Geochemistry Geophysics Geosystems G3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 6, Number 1
26 February 2005
Q02L07, doi:10.1029/2004GC000757
ISSN: 1525-2027

Origin of depleted components in basalt related to the Hawaiian hot spot: Evidence from isotopic and incompatible element ratios

F. A. Frey and S. Huang
Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA (fafrey@mit.edu)

J. Blichert-Toft
Ecole Normale Supérieure de Lyon, 69364, Lyon Cedex 7, France

M. Regelous
Department of Earth Sciences, University of Bristol, Bristol, UK

Max Planck-Institut für Chemie, Postfach 3060, 55020, Mainz, Germany

M. Boyet
Ecole Normale Supérieure de Lyon, 69364, Lyon Cedex 7, France

[1] The radiogenic isotopic ratios of Sr, Nd, Hf, and Pb in basaltic lavas associated with major hot spots, such as Hawaii, document the geochemical heterogeneity of their mantle source. What processes created such heterogeneity? For Hawaiian lavas there has been extensive discussion of geochemically enriched source components, but relatively little attention has been given to the origin of depleted source components, that is, components with the lowest $^{87}Sr/^{86}Sr$ and highest $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$. The surprisingly important role of a depleted component in the source of the incompatible element-enriched, rejuvenated-stage Hawaiian lavas is well known. A depleted component also contributed significantly to the ~76–81 Ma lavas erupted at Detroit Seamount in the Emperor Seamount Chain. In both cases, major involvement of MORB-related depleted asthenosphere or lithosphere has been proposed. Detroit Seamount and rejuvenated-stage lavas, however, have important isotopic differences from most Pacific MORB. Specifically, they define trends to relatively unradiogenic Pb isotope ratios, and most Emperor Seamount lavas define a steep trend of $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$. In addition, lavas from Detroit Seamount and recent rejuvenated-stage lavas have relatively high Ba/Th, a characteristic of lavas associated with the Hawaiian hot spot. It is possible that a depleted component, intrinsic to the hot spot, has contributed to these young and old lavas related to the Hawaiian hot spot. The persistence of such a component over 80 Myr is consistent with a long-lived source, i.e., a plume.

Components: 11,586 words, 8 figures, 4 tables.

Keywords: Emperor Seamounts; Hawaiian hot spot; Hf isotopic ratio; mantle heterogeneity.

Index Terms: 1040 Geochemistry: Radiogenic isotope geochemistry; 1025 Geochemistry: Composition of the mantle; 1065 Geochemistry: Major and trace element geochemistry; 1212 Geodesy and Gravity: Earth's interior: composition and state (7207, 7208, 8105, 8124); 9355 Geographic Location: Pacific Ocean.

Received 10 May 2004; **Revised** 13 November 2004; **Accepted** 24 November 2004; **Published** 26 February 2005.

Frey, F. A., S. Huang, J. Blichert-Toft, M. Regelous, and M. Boyet (2005), Origin of depleted components in basalt related to the Hawaiian hot spot: Evidence from isotopic and incompatible element ratios, *Geochem. Geophys. Geosyst.*, *6*, Q02L07, doi:10.1029/2004GC000757.

Theme: Movement, Dynamics and Geochemical Evolution of the Hawaiian Hot Spot
Guest Editors: R. Duncan, J. A. Tarduno, D. Scholl, and T. Davies

1. Introduction

[2] The diverse geochemical characteristics of ocean island basalt (OIB) commonly attributed to mantle plumes, such as Iceland, Galapagos and Hawaii, reflect, in part, processes that create geochemical heterogeneity in the mantle. For example, geochemical data for such OIB have been used to argue that their mantle sources include materials recycled into the mantle at subduction zones, i.e., sediments, upper and lower igneous crust and lithospheric mantle [e.g., *Lassiter and Hauri*, 1998; *Blichert-Toft et al.*, 1999; *Chauvel and Hémond*, 2000; *Skovgaard et al.*, 2001; *Niu and O'Hara*, 2003]. Although the origin of enriched components, commonly referred to as EM1, EM2 and HIMU, in OIB has been discussed extensively [e.g., *Zindler and Hart*, 1986; *Hart*, 1988; *Hofmann*, 1997], the equally important role of depleted components in OIB has received less attention. Compared to primitive mantle, depleted components have relatively low $^{87}Sr/^{86}Sr$, high $^{143}Nd/^{144}Nd$ and high $^{176}Hf/^{177}Hf$.

