx) is the primary host of several incompatible trace elements (*e.g.* Hf, Sr, Nd) in mantle peridotites and is chemically resistant to alteration, making it well-suited for isotopic studies of mantle peridotites. The Hf isotope analyses of cpx are routinely taken to closely approximate the bulk peridotite Hf isotopic composition [13,18,23,24]. The  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of a peridotite increases during melt extraction because Lu is more compatible than Hf in the mantle (*e.g.* [25]) so that an aged and melt-depleted peridotite will develop, with time, relatively radiogenic  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios. Also, because Hf is more compatible than either Nd or Sr during peridotite melting (*e.g.* [25]), the Hf isotopic composition of peridotitic cpx is less susceptible to metasomatism than Nd or Sr [13]. Therefore, Hf and Os isotope variations in peridotites can provide two complementary records of ancient depletion events that are relatively unaffected by subsequent metasomatism.

### 3. Sample description and analytical methods

The samples studied here are spinel peridotites (with no plagioclase) from the Pali and Kaau vents (hereafter grouped together as PK) and SLC vents [10,13]. The analyzed specimens belong to the Presnall collection (housed at the Florida International University), and the Jackson collection (housed at the National Museum of Natural History). Compared to typical abyssal peridotites, the peridotites studied here are exceptionally fresh and free of serpentinization. None of these samples show any visible signs of modal metasomatism (*e.g.* phlogopite or amphibole) or melt infiltration (*e.g.* veins). The studied peridotites are typically allotriomorphic-granular and coarse-grained porphyroclastic with large olivines and orthopyroxenes (often >2 mm). Clinopyroxene (<5% to <15% modal abundance) and spinel (<2% modal) are smaller in size. This study combines new Hf and Os isotope data with previously published data for peridotite xenoliths from the SLC and PK vents. These data, combined with complementary major and trace element data for minerals, place important constraints on the nature and origin of these xenoliths, the composition of the Hawaiian plume, and the extent of plume–lithosphere interaction.

The major element concentrations of cpx, orthopyroxene and spinel mineral phases were determined on a JEOL 8200 Superprobe at the University of Mainz [26] and on a JEOL 8900R Superprobe at the FCAEM, Florida International University [27,28] and are given in the Supplementary material (Tables A1, A2, A3).

The cpx trace element data are provided as Supplementary material (Table A4). The cpx trace

element concentrations were determined either by solution ICP-MS following the methods described in detail elsewhere [13,28], or by ion microprobe with the CAMECA IMS-3f (MPI, Mainz) using the methods outlined in [29]. Some samples were also analysed by laser ablation ICP-MS at FSU. Briefly, for the laser ablation we used a 213 nm laser ablation system (New Wave) coupled to a Finnigan ELEMENT-1 ICP-MS, equipped with a CD-1 guard electrode. Helium gas was used to flush the ablation chamber. The cpx grains were mounted in epoxy and polished down to 0.3  $\mu\text{m}$  prior to ablation. The laser was operated at 10 Hz, 80–100  $\mu\text{m}$  spot size and at 55% energy. Trace element concentrations were calculated against the NIST SRM-612 glass standard, using the preferred concentrations reported in [30], and  $^{43}\text{Ca}$  for internal normalization.

Some samples were analyzed by both the ion microprobe (at MPI) and the ICP-MS techniques (at FSU). The ion probe and ICP-MS data compare well for a wide range of concentrations and elements (Fig. A1, in the Supplementary material). For samples that were analyzed by both techniques, we also report the concentrations measured by the ion microprobe in Table A5 of the Supplementary material.

The Hf, Nd and Sr isotopic compositions were determined at the NHMFL-FSU, on hand-picked cpx mineral separates (*ca.* 100–150 mg) as in previous studies [13,28]. Briefly, the hand-picked cpx were finely crushed in a clean agate mortar and then leached in 6 N HCl at 100 °C overnight. The leached fraction was subsequently rinsed with 18 M $\Omega$  water several times and then dissolved in HF:HNO<sub>3</sub> (3:1) mixture and processed for Hf separation following the methods of [31]. Neodymium and Sr were separated with conventional methods from the fraction that contains most of the bulk rock recovered from the Hf column chemistry. Hafnium isotopes were determined on the VG-ISOLAB using the HOT-SIMS technique [13,18,28,32] and Nd and Sr isotopes on a Finnigan MAT-262 TIMS. Osmium isotopes and Re, Os concentrations were determined on bulk rock powders at MPI, Mainz, following the techniques outlined in Lassiter et al. [33]. The isotope data and Re concentrations, together with further analytical details are given in Table 1.

## 4. Results

### 4.1. Major and trace element systematics

The cpx are chrome–diopsides with Mg# = 0.88–0.92 (molar Mg/Mg+Fe ratio) while the spinels have Cr# = 0.15–0.54 (molar Cr/Cr+Al ratio). Fig. 1 shows a

Table 1  
Sr–Nd–Hf–Os isotopic compositions of the O'ahu peridotites

	$^{87}\text{Sr}/^{86}\text{Sr}$ cpx	$2\sigma$	$^{143}\text{Nd}/^{144}\text{Nd}$ cpx	$2\sigma$	$\epsilon_{\text{Nd}}$	$^{176}\text{Hf}/^{177}\text{Hf}$ cpx	$2\sigma$	$\epsilon_{\text{Hf}}$	$^{187}\text{Os}/^{188}\text{Os}$ (bulk rock)	Os concentration (ppb)	Re concentration (ppb)	T RD (Ma)
<i>SLC vent</i>												
SLC 470 <sup>a</sup>	0.70329	± 8	0.513019	± 10	7.43	0.284409	± 27	57.9	0.1168			1,482
SLC 319 <sup>a</sup>	0.70323	± 8	0.513049	± 13	8.02	0.283326	± 13	19.6	0.1185			1,237
SLC 320 <sup>a</sup>	0.703302	± 8	0.513051	± 10	8.06	0.286009	± 69	114.5	nd			
SLC 405 <sup>a</sup>	0.703337	± 10	0.513045	± 14	7.94	0.283528	± 29	26.7	0.1237			483
115048-2	0.703372	± 15	0.513009	± 9	7.24	0.284049	± 50	45.2	0.1187	3.05		1,208
114989-2	0.703589	± 6	0.513101	± 20	9.03	0.28337	± 41	21.1	0.1176	1.98		1,367
115048-1	0.703282	± 6	0.513030	± 10	7.65	0.283497	± 30	25.6	0.1189	2.98	0.13	1,180
115048-26	0.703374	± 0	0.513011	± 6	7.28	0.283727	± 17	33.8	0.1138	2.56		1,910
114989-4	0.703339	± 7	0.512780	± 11	2.77	0.282874	± 17	3.6	0.1163	2.98	0.35	1,553
114989-38	0.703421	± 7	0.512855	± 6	4.23	0.283146	± 25	13.2	0.1206	2.94	0.56	934
114989-37	0.703283	± 7	0.513035	± 6	7.74	0.283198	± 23	15.1	0.1291	8.17	0.16	–
115048-5	0.703161	± 7	0.512832	± 7	3.78	0.283766	± 23	35.2	0.1225	2.56		658
115048-3	0.703324	± 7	0.513021	± 9	7.47	0.283214	± 23	15.6	0.1227	2.76	0.14	629
115048-4	0.703284	± 7	0.513034	± 6	7.72	nd	±		0.1231	2.86	0.09	571
115048-25	0.703348	± 7	0.513023	± 6	7.51	0.284051	± 20	45.2	0.1244	2.94		381
114989-3	0.70324	± 6	0.513077	± 13	8.56	0.283504	± 13	25.9	0.1251	2.6		279
114989-36	nd		nd			nd			0.1195	1.8		1,093
114745-2 <sup>b</sup>	0.70326		0.513090		8.8	0.283207	± 24	15.4	0.1258			176
114745-3 <sup>b</sup>	0.70327		0.513085		8.7	0.28296	± 36	6.6	0.1297			–
<i>Pali-Kaau vent</i>												
114744-1 <sup>b</sup>	0.70338		0.513080		8.6				0.126	0.65	0.2	191
114744-2B <sup>b</sup>	0.70303		0.51311		9.2	0.283294	66	18.5	0.1269			15
114908-20 <sup>b</sup>	0.703287	± 8	0.513022	± 10	7.5	0.283713	± 17	33.3	0.1238			469
114908-22 <sup>b</sup>	0.703191	± 7	0.513252	± 7	12	0.283527	± 64	26.7	0.1259			162
KAPS36 <sup>a</sup>	0.703219	± 12	0.513064	± 15	8.3	0.283116	± 17	12.2	0.124			440
Pa27 <sup>a</sup>	0.703234	± 9	0.51318	± 8	10.57	0.283319	± 23	19.3	0.1262			118
114908-7									0.1252			264
114908-21									0.1248	1.13	0.16	322
114908-1									0.1213	1.25	0.1	828
114908-2									0.1215	1.05	0.19	797
114908-3									0.1251	1.66	0.13	278
114908-5									0.1216	1.47	0.21	788
114886-3									0.1218	2.61	0.12	760
114886-4									0.1218	2.15	0.19	760