[3] There has been controversy about the origin of depleted components in OIB. For Iceland, *Hanan et al.* [2000] argued that the depleted component is "the usual surrounding depleted MORB mantle source" (MORB designates mid-ocean ridge basalt). Recent papers, however, have emphasized geochemical differences between North Atlantic MORB and depleted Icelandic lavas. For example, *Thirlwall* [1995], *Kerr et al.* [1995], *Chauvel and Hémond* [2000], *Kempton et al.* [2000], *Skovgaard et al.* [2001], *Fitton et al.* [2003], and *Thirlwall et al.* [2004] all conclude that a depleted component is intrinsic to the Iceland plume. The origin of the depleted component expressed in lavas from the Galapagos Islands has also been debated. For example, *Blichert-Toft and White* [2001] concluded that "the Galapagos depleted component is so compositionally similar to the depleted upper mantle that it seems most likely that it is depleted upper mantle." In contrast, *Hoernle et al.* [2000, Figure 4] proposed that the depleted component is related to the Galapagos plume.

[4] Like the mantle sources of Icelandic and Galapagos lavas, the source of Hawaiian lavas is geochemically heterogeneous. The scale of this heterogeneity is reflected by geochemical variability within an individual Hawaiian volcano. For example, $^{87}Sr/^{86}Sr$ decreases and $^{143}Nd/^{144}Nd$ increases as Haleakala Volcano evolved from shield-stage to postshield-stage volcanism [*Chen and Frey*, 1985]. Furthermore at a given Hawaiian volcano, rejuvenated-stage lavas have the lowest $^{87}Sr/^{86}Sr$ and highest $^{143}Nd/^{144}Nd$. An important aspect of this temporal trend is the role of MORB-related depleted components, i.e., asthenospheric source of MORB or oceanic lithosphere. Since rejuvenated-stage lavas erupt after a volcano has migrated away from the hot spot, a common interpretation [e.g., *Chen and Frey*, 1985; *Yang et al.*, 2003] is that MORB-related asthenosphere or lithosphere was a source component.

[5] Studies of drill core from Detroit Seamount, a 76–81 Ma volcanic complex in the northern Emperor Seamount Chain [*Duncan and Keller*, 2004] document another example of a depleted source component in lavas attributed to the Hawaiian hot spot [*Keller et al.*, 2000; *Regelous et al.*, 2003; *Huang et al.*, 2005]. On the basis of the proximity of Detroit Seamount to a spreading ridge axis at ~80 Ma, two alternative hypotheses have been proposed. *Keller et al.* [2000] proposed that MORB volcanism at the spreading ridge dominated the magma flux originating from the hot spot. In contrast *Regelous et al.* [2003] emphasized that the trend to unradiogenic Pb isotopic ratios in Detroit Seamount lavas is unlike that of most Pacific MORB; they inferred that melting of a depleted plume component was facilitated by plume ascent beneath young and thin oceanic lithosphere. Using geochemical data for lavas from newly drilled sites on Detroit Seamount, *Huang et al.* [2005] evaluated these alternative hypotheses. They concurred with *Regelous et al.* [2003] that Pb isotopic data for lavas from Detroit Seamount define a trend to low $^{206}Pb/^{204}Pb$ that does not overlap with the field of Pacific MORB. However, *Huang et al.* [2005] noted that lavas erupted within the Garrett transform fault at 13°28′S on the East Pacific Rise (EPR) have lower Pb isotope ratios than the most extreme lavas from Detroit Seamount. Hence a suitably unradiogenic Pb component is

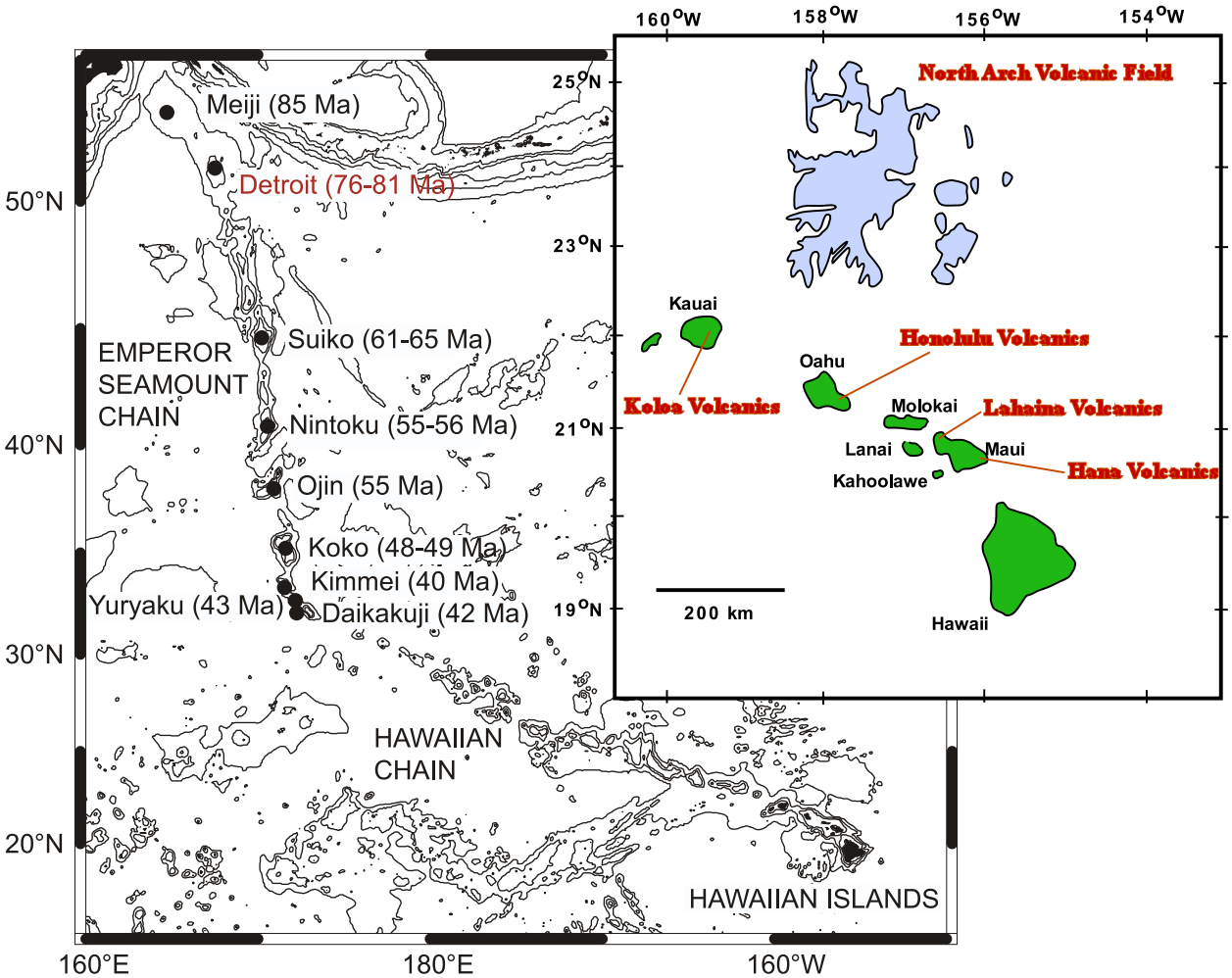

Figure 1. Map showing volcanoes along the Emperor Seamount Chain (eruption ages within parentheses). Inset shows the Hawaiian Islands and locations of rejuvenated-stage and North Arch lavas that have been analyzed for Hf isotopic ratios. Figure is modified from *Dixon and Clague* [2001] and *Regelous et al.* [2003] by adding Ar-Ar ages for Emperor Seamounts from *Sharp and Clague* [2002] and *Duncan and Keller* [2004].

present in the Pacific asthenosphere, but MORB with such unradiogenic Pb isotope ratios are uncommon [*Huang et al.*, 2005].

[6] We emphasize that there are similarities in Sr, Nd and Pb isotopic ratios between rejuvenated-stage lavas erupted at Hawaiian volcanoes and Detroit Seamount lavas. Note that in our discussion we include the geochemically similar North Arch lavas with rejuvenated-stage lavas [e.g., *Yang et al.*, 2003]. In this paper, we report Hf isotopic data for rejuvenated-stage and Emperor Seamount lavas. In our discussion, we use isotopic data for Sr, Nd, Hf and Pb and incompatible element abundance ratios to evaluate whether the depleted components that contributed to rejuvenated-stage lavas erupted in the Hawaiian Islands (<5 Ma) and lavas forming Detroit Seamount (76–81 Ma) are intrinsic to the Hawaiian plume.