<sup>a</sup>Hf–Nd–Sr data from [16].

<sup>b</sup>Os–Nd–Sr data from [15]. Values in italics are from those two studies, but are included here for completeness. Hf, Nd, Sr isotopes in cpx were determined as in [16,23]. The  $^{176}\text{Hf}/^{177}\text{Hf}$  ratio of the JMC-475 standard was measured at 0.282186 ( $\pm 0.000018$ , 2 S.D.,  $n=31$ ) and the ratios are reported relative to the accepted JMC-475 value of 0.282160. Errors are  $2\sigma$  ( $2 \times$  standard deviation/ $n$ ,  $n$ =number of ratios) and Hf blanks  $<20$  pg.  $\epsilon_{\text{Hf}}$  and  $\epsilon_{\text{Nd}}$  values are present day and calculated using  $^{176}\text{Hf}/^{177}\text{Hf}_{\text{CHUR}}=0.282772$  and  $^{143}\text{Nd}/^{144}\text{Nd}_{\text{CHUR}}=0.512638$ . Bulk rock  $^{187}\text{Os}/^{188}\text{Os}$  ratios were determined at MPI using the methods outlined in [38] with all errors less than 0.4% ( $2\sigma$ ). Total procedural blanks for Os are less than 1 pg/g and are insignificant for the relatively high Os contents of peridotites. Sr and Nd standard measurements are identical to those reported in [23]. Re-depletion ages ( $T_{\text{RD}}$ ) in million years (Ma) are calculated assuming derivation from chondritic initial composition [28].

positive correlation between cpx and spinel Cr# in the O'ahu peridotites, and these compositions overlap those of abyssal peridotites. This suggests that the O'ahu peridotites have experienced similar degrees of depletion as abyssal peridotites, which in turn are thought to represent the residues of MORB melting. The overall lower Cr# in the PK peridotites (Fig. 1) suggests that they are less depleted than the SLC and abyssal peridotites. The SLCP cpx have higher Na contents,

for a given Cr#, than abyssal peridotites (not shown, but similar to Fig. 1 in [13]), which is inconsistent with them being simple residues of melting but instead requires some metasomatic enrichment of a depleted peridotite protolith [10,13].

The majority of the SLCP cpx have characteristically “humped” chondrite-normalized REE patterns showing a maximum in the Pr–Nd range (Fig. 2). The three exceptions with convex-down or flat patterns are labeled

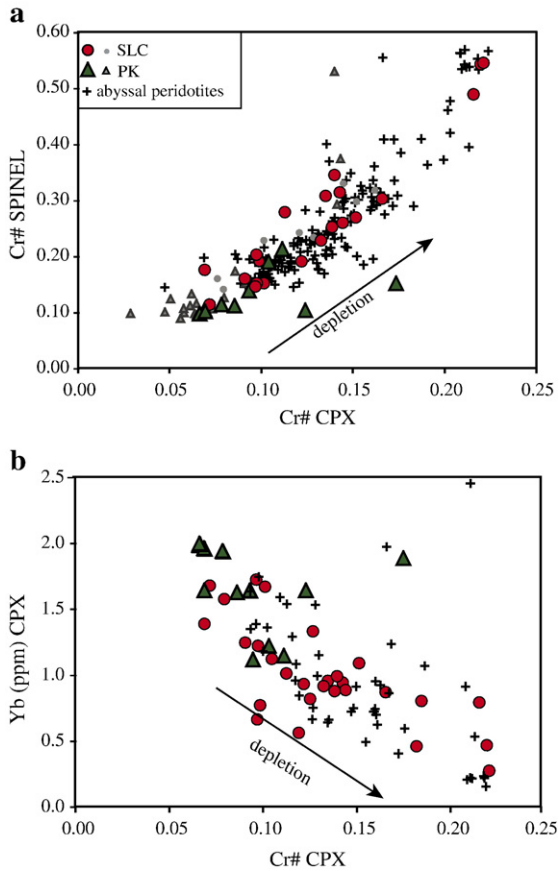


Fig. 1. a) Cr# in cpx vs. Cr# in spinel and b) Cr# vs. Yb (ppm) in cpx. SLCP and PK peridotites compared with abyssal peridotites [29,48,67–71]. Large circles: SLCP data from this study (Tables A1 and A3 in the Supplementary material) and [13]. Small circles: SLCP data from [10,13] and references therein. Large triangles: PK peridotite data from this study and [13]. Small triangles: PK peridotite data from [10]. The arrow points towards the direction of increasing melt depletion. The SLCP compositions overlap with the global variability seen in abyssal peridotites.

separately in Fig. 2. The PK cpx show more variable REE patterns with both convex and concave patterns but in general, they have flatter MREE-HREE slopes than the SLCP. The LREE concentrations do not correlate with Cr# in cpx or other major element indices of melt depletion, but Na and Nd contents show a positive correlation in the SLCP (not shown), pointing to a common source of the Na and LREE enrichment. Ytterbium (and the other heavy REE) is moderately incompatible in cpx, and less sensitive to metasomatism than the more incompatible LREE elements. As a result, Yb is often used as an indicator of depletion [29]. The Yb vs. Cr# variability in the SLCP cpx overlaps the entire range seen in abyssal peridotite cpx (Fig. 1b),

again suggesting that the SLCP are residues of variable degrees of melting and some show extents of depletion similar to the most depleted abyssal peridotites.