2. Samples

[7] The samples studied range from some of the oldest lavas associated with the Hawaiian hot spot (Meiji, Detroit, and Suiko Seamounts) in the Emperor Seamount Chain to the relatively young rejuvenated-stage and North Arch lavas erupted in the Hawaiian Islands (Figure 1). All samples analyzed for Hf isotope ratios (Tables 1a and 1b) have been previously analyzed for Sr, Nd and Pb isotope ratios. They include 4 samples from Meiji Seamount obtained during DSDP Leg 19 [*Regelous et al.*, 2003], 28 samples recovered from Detroit Seamount on ODP Legs 145 and 197 [*Regelous et*

Table 1a. Hf Isotopic Ratios of North Arch and Hawaiian Rejuvenated-Stage Lavas

	Sample	$^{176}Hf/^{177}Hf$	2-sigma	Lu/Hf
North Arch[a]				
Alkalic basalt	F11-88-HW 21D-5	0.283181	0.000006	0.072
Alkalic basalt	F11-88-HW 22D-2	0.283188	0.000007	0.13
Alkalic basalt	F11-88-HW 23D-6	0.283188	0.000008	0.036
Alkalic basalt	F11-88-HW 36D	0.283176	0.000005	0.078
Honolulu[b]				
Alkalic basalt	Kalama	0.283175	0.000010	
Alkalic basalt	Kaupo	0.283159	0.000012	
Basanite	BP-F1	0.283156	0.000008	
Basanite	Makuku	0.283171	0.000010	
Nepheline melilitite	PF-1	0.283180	0.000008	
Nephelinite	Ainoni	0.283168	0.000010	
Nephelinite	Kamanaiki-A	0.283183	0.000010	
Nephelinite	Kamanaiki-B	0.283151	0.000011	
Nepheline melilitite	Rocky Hill	0.283179	0.000007	
Koloa[c]				
Basanite	94-PRKP-4	0.283137	0.000006	
Basanite	94-PRKP-6	0.283148	0.000008	
Basanite	94-PRKP-12	0.283149	0.000007	
Basanite	94-PRKP-14	0.283156	0.000008	
Nephelinite	95-HTZ-525	0.283121	0.000016	
Nephelinite	95-HTZ-525 dup	0.283122	0.000011	
Alkalic basalt	95-HTZ-1000	0.283189	0.000007	
Hana[d]				
Alkalic basalt	H62-47	0.283180	0.000005	0.049

[a] Major and trace element analyses and Sr and Pb isotopic ratios for these samples are reported by *Clague et al.* [1990] and *Frey et al.* [2000].
[b] Sr, Nd, and Pb isotopic ratios are reported by *Lassiter et al.* [2000], except for Sample PF-1, which has $^{87}Sr/^{86}Sr = 0.70335$, $^{143}Nd/^{144}Nd = 0.513050$, $^{206}Pb/^{204}Pb = 18.05$, $^{207}Pb/^{204}Pb = 15.44$, and $^{208}Pb/^{204}Pb = 37.71$ (J. Lassiter, unpublished data).
[c] Major and trace element analyses and Sr, Nd, and Pb isotoic ratios are reported by *Reiners and Nelson* [1998].
[d] Hf isotopic datum reported by *Blichert-Toft et al.* [1999]. Major and trace element analyses and Sr, Nd isotopic data are reported by *Chen et al.* [1990]. Sr, Nd, and Hf isotopic data for Hana lavas are also reported by *Stracke et al.* [1999]. Note that the Hana Volcanics have been reclassified as postshield lavas [*Sherrod et al.*, 2003]. We include them because they define the extreme isotope ratios for Haleakala volcano.

al., 2003; *Huang et al.*, 2005], 4 samples from Suiko Seamount obtained during DSDP Leg 55 [*Lanphere et al.*, 1980], 16 samples from rejuvenated-stage lavas, 9 from the Honolulu Volcanics, 7 from the Koloa Volcanics [*Reiners and Nelson*, 1998; *Lassiter et al.*, 2000], and 4 samples from the North Arch volcanic field which are geochemically similar to rejuvenated-stage lavas [*Frey et al.*, 2000; *Yang et al.*, 2003]. In addition, garnet and clinopyroxene separates from three garnet pyroxenite xenoliths from Salt Lake Crater, Oahu were analyzed for Hf and Nd isotopic ratios.