## 4.2. Os–Hf–Nd–Sr isotopic compositions

### 4.2.1. Sr–Nd isotope systematics

In Sr–Nd isotope space (Fig. 3), most of the SLCP overlap the HV and other Hawaiian post-erosional lava compositions and show the well-documented shift towards high  $^{87}\text{Sr}/^{86}\text{Sr}$  (for a given  $^{143}\text{Nd}/^{144}\text{Nd}$ ) relative to the Pacific MORB [7,11,13,34]. However, three SLCP samples (114989-38, 115048-5, 114989-4; Table 1) have relatively unradiogenic  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios ( $<0.51286$ ) for a given  $^{87}\text{Sr}/^{86}\text{Sr}$  and plot below the Hawaiian lava field in Sr–Nd space (Fig. 3), unlike all previously published Hawaiian xenolith data. Their Nd–Sr isotopic compositions straddle the so-called “Lo–Nd” array [35] and fall between the HIMU and EMI mantle endmember

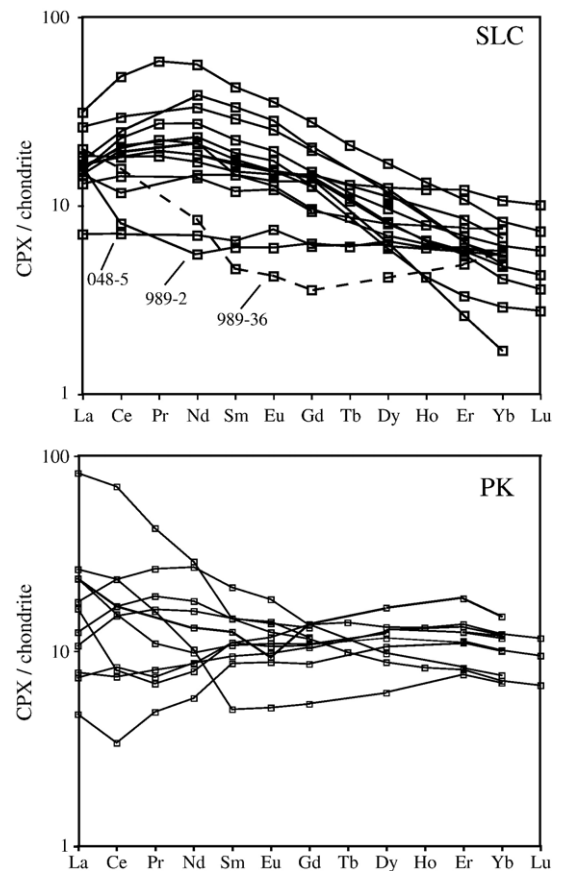


Fig. 2. Chondrite-normalized REE concentration of cpx (normalization values from [72]). Top panel shows the SLCP compositions and bottom panel the PK compositions.

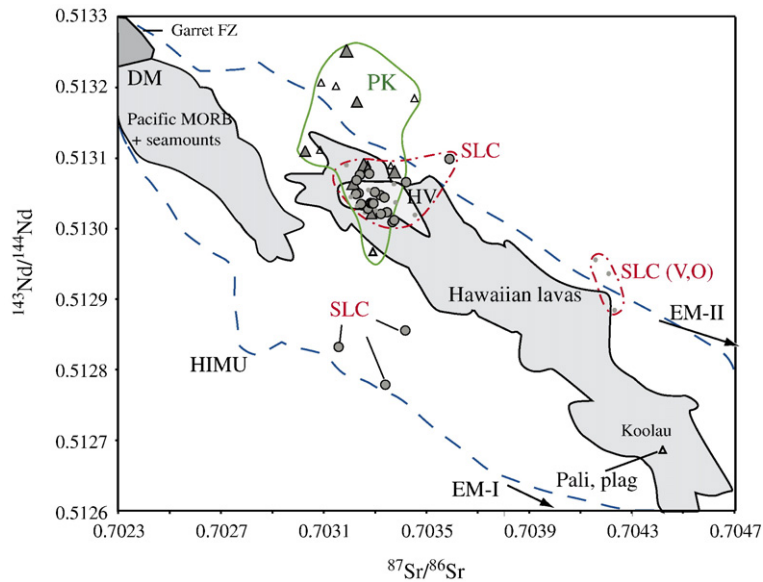


Fig. 3. Sr–Nd isotope compositions of the SLCP and PK cpx compared with the Pacific MORB, Pacific seamounts and Hawaiian lavas. Symbols as in Fig. 1 and data from Table 1. Other peridotite data: open triangles PK peridotites from [34], small circles SLCP from [11,16]. Fields for Pacific MORB and other Pacific seamount data are compiled from the GEOROC [73] and PETDB [74] databases. The Pacific MORB samples with the most radiogenic  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios from the Garret fracture zone [37] are shown separately for comparison. The data fields for the HV and Ko‘olau lavas from O‘ahu are shown separately for comparison. Most of the SLCP overlap the HV lavas. The PK peridotites extend to more radiogenic  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios than the SLCP or the Hawaiian lavas, similar to the most radiogenic Pacific MORB (Garret FZ). The three SLCP with low  $^{143}\text{Nd}/^{144}\text{Nd}$  for a given  $^{87}\text{Sr}/^{86}\text{Sr}$  are pointed out separately. The SLCP field labeled “SLC V, O” encloses three SLCP data from [11,16] with relatively radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. A plagioclase separate from a plagioclase peridotite [36] is the only reported O‘ahu peridotite with Nd–Sr isotope compositions that overlap the Ko‘olau lavas.

components in Sr–Nd isotope space. These compositions contrast both with the majority of O‘ahu peridotites with radiogenic Nd isotopes ( $^{143}\text{Nd}/^{144}\text{Nd} > 0.5130$ ) and with the four previously reported O‘ahu peridotites with  $^{143}\text{Nd}/^{144}\text{Nd} < 0.5130$  [11,16,36]. Those four samples also have radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, similar to the enriched Ko‘olau lavas (Fig. 3) and were previously explained by metasomatism of the *in situ* Pacific lithosphere by ascending Ko‘olau-type magmas. In case of the three SLCP samples with the unradiogenic  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios reported here however, the absence of such low  $^{143}\text{Nd}/^{144}\text{Nd}$ –low  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in the erupted Hawaiian lavas suggests that these xenoliths were not significantly metasomatized by erupted Hawaiian lavas. This is also supported by the lack of correlation between  $^{143}\text{Nd}/^{144}\text{Nd}$  and Sm/Nd or Sr/Nd ratios in the SLCP (not shown) which rules out possible hyperbolic mixing lines between Ko‘olau melts and a depleted (Pacific MORB or HV-type) component as an explanation for these low  $^{143}\text{Nd}/^{144}\text{Nd}$ –low  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios.

The PK samples extend to more radiogenic  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios than the SLCP and all Hawaiian lavas, similar to the most radiogenic Pacific MORB (Garret fracture zone; [37] (Fig. 3), but they also have  $^{87}\text{Sr}/^{86}\text{Sr}$

ratios above 0.7030, distinctly more radiogenic than Pacific MORB or seamounts (Fig. 3).

#### 4.2.2. Nd–Hf isotope systematics

Fig. 4 compares the Nd–Hf isotopic compositions of the O‘ahu peridotites with that of the Hawaiian lavas and the global Nd–Hf isotopic variability of MORB and OIB. The SLCP extend to highly radiogenic  $\epsilon_{\text{Hf}}$  values at near constant Nd isotopic compositions ( $\epsilon_{\text{Hf}} = +3.6$  to  $+114$ ,  $\epsilon_{\text{Nd}} \sim 7.5$ , Table 1), higher than any other samples from the present-day oceanic mantle, forming a near vertical array in Nd–Hf isotope space. None of the SLCP overlap the MORB field (Fig. 4). Our new data confirm the abundance of highly radiogenic Hf isotopic compositions in the SLCP, first reported by Salters and Zindler [18]. In contrast, the PK peridotites have less radiogenic Hf isotopic compositions than the SLCP and some overlap with the MORB field (Fig. 4).

The SLCP samples 114989-38, 115048-5 and 114989-4 with the relatively unradiogenic  $^{143}\text{Nd}/^{144}\text{Nd}$  deviate from the vertical distribution defined in Hf–Nd space by the rest of the peridotites. In particular, sample 114989-4 also has a  $^{176}\text{Hf}/^{177}\text{Hf}$  ratio as unradiogenic as the most unradiogenic lava so far reported from Hawaiian volcanoes (sample 96 L-17

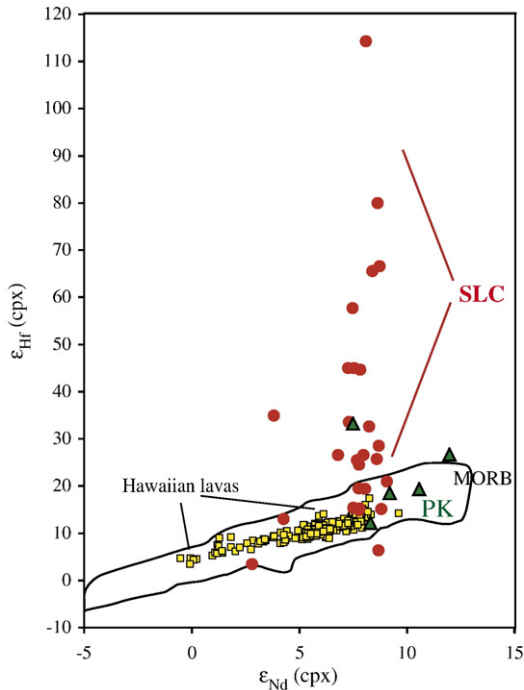


Fig. 4. Nd–Hf isotopic compositions of the SLC and PK peridotites, compared with the Hawaiian lavas and the variability of the global MORB and OIB. All peridotite data are from Table 1 and [13,18]. Hawaiian lava data from [6–8,38,75–79] and references therein. The outlined field encompasses the global Nd–Hf isotopic variability of MORB and OIB (data from the GEOROC [73] and PETBD [74] databases).

from Lanai; [38]). Sample 114745-3 also has relatively unradiogenic  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios, similar to the Ko’olau tholeiites, but falls below the mantle array in Hf–Nd space, at the radiogenic part of the array (Fig. 4).

Salters and Zinlder [18] and Bizimis et al. [13] have shown that recent metasomatism of an ancient depleted peridotite through a melt–peridotite interaction can generate melts with highly hyperbolic compositions in Hf–Nd space, where metasomatism affects Hf isotopes less than Nd isotopes, and can reproduce an Hf–Nd decoupling similar to that seen in the SLCP. Such decoupling between Hf and Nd isotopic compositions in peridotites has recently been observed in continental mantle xenoliths as well [23,39]. These studies proposed that diffusion in the mantle may be slower for Hf than Nd resulting in fast equilibration of cpx with metasomatic melts or fluids for Nd (hence the near identical Nd isotopic compositions between peridotites and host lavas in Fig. 4) but not for Hf. Irrespective of the process however, it appears that Hf isotopes in peridotites are less susceptible to metasomatism than Nd (and Sr), and therefore better retain a record of the original mantle composition.

#### 4.2.3. $^{187}\text{Os}/^{188}\text{Os}$ ratios and Hf–Os isotope systematics

Osmium in abyssal peridotites is believed to reside primarily in discrete sulfides, although Cr–spinel may also be an important host. Several studies have revealed significant Os isotopic heterogeneity among individual samples of a single peridotite [40–42]. Overall, the distribution of  $^{187}\text{Os}/^{188}\text{Os}$  in individual sulfides and spinels from abyssal peridotites is similar to that of abyssal peridotite wholerock data, although sulfides trapped as inclusions within other mineral grains extend to somewhat less radiogenic ratios [41,42]. However, bulk rock Os isotope analyses such as the ones reported here will likely “average out” the Os isotope heterogeneity present in individual sulfides within a single sample, and are more appropriate for examining the relationship between Os-isotope composition and mineral composition proxies for past silicate melt depletion.

The bulk rock  $^{187}\text{Os}/^{188}\text{Os}$  ratios of the SLCP range from 0.1138 to 0.1297 (Table 1), extending to less radiogenic ratios than previously reported for abyssal peridotites and well below the estimates for the depleted upper mantle (DMM:  $^{187}\text{Os}/^{188}\text{Os}=0.125\text{--}0.128$ , [43–45]), or primitive upper mantle (PUM:  $^{187}\text{Os}/^{188}\text{Os}=0.129$ , [46]). Eight of the eighteen SLCP have  $^{187}\text{Os}/^{188}\text{Os} < 0.120$  and four have  $^{187}\text{Os}/^{188}\text{Os} < 0.118$ . In contrast, the majority of abyssal peridotites have  $^{187}\text{Os}/^{188}\text{Os}$  ranging from 0.120 to 0.130, and less than 2% of abyssal peridotites have  $^{187}\text{Os}/^{188}\text{Os} < 0.118$  (c.f. [42]). To date, no abyssal peridotites have been reported with  $^{187}\text{Os}/^{188}\text{Os}$  values as low as the least radiogenic SLCP (sample 115048-26 with  $^{187}\text{Os}/^{188}\text{Os}=0.1138$ , Table 1). In contrast, the PK peridotites have  $^{187}\text{Os}/^{188}\text{Os}$  values indistinguishable from normal abyssal peridotites, with  $^{187}\text{Os}/^{188}\text{Os}$  ranging from 0.1213 to 0.1269 (Table 1).

The  $^{187}\text{Os}/^{188}\text{Os}$  isotope ratios in peridotites can be used to calculate Re-depletion model ages (or  $T_{\text{RD}}$ ) [21], which may represent the age of the last major melt depletion event that affected these peridotites. These model ages are *minimum* estimates and assume that Re is completely removed during melting and that these peridotites originate from a chondritic reservoir with  $^{187}\text{Os}/^{188}\text{Os}=0.127$  [21]. Eight of the analyzed SLCP record Re-depletion ages between 1 and 1.9 Ga (Table 1). If we assume that the peridotites originate from a PUM reservoir, the calculated Re-depletion ages become even older (up to 2.2 Ga). These ages are in stark contrast with the  $\sim 100$  Ma age of the Pacific lithosphere at O’ahu, and suggest that these peridotites have experienced an ancient depletion event, unrelated to the formation of Pacific lithosphere.