3. Analytical Procedure

[8] Following the procedures described by *Blichert-Toft et al.* [1997], Hf isotopic compositions were measured by MC-ICP-MS using a VG Plasma 54 at the Ecole Normale Supérieure in Lyon, France. In order to monitor machine performance, the JMC-475 Hf standard was analyzed after every two samples and gave 0.282160 ± 0.000010 (2 sigma) for $^{176}Hf/^{177}Hf$ throughout this study, corresponding to an external reproducibility of 35 ppm. $^{176}Hf/^{177}Hf$ was normalized for mass fractionation relative to $^{179}Hf/^{177}Hf = 0.7325$. Hafnium total procedural blanks were less then 25 pg. Uncertainties reported on Hf measured isotope ratios are in-run $2\sigma/\sqrt{n}$ analytical errors, where n is the number of measured isotope ratios (Tables 1a and 1b).

[9] For Hf and Nd isotope analysis 100–200 mg of garnet and clinopyroxene were separated from three garnet pyroxenite xenoliths collected at Salt Lake Crater, Oahu (Table 2). Grains with inclusions were excluded. In order to minimize blank levels, the hand-picked minerals were not crushed, but dissolved whole. Prior to dissolution, the mineral grains were acid leached in an ultrasonic bath using both HF and HCl to eliminate grain coatings. Due to the refractory nature of garnet, the garnet separates were dissolved in steel-jacketed Teflon bombs at 160°C for one week. For consistency, the clinopyroxene separates were treated similarly. Upon complete dissolution, a Hf-bearing

Table 1b. Hf Isotopic Ratios of Emperor Seamount Lavas

	Sample	$^{176}Hf/^{177}Hf$	2-sigma	Lu/Hf	Initial $^{176}Hf/^{177}Hf$	2-sigma
Suiko Seamount (65 Ma)[a]						
Tholeiitic basalt	DSDP 55-433C-13-2:55-56	0.283115	0.000005	0.082	0.283100	0.000005
Tholeiitic basalt	DSDP 55-433C-19-5:57-65	0.283122	0.000004	0.097	0.283105	0.000004
Tholeiitic basalt	DSDP 55-433C-39-5:87-94	0.283111	0.000004	0.080	0.283097	0.000004
Tholeiitic basalt	DSDP 55-433C-42-1:56-63	0.283117	0.000004	0.089	0.283101	0.000004
Detroit Seamount: Site 883 (76 Ma)[b]						
Alkalic basalt	145-1	0.283113	0.000006	0.13	0.283087	0.000006
Alkalic basalt	145-2	0.283100	0.000006	0.12	0.283076	0.000006
Alkalic basalt	145-3	0.283104	0.000005	0.12	0.283079	0.000005
Alkalic basalt	145-4	0.283112	0.000006	0.12	0.283088	0.000006
Alkalic basalt	145-5	0.283107	0.000006	0.13	0.283081	0.000006
Alkalic basalt	145-6	0.283108	0.000006	0.12	0.283084	0.000006
Detroit Seamount: Site 1203 (76 Ma)[c]						
Tholeiitic basalt	1203A17R4W43-47, Unit 1	0.283103	0.000003	0.12	0.283078	0.000003
Tholeiitic basalt	1203A20R3W10-14, Unit 3	0.283100	0.000003	0.12	0.283075	0.000003
Tholeiitic basalt	1203A31R1W46-50, Unit 8	0.283127	0.000003	0.12	0.283102	0.000003
Tholeiitic basalt	1203A32R4W76-80, Unit 11	0.283106	0.000004	0.13	0.283080	0.000004
Tholeiitic basalt	1203A38R1W123-126, Unit 16	0.283138	0.000004	0.14	0.283109	0.000004
Tholeiitic basalt	1203A49R3W50-54, Unit 21	0.283126	0.000004	0.14	0.283098	0.000004
Tholeiitic basalt	1203A59R2W69-73, Unit 24	0.283099	0.000004	0.13	0.283073	0.000004
Tholeiitic basalt	1203A68R4W40-43, Unit 31B	0.283137	0.000006	0.14	0.283109	0.000006
Alkalic basalt	1203A54R4W74-78, Unit 23	0.283087	0.000003	0.11	0.283064	0.000003
Alkalic basalt	1203A63R4W19-22, Unit 26	0.283071	0.000004	0.10	0.283051	0.000004
Aalkalic basalt	1203A65R4W9-13, Unit 29	0.283102	0.000005	0.11	0.283079	0.000005
Alkalic basalt	1203A66R2W8-10, Unit 30	0.283090	0.000005	0.11	0.283067	0.000005
Detroit Seamount: Site 1204 (76 Ma)[c]						
Alkalic basalt	1204A10R2W108-112, Unit 1	0.283170	0.000004	0.13	0.283144	0.000004
Alkalic basalt	1204B3R2W41-44, Unit 1	0.283165	0.000006	0.14	0.283138	0.000006
Alkalic basalt	1204B7R3W68-72, Unit 2A	0.283175	0.000006	0.14	0.283147	0.000006
Alkalic basalt	1204B10R4W43-47, Unit 2B	0.283162	0.000006	0.13	0.283136	0.000006
Alkalic basalt	1204B17R1W107-110, Unit 3	0.283157	0.000007	0.13	0.283131	0.000007
Detroit Seamount: Site 884 (81 Ma)[b]						
Tholeiitic basalt	145-7	0.283178	0.000006	0.20	0.283135	0.000006
Tholeiitic basalt	145-8	0.283174	0.000008	0.20	0.283130	0.000008
Tholeiitic basalt	145-9	0.283194	0.000006	0.21	0.283149	0.000006
Tholeiitic basalt	145-10	0.283185	0.000007	0.21	0.283139	0.000007
Tholeiitic basalt	145-11	0.283199	0.000011	0.20	0.283156	0.000011
Meiji Seamount (85 Ma)[b]						
Alkalic basalt	19-1	0.283081	0.000006	0.13	0.283050	0.000006
Alkalic basalt	19-2	0.283079	0.000005	0.12	0.283051	0.000005
Alkalic basalt	19-3	0.283068	0.000006	0.14	0.283036	0.000006
Alkalic basalt	19-4	0.283072	0.000006	0.14	0.283040	0.000006