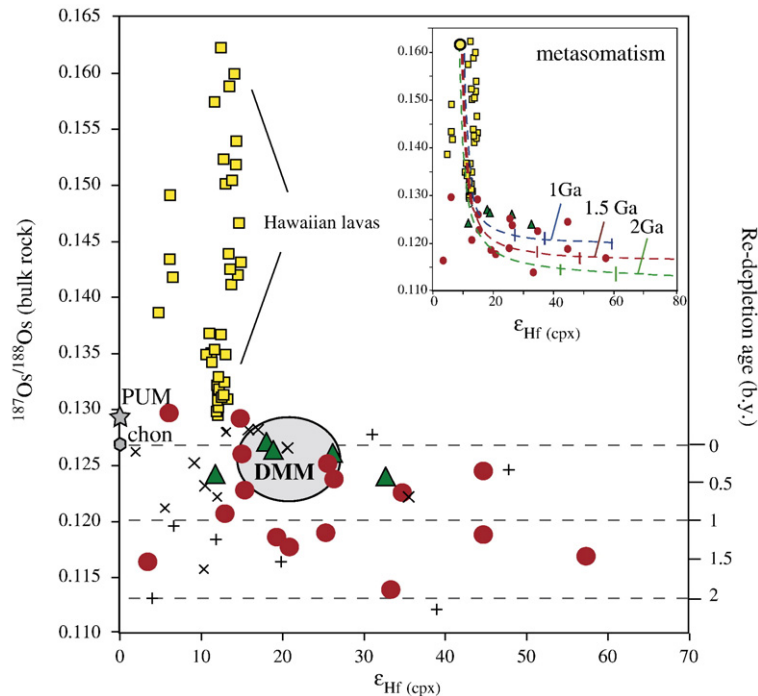


Fig. 5.  $^{187}\text{Os}/^{188}\text{Os}$  vs.  $\epsilon_{\text{Hf}}$  isotopic compositions of the SLCP and PK peridotites compared with Hawaiian lavas. Peridotite data from Table 1 and symbols as in Fig. 1; squares: Hawaiian lavas ([4,7,12,77,79,80], references therein and J. Lassiter, unpubl. data). Right vertical axis shows the corresponding Re-depletion ages in Ga for a given  $^{187}\text{Os}/^{188}\text{Os}$  ratio [21]. The 0, 1 and 2 Ga depletion ages and corresponding  $^{187}\text{Os}/^{188}\text{Os}$  ratios are connected with dashed lines for clarity. Error bars are smaller than the symbol sizes. The  $^{187}\text{Os}/^{188}\text{Os}$  range of the DMM field is defined by the Os isotopic composition of abyssal peridotites and encompasses all previous estimates of DMM ( $^{187}\text{Os}/^{188}\text{Os}=0.126\pm 0.004$ , 1 sd). The Hf isotopic range of DMM ( $\epsilon_{\text{Hf}}=15\text{--}28$ ) is from [58] and the observed Hf isotope variability of MORB. PUM:  $^{187}\text{Os}/^{188}\text{Os}=0.129$  [46] and  $\epsilon_{\text{Hf}}=0$ . Chon=chondritic earth isotopic composition with  $^{187}\text{Os}/^{188}\text{Os}=0.127$  [21] and  $\epsilon_{\text{Hf}}=0$ . Also plotted for comparison are cratonic peridotite xenoliths from Siberia (x: Tok volcanic field [24]) and the Wyoming craton (crosses: Homestead kimberlite, Montana; [23]). Inset figure shows the compositions generated by metasomatism (modeled as binary mixing) of a 1, 1.5, or 2 Ga depleted peridotite by a Hawaiian-type melt. We assume a Hawaiian melt with  $^{187}\text{Os}/^{188}\text{Os}=0.16$ , 0.3 ppb Os,  $\epsilon_{\text{Hf}}=10$ , and 2.7 ppm Hf, and a depleted peridotite with 3 ppb Os in the bulk rock, 0.37 ppm Hf in cpx,  $^{187}\text{Os}/^{188}\text{Os}=0.12$ , 0.1165, and 0.113, and  $\epsilon_{\text{Hf}}=60$ , 81 and 121 for the 1, 1.5 and 2 Ga depletion ages, respectively. The  $^{187}\text{Os}/^{188}\text{Os}$  ratios of the peridotite assume complete removal of Re.  $\epsilon_{\text{Hf}}$  is calculated from the melting model and parameters given in [13], and assume 4% incremental batch melting of a peridotite with DMM composition. Larger degrees of melt depletion will essentially move the peridotites further to the right (*i.e.* more radiogenic Hf isotopic compositions), but this has no effect on our discussion or conclusions.

Fig. 5 compares the Os and Hf isotopic compositions of the SLCP and PK peridotites with those of the Hawaiian lavas, the composition of DMM (the proposed source of mid ocean ridge basalts or MORB), PUM and chondritic earth. Because Os is compatible and Hf incompatible in the upper mantle, the Os–Hf isotopic composition of DMM is best constrained by the  $^{187}\text{Os}/^{188}\text{Os}$  ratios of abyssal peridotites, the residues of MORB melting [47,48] and the Hf isotopic range of MORB. The PK and some SLCP have Os and Hf isotopic compositions that fall close to, or within, the compositional range of DMM, and only marginally overlap the range of the Hawaiian lavas, which extend to higher  $^{187}\text{Os}/^{188}\text{Os}$  and lower  $\epsilon_{\text{Hf}}$  (Fig. 5). In contrast, the SLCP with unradiogenic  $^{187}\text{Os}/^{188}\text{Os}$  ratios tend to have the most radiogenic Hf isotopic compositions and are far removed from the Hawaiian lava or MORB fields.

The one exception is sample 114989-4 which has a low  $^{187}\text{Os}/^{188}\text{Os}$  ratio (0.1168) and unradiogenic  $\epsilon_{\text{Hf}}$  (Fig. 5).

## 5. Discussion

Any model aimed to explain the origin and evolution of the O'ahu peridotites must account for the following key observations:

- 1) The  $^{187}\text{Os}/^{188}\text{Os}$  ratios of the SLCP extend to very unradiogenic values, far removed from the estimated average composition of the depleted mantle. The corresponding 1–2 Ga Re-depletion ages suggest that (at least some of) the SLCP samples are residues of an ancient depletion event(s), which is inconsistent with an origin from the ~100 Ma Pacific lithosphere beneath the Hawaiian Islands.

- 2) Highly radiogenic  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios are common in the SLCP and unlike any MORB or OIB analyzed thus far. The coupling of radiogenic Hf with unradiogenic Os isotopic compositions in the SLCP suggests a link between the radiogenic Hf isotopes and ancient depletion.
- 3) The PK peridotite Os–Hf isotopic compositions are compatible with an origin from the MORB-depleted Pacific lithosphere (except for their relatively radiogenic Sr isotopic compositions). The differences in Os–Hf isotopic compositions between PK and SLCP are strong evidence for at least two distinct peridotite populations being brought to surface by the HV lavas.

### 5.1. The O'ahu peridotites as ancient residues of melting

The highly unradiogenic  $^{187}\text{Os}/^{188}\text{Os}$  ratios of the SLCP are incompatible with an origin from the recent

oceanic upper mantle, and require that they are residues of an ancient melt depletion event. An important observation is the correlation of Os and Hf isotopic compositions with indices of melt depletion in peridotites (Fig. 6). With increasing degree of depletion, Mg# and Cr# increase and Ti decreases in the peridotitic cpx, and these parameters are little affected by subsequent metasomatic alteration because they involve compatible (Mg, Cr) or moderately incompatible (Fe, Al, Ti) elements in cpx. Fig. 6 shows that the most depleted SLCP (*i.e.* highest Mg#–Cr#, lowest Ti) tend to have the most unradiogenic Os and most radiogenic Hf isotopic compositions. The correlation between  $^{187}\text{Os}/^{188}\text{Os}$  ratios and the cpx major/trace element compositions is analogous to the “alumichrons”, the  $^{187}\text{Os}/^{188}\text{Os}$  vs. bulk rock  $\text{Al}_2\text{O}_3$  correlations observed in some alpine and continental mantle peridotites where  $\text{Al}_2\text{O}_3$  is taken as a proxy for Re/Os ratios [23,24,49]. The  $^{187}\text{Os}/^{188}\text{Os}$  vs.  $\text{Al}_2\text{O}_3$  correlations have been previously interpreted

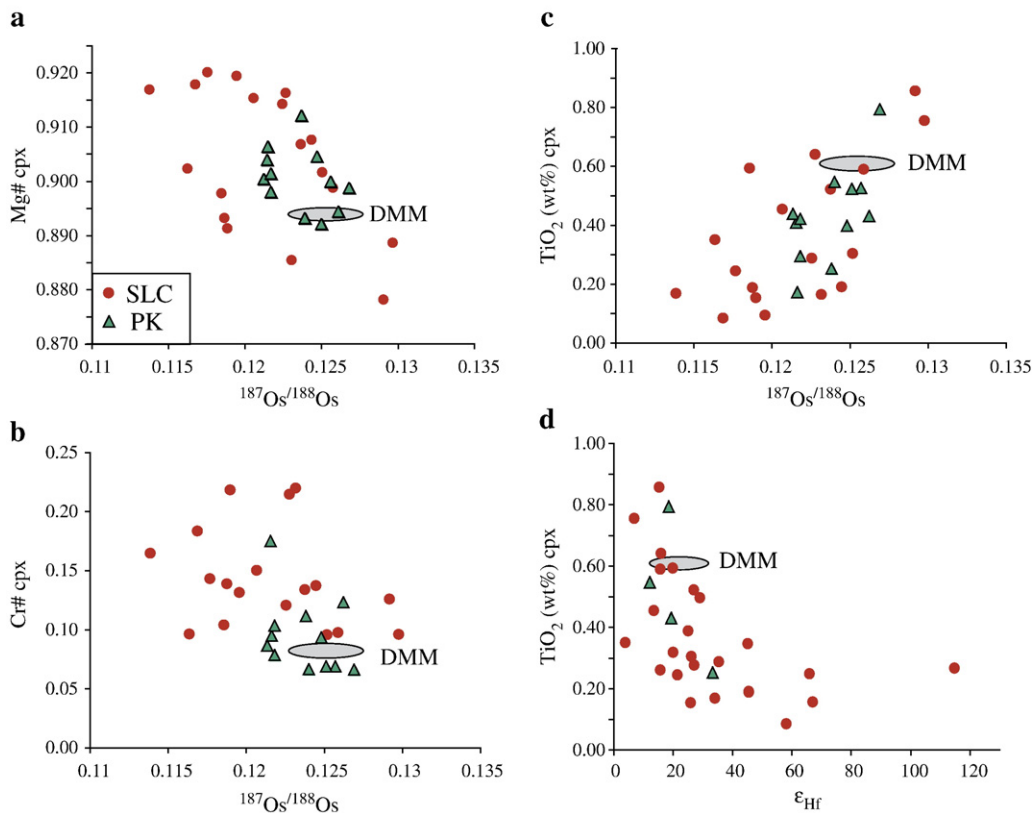


Fig. 6. Correlations of Os and Hf isotopic compositions with major and trace elements in the SLCP and PK peridotites:  $^{187}\text{Os}/^{188}\text{Os}$  vs. a) Mg# in cpx, b) Cr# in cpx, c)  $\text{TiO}_2$  in cpx, and d)  $\text{TiO}_2$  vs.  $\epsilon_{\text{Hf}}$  in cpx. Also shown for comparison are the Mg#, Cr# and  $\text{TiO}_2$  concentrations of a hypothetical cpx from a peridotite with DMM composition (shaded ellipse), using the Hf–Os isotopic range of DMM from Fig. 5. Note that the most depleted SLCP (higher Mg#, Cr#, and lower Ti contents) have the least radiogenic Os and most radiogenic Hf compositions. The Mg# of the DMM cpx (0.894) is taken equal to that of DMM [58]. The Ti content of the DMM cpx ( $\text{TiO}_2=0.61\%$ ) is calculated by mass balance, assuming DMM  $\text{TiO}_2=0.19\%$  and a spinel peridotite mineralogy with the following phase proportions: olivine = 58%, orthopyroxene = 25%, cpx = 15%, and spinel = 2%, and Ti partition coefficients:  $D_{\text{olivine}}=0.01$ ,  $D_{\text{orthopyroxene}}=0.15$ ,  $D_{\text{cpx}}=0.3$ , and  $D_{\text{olivine}}=0.15$ . Similar calculations give DMM cpx Cr#=0.08.

as representing variable degrees of depletion, at one time, of a once (presumably) homogenous mantle. The correlations between  $^{187}\text{Os}/^{188}\text{Os}$  and mineral chemistry shown here (Fig. 6) suggest that the SLCP represent different pieces of a variably depleted and aged mantle protolith, with the least radiogenic  $^{187}\text{Os}/^{188}\text{Os}$  ratios best reflecting the “true” age of depletion (*i.e.*  $\sim 2$  Ga for the SLCP).

The  $\epsilon_{\text{Hf}}$  vs.  $\text{TiO}_2$  correlation (Fig. 6d), as well as the Lu/Hf systematics (Fig. 7) are also consistent with this interpretation. The SLCP have more radiogenic  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios, for a given  $^{176}\text{Lu}/^{177}\text{Hf}$ , than that expected for peridotites from the 100 Ma Pacific lithosphere and a regression line (correlation coefficient  $r^2=0.49$ ) through all the SLCP data gives an age of 1.06 Ga, which is distinctly older than the 100 Ma age of the Pacific lithosphere at O’ahu (Fig. 7). Therefore, the Lu/Hf systematics also argue for an ancient (older than 1 Ga) depleted origin for the SLC peridotites, in agreement with the Os isotopic compositions.