[a] Major and trace element data are reported by *Kirkpatrick et al.* [1980] and *Clague and Frey* [1980]. Nd isotopic ratios in Figures 5b and 5c are unpublished data of F. A. Frey.

[b] Major and trace element data and Sr, Nd, and Pb isotopic ratios are reported by *Regelous et al.* [2003], except new Nd data for samples 145-5 and -6, which are given in the Figures 5a–5d caption.

[c] Major and trace element data and Sr, Nd, and Pb isotopic ratios are reported by *Huang et al.* [2005].

Table 2. Nd-Hf Isotopic Ratios of Clinopyroxene and Garnet From Salt Lake Crater Garnet Pyroxenite Xenoliths

Sample	Mineral	$^{143}Nd/^{144}Nd$	2-sigma	$^{176}Hf/^{177}Hf$	2-sigma
3B9	garnet	0.512867	0.000016	0.283145	0.000024
	clinopyroxene	0.513010	0.000010	0.283154	0.000008
3B11	garnet	0.512920	0.000024	0.283166	0.000019
	clinopyroxene	0.513027	0.000024	0.283132	0.000011
3B15	garnet	0.513026	0.000025	0.283141	0.000013
	clinopyroxene	0.513031	0.000013	0.283153	0.000009

fraction was first separated from a REE-bearing fraction on a cation-exchange column. Nd was subsequently isolated from the latter on an HDEHP column, while Hf was further purified, first through an anion-exchange column to remove remaining matrix elements, then through a cation-exchange column serving to separate Ti and some Zr from the Hf [*Blichert-Toft et al.*, 1997, 2002; *Blichert-Toft*, 2001]. Total procedural Nd and Hf blanks were <200 and <25 pg, respectively.

[10] Isotopic analyses of Nd were carried out by MC-ICP-MS on the VG Plasma 54 instrument in Lyon following the procedures described by *Blichert-Toft et al.* [2002]. In order to monitor machine performance, the La Jolla standard was run systematically before and after each sample and gave, throughout this study, 0.511858 ± 0.000018 for $^{143}Nd/^{144}Nd$ (two standard deviations), corresponding to an external reproducibility of 35 ppm.

4. Results

4.1. Comparison of Isotopic Data (Sr, Nd, Hf, and Pb) for Rejuvenated-Stage/North Arch and Detroit Seamount Lavas

[11] Figure 2a shows the well-known observation that despite their relative enrichment in highly incompatible elements, the alkalic rejuvenated-stage and North Arch samples have lower $^{87}Sr/^{86}Sr$

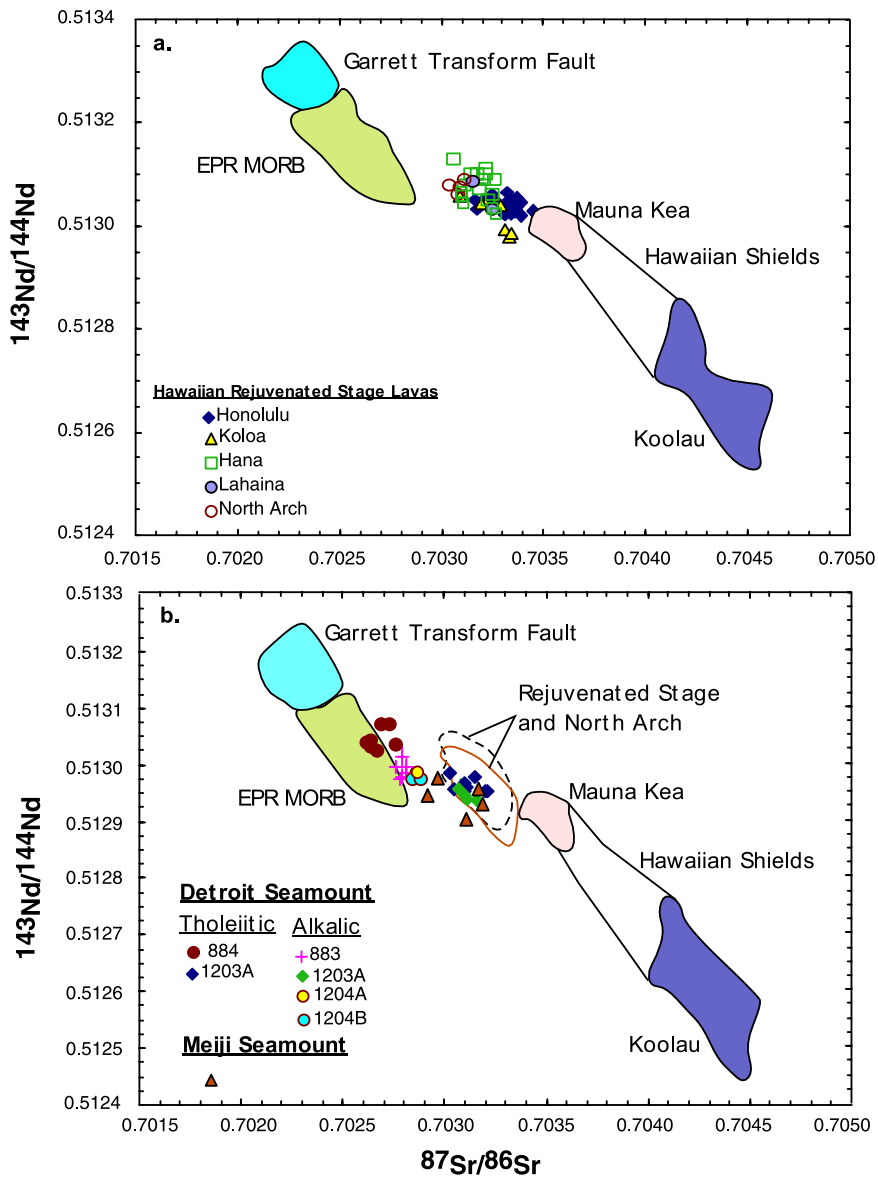

Figure 2

Table 3. Parent/Daughter Ratios Used to Calculate Initial Ratios for Fields in Figures 2–6

	Koolau	Mauna Kea	EPR-MORB	GTF[a]	Mauna Loa	Kahoolawe
Rb/Sr	0.015	0.021	0.0062	0.0040	–	–
Sm/Nd	0.26	0.27	0.36	0.39	0.28	0.28
Th/Pb	0.52	0.97	0.40	0.22	0.55	–
U/Pb	0.15	0.31	0.16	0.15	0.17	0.15
Lu/Hf	0.074	0.074	0.22	0.23	0.090	0.078

[a] GTF, Garrett transform fault lavas.

and trend to higher $^{143}Nd/^{144}Nd$ than the field for tholeiitic Hawaiian shield lavas. Relative to the EPR MORB field they have higher $^{87}Sr/^{86}Sr$ and trend to lower $^{143}Nd/^{144}Nd$; consequently, the field for EPR MORB does not lie on an extrapolation of the Hawaiian field (Figure 2a; see Table 3).