The correlations between isotopes and mineral chemistry suggest that an ancient melting event is the primary controlling mechanism for the Os and Hf isotope systematics of the SLCP peridotites. It could be argued, however, that recent metasomatism has obscured the Os–Hf isotope systematics. The effect of metasomatism on the Hf–Os systematics is shown

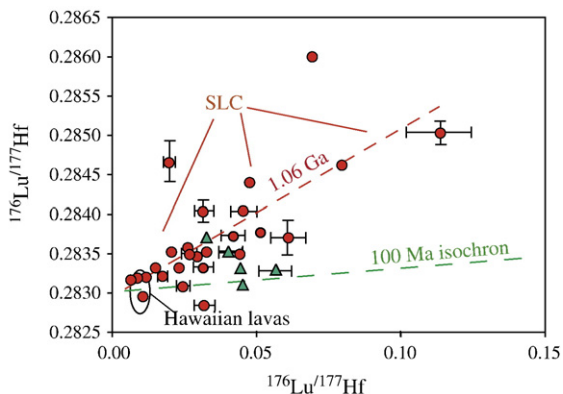


Fig. 7. Lu–Hf isotope systematics in the SLCP and PK cpx. Symbols as in Fig. 1. Data from Table 1, [13,18] and Bizimis (unpubl.). Error bars are shown for samples where the Lu/Hf ratio is determined by solution or laser ablation ICP-MS or ion probe and are assumed at 10%. Where no Lu data is available, Lu is calculated assuming chondritic Lu/Yb ratio. All other errors are smaller than the symbol size. Field labeled “Hawaiian lavas” shows the range of Hawaiian lava compositions. A 100 Ma isochron, representing the age of the Pacific lithosphere at O’ahu, is drawn for comparison. The 1.06 Ga isochron line is a regression through the SLCP data (see text for discussion). The SLCP have more radiogenic  $^{176}\text{Lu}/^{177}\text{Hf}$  for a given  $^{176}\text{Lu}/^{177}\text{Hf}$ , consistent with an ancient ( $> 100$  Ma) depletion event.

graphically in Fig. 5 where a 2 Ga depleted peridotite is metasomatized by a Hawaiian melt. Such metasomatism (modeled here as simple binary mixing between peridotite and melt) will move the most extreme peridotite Hf–Os isotopic compositions towards the DMM and Hawaiian lava compositions, and this will only serve to minimize, not produce, the extreme Hf–Os isotopic compositions observed in the SLC peridotites. The lack of correlation, today, between Re/Os and  $^{187}\text{Os}/^{188}\text{Os}$  (not shown) reflects the greater sensitivity of bulk rock peridotite Re concentrations to recent alteration (*e.g.* metasomatism or melt/rock interaction) than Os-isotopes or mineral chemistry. Therefore, the Hf–Os isotope arguments for ancient depletion presented above are valid even if the peridotites have been extensively metasomatized.

## 5.2. Origin of the SLC peridotites

The major and trace element systematics of the O’ahu peridotites are similar to those of abyssal peridotites (Fig. 1), arguing for an oceanic upper mantle origin, while their Hf and Os isotopic compositions require an ancient depletion event(s) unrelated to the recent Pacific MORB melting event. Recent Os-isotope work [42] has shown that some peridotites from the Mid-Atlantic ridge have lower  $^{187}\text{Os}/^{188}\text{Os}$  ratios (0.1206 average) than all other published abyssal peridotites (0.1246 average), which suggests they record an ancient melt-depletion event unrelated to the recent Mid-Atlantic ridge magmatism. These Os isotopic compositions were taken as evidence for a heterogeneous upper mantle where Os isotopes retain a record of ancient depletion events, unaffected by recent melting, long-term storage and convection in the upper mantle. Based on this it could be argued that the SLCP represent fragments of a heterogeneous upper mantle, either as pieces of the Pacific lithosphere or as entrained asthenosphere by the plume. However, such unradiogenic bulk rock Os isotopic compositions as seen in the SLCP are extremely rare in abyssal peridotites. There is only one sample with  $^{187}\text{Os}/^{188}\text{Os} < 0.118$  out of  $\sim 60$  abyssal peridotite (*i.e.*  $< 2\%$  of the population) reported in the literature and only 15% of those have  $^{187}\text{Os}/^{188}\text{Os} < 0.120$  [40–42,44,45,50,51]. In contrast, 4 out of 18 SLCP ( $> 20\%$ ) have  $^{187}\text{Os}/^{188}\text{Os} < 0.118$  and 8 out of 18 ( $> 40\%$ ) have  $^{187}\text{Os}/^{188}\text{Os} < 0.120$ . Based on these data we consider it statistically unlikely that the SLCP are sampling the same upper mantle reservoir as abyssal peridotites.

An alternative hypothesis is that the SLCP are fragments of an ancient depleted subcontinental lithosphere, as has been proposed for some Kerguelen Plateau

peridotite xenoliths [52]. Subcontinental lithospheric mantle “rafts” may become incorporated into the oceanic upper mantle during continental breakup [53]. Because this lithospheric mantle can remain isolated from the convecting mantle for billions of years, it can develop unradiogenic Os and radiogenic Hf isotopes similar to those observed in the SLCP. For example, Fig. 5 shows the Os–Hf isotopic compositions of two cratonic peridotite xenolith suites from Wyoming [23] and Siberia [24]. Some of the Siberian and most of the Wyoming peridotites extend towards unradiogenic  $^{187}\text{Os}/^{188}\text{Os}$  and some have radiogenic Hf isotopic compositions, with a similar distribution to that of the SLCP. However, whereas portions of the Kerguelen Plateau have a seismic structure similar to continental passive margins [54], there is no seismic evidence to suggest the presence of continental lithosphere beneath the Hawaiian Islands. This and the isolation of the Hawaiian Islands in the middle of the Pacific plate, far removed from continental boundaries, make it highly unlikely that fragments of delaminated subcontinental lithosphere could be accidentally present within the Pacific mantle lithosphere under O’ahu.

The near total absence of the SLCP-like Os–Hf isotopic compositions from the present-day oceanic upper mantle, as sampled by MORB, OIB and abyssal peridotites, argues against the SLCP originating from present-day DMM or the 100 Ma old MORB-depleted Pacific lithosphere. Instead, the presence of these peridotites at the site of the Hawaiian plume, and on the apron of the Ko’olau caldera whose lavas are thought to sample recycled crustal material [3,4], suggests a possible genetic link with the Hawaiian plume. Another important feature of the SLC vs. the other post-erosional vents on O’ahu is the presence of garnet pyroxenites at SLC [10,14]. Thermobarometric calculations show that the SLC pyroxenites originate deeper (>60–90 km; [10,28,55]) than xenoliths from the other vents [19,28,55]. Also, the presence of garnets with majoritic precursors [27] and nanodiamonds [56] suggests that some of these pyroxenites may initially have originated from depths much greater than the thickness of the ~100 Ma old Pacific lithosphere (~100 km), possibly as deep as the transition zone.

We propose that the isotopically extreme SLCP are fragments of an ancient (>1 Ga) depleted lithospheric mantle that is part of the upwelling Hawaiian plume. This lithospheric mantle was created some 1–2 Ga ago as residue of variable degrees of melting, perhaps at a mid oceanic ridge setting. The depleted mantle lithosphere was eventually subducted back into the mantle along with the oceanic crust and both were later

incorporated within the upwelling Hawaiian plume. The proposed model requires a close spatial relationship between recycled crust and associated lithosphere in the upwelling Hawaiian plume. Farnetanni et al. [57] proposed that heterogeneities introduced into the source of a mantle plume (such as subducted oceanic crust and the accompanying depleted lithospheric mantle) will persist in the upwelling plume, but may undergo a series of stretching and folding events and be reduced to thin filaments. In this case, the package of subducted crust+lithosphere at the source of a plume may become a series of spatially related but dispersed pyroxenite and peridotite bodies as the upwelling plume material approaches the melting regime. Eventually, fragments of this lithosphere are brought to the surface by the rejuvenated stage volcanism and are seen in the SLCP xenoliths.