[12] Figure 2b shows that lavas from Detroit Seamount range from overlap with the field for rejuvenated-stage/North Arch lavas to overlap with the EPR MORB field. Although most lavas from Detroit Seamount are also slightly offset from the MORB field to high $^{87}Sr/^{86}Sr$, this offset is dependent upon the age corrections. The isotopic overlap of Site 1203 lavas, a 453 m section of Detroit Seamount with tholeiitic basalt overlying alkalic basalt [*Huang et al.*, 2005], with the field for alkalic, rejuvenated-stage/North Arch lavas is surprising. The simplest inference is mixing between MORB-related and plume-related components. At Detroit Seamount an important role for a MORB component is consistent with the proximity of the plume to a spreading ridge center at ~80 Ma [*Keller et al.*, 2000]. For rejuvenated-stage lavas involvement of MORB-related asthenosphere or lithosphere has been proposed as the volcano migrates away from the hot spot [e.g., *Chen and Frey*, 1985; *Reiners and Nelson*, 1998; *Yang et al.*, 2003].

[13] Although Sr-Nd isotopic variations are consistent with a MORB-related component, plots of Pb isotopic ratios show that the fields for rejuvenated-

Figure 2. Values of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ showing fields for lavas from Hawaiian shields, EPR MORB, and Garrett transform fault. In this and subsequent isotopic ratio figures (Figures 2–6), a two sigma error bar is indicated unless the symbol is larger than the error bar. Data for lavas erupted within the Garrett transform fault, ~13°30′S on the East Pacific Rise, are plotted as a separate field because as shown in Figures 3a–3e they have significantly lower Pb isotopic ratios than most Pacific MORB. Data sources for fields in both panels are as follows: Koolau [*Roden et al.*, 1994; *Lassiter and Hauri*, 1998], Mauna Kea [*Lassiter et al.*, 1996; J. G. Bryce et al., Sr, Nd, and Os isotopes in a 2.84 km section of Mauna Kea Volcano: Implications for the geochemical structure of the Hawaiian plume, submitted to *Geochemistry, Geophysics, Geosystems*, 2004]; EPR MORB [*Niu et al.*, 1999; *Regelous et al.*, 1999; *Castillo et al.*, 2000]; Garrett transform fault [*Wendt et al.*, 1999]. (a) Data points for rejuvenated-stage and North Arch lavas. Data sources are *Stille et al.* [1983], *Roden et al.* [1984], *Chen and Frey* [1985], *Tatsumoto et al.* [1987], *West et al.* [1987], *Reiners and Nelson* [1998], *Stracke et al.* [1999], and *Frey et al.* [2000]. Although the Hana Volcanics at Haleakala Volcano have been reclassified as postshield lavas [*Sherrod et al.*, 2003], we include them here because in terms of Sr and Nd isotopic ratios, they define the depleted extreme for Haleakala lavas. Also they overlap with data for rejuvenated-stage lavas from other volcanoes. (b) Data points for Detroit Seamount lavas from *Keller et al.* [2000], *Regelous et al.* [2003], and *Huang et al.* [2005]. Site 883, 1203, and 1204 lavas are age-corrected to 76 Ma [*Duncan and Keller*, 2004]; Site 884 lavas are corrected to 81 Ma, and Meiji lavas are corrected to 85 Ma [*Keller et al.*, 2000]. Age corrections in general use parent/daughter ratio of acid-leached samples (see *Huang et al.* [2005] for details). The fields for Hawaiian shields, EPR MORB, and Garrett transform fault are age-corrected to 76 Ma. The parent/daughter ratios for these age corrections in Figures 2b, 3b, 3d, 4b, 5b, and 6b should be those of the magma source. As a crude estimate of these ratios for tholeiitic basalt, we use average parent/daughter ratios in unaltered lavas (see Table 3). For the Sr and Pb isotopic systems, this approach leads to overestimates for the age correction, and for the Nd and Hf isotopic systems the age corrections are underestimates. Parent/daughter ratios in Koolau, Mauna Kea, Kahoolawe, and Mauna Loa lavas are average values of relatively unaltered samples ($K_2O/P_2O_5 > 1.3$) from *Huang and Frey* [2003], S. Huang and F. A. Frey (Temporal geochemical variation within the Koolau shield: A trace element perspective, submitted to *Contributions to Mineralogy and Petrology*, 2004), S. Huang (unpublished), and *Hofmann and Jochum* [1996], respectively. Parent/daughter ratios in EPR-MORB are average N-MORB values from *Sun and McDonough* [1989]. Parent/daughter ratios in Garrett transform fault lavas are average values of lavas with $^{206}Pb/^{204}Pb < 18$ [*Wendt et al.*, 1999]. Because rejuvenated-stage and North Arch alkalic basalt were formed by low extents