It could be argued that the SLCP represent delaminated subcontinental lithospheric mantle that is now present within the Hawaiian plume (as opposed to rafting in the upper mantle as described above). The subcontinental lithospheric mantle constitutes only about 2.5% of the total mantle, whereas it has been estimated that the mass of MORB-depleted lithosphere that could have been produced and recycled back into the mantle over the age of the Earth may be equivalent to ~80% of the total mantle mass [58]. It therefore appears far more likely that the ancient depleted lithosphere sampled by the SLCP represents recycled oceanic lithospheric mantle rather than delaminated subcontinental lithospheric mantle.

### 5.3. Implications for the composition of the Hawaiian plume and erupted lavas

The SLCP Hf–Os isotopic compositions provide the first direct evidence that *both* Hf and Os isotopes in oceanic mantle peridotites record ancient depletion events, unrelated to recent MORB or OIB magmatism, and can survive long-term storage and stirring in the mantle. However, if such material is present within the Hawaiian plume (or even dispersed in the upper mantle) it raises the question why such compositions are not readily recognized in Hawaiian lavas (or other MORB and OIB). The lack of such compositions in the erupted lavas can be explained by the depleted character of these peridotites. The major and trace element compositions of the SLCP overlap those of abyssal peridotites (Fig. 1), suggesting that they are residues of extensive melting, and trace element modeling suggests that some of these SLCP may represent up to 12% melt extraction from DMM-type mantle or up to 15% melt extraction from

PUM [13]. Melting experiments indicate that the peridotite solidus increases by *ca.* 7 °C for each 1% increment of melt extraction [59]. Therefore, the solidus of these SLCP may be more than 100 °C higher than that of PUM. We assume here that a mantle plume containing both depleted (SLCP-type) and fertile (PUM-type) peridotites upwells along an adiabat with a slope 10–12 °C/GPa, and that both peridotite solidi have a slope of 70 °C/GPa [60]. In this scenario, the SLCP-type depleted peridotite will start melting *ca.* 50 km shallower than the PUM-type fertile peridotite. Furthermore, if the fertile and depleted peridotites are in contact and can exchange heat within the upwelling mantle, the heat consumed by the deeper-melting fertile peridotite will further cool the accompanying depleted peridotite, resulting in even shallower onset of melt generation for the depleted peridotite [61]. This heat exchange also results in higher melt productivity for the fertile peridotite than the depleted peridotite [61]. If there are other more fertile materials within the plume (*i.e.* pyroxenite or eclogite) these differences in melt productivity and depth of melt initiation will be further exaggerated. Finally, the depleted peridotite also has low concentrations of incompatible trace elements (*e.g.* Sr, Nd, Pb and Hf) resulting in even lower concentrations in these elements in the melts produced from the depleted peridotite than melts of fertile peridotite. As a result, the isotopic composition of melts generated from a mixed fertile peridotite/depleted peridotite source will be predominantly controlled by the composition of the fertile component. In summary, depleted peridotites within upwelling mantle (plume or otherwise) may not significantly melt compared to the more fertile components and if they do, their trace element contribution to the erupted lavas will be minor. The refractory nature of melt-depleted peridotitic residues makes such components difficult to detect through conventional isotope studies of oceanic basalts, but their depleted signatures are preserved in their Hf–Os isotope systematics.

If the upper mantle P–T conditions are such that a depleted peridotite with extreme Hf–Os isotopes like the SLCP does melt, it will generate melts with high Hf/Os ratios, due to the relative compatibility of these elements in the mantle. Such melts will then be easier to detect in the Hf rather than the Os isotopic compositions of basalts. Recent Hf–Nd isotope studies of Hawaiian lavas [7,8] and garnet pyroxenite xenoliths of cumulate origin [28] have suggested the presence of a long-lived depleted component with relatively radiogenic Hf isotopic compositions, that is intrinsic to the Hawaiian plume. We propose here that the SLCP may be fragments of this inferred depleted plume component,

and that the contribution of depleted materials to the Hawaiian volcanism may not be as limited as previously thought.

#### 5.4. Erosion of the Pacific lithosphere by the Hawaiian plume

An important question is the depth of origin of the SLCP. If plume-related peridotitic material has been emplaced at lithospheric depths (*e.g.* <100 km) then this would be evidence for mechanical erosion and replacement of the lithosphere by the plume, with important implications for models of plume–lithosphere interaction and the origin of the Hawaiian swell [62,63]. The thickness of the Pacific lithosphere beneath the Big Island of Hawai‘i (present-day center of the Hawaiian plume) is about 90–110 km [63], and the undisturbed lithosphere around O‘ahu should be of similar thickness. Although there is no widely accepted barometer for the spinel peridotite mineralogy, the absence of garnet from all these peridotites, combined with two-pyroxene temperature estimates [64], can constrain their *maximum* depth of *last* equilibration. Both PK and SLC peridotites record similar temperatures of last equilibration ( $\sim 1000 \pm 100$  °C, Table A2). Close to the peridotite solidus, spinel is stable at up to 2.5–3.1 GPa (75–95 km depth) [59]. However, because the spinel–garnet transition has a positive Clapeyron slope [65,66] the spinel–garnet transition shifts to lower pressures with decreasing temperature. The absence of garnet from the O‘ahu peridotites, given these equilibration temperatures, suggests that their *maximum* depth of last equilibration is about  $60 \pm 10$  km (or  $2 \pm 0.3$  GPa), *i.e.* within lithospheric depths. If the depleted SLCP are pieces of the plume, as proposed here, then the Hawaiian plume may have eroded the Pacific lithosphere under O‘ahu by perhaps as much as 30 km. Although this statement can currently be made only for the lithosphere beneath the SLC vent, it is nevertheless in agreement with recent seismic evidence suggesting thinning of the Pacific lithosphere between O‘ahu and Kauai [63].

## 6. Conclusions

The combined highly unradiogenic  $^{187}\text{Os}/^{188}\text{Os}$  and radiogenic  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios of the SLCP xenoliths and their correlations with degree of melt depletion suggest that the SLCP are residues of an ancient melting event, unrelated to the 100 Ma Pacific lithosphere. We propose that these xenoliths represent pieces of ancient (perhaps as old as 2 Ga) recycled lithospheric mantle that are part of the Hawaiian plume and are brought to the surface by the

Hawaiian volcanism. The SLCP xenoliths are the first direct evidence for the presence of ancient depleted materials within the otherwise isotopically enriched Hawaiian plume. The absence of such extreme Hf and Os isotopic compositions in the erupted lavas is explained by the melt-depleted character of these peridotites. The melt-depletion leads to higher solidus temperatures and lower melt productivity in the depleted peridotites compared to other fertile components (peridotite and/or pyroxenite) within the upwelling plume, so that the depleted component is underrepresented in the compositions of the erupted lavas. If the isotopically enriched component observed in the Hawaiian lavas is recycled oceanic crust, then the presence of recycled lithospheric mantle in the plume suggests that crust and residual lithospheric mantle may remain coupled in the mantle for geologically long periods (>1 Ga). Thermobarometry shows that these xenoliths last equilibrated at depths  $<60 \pm 10$  km, shallower than the thickness of the undisturbed  $\sim 100$  Ma Pacific lithosphere, indicating erosion and partial replacement of the Pacific lithosphere by the Hawaiian plume.

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### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.epsl.2007.02.036](https://doi.org/10.1016/j.epsl.2007.02.036).

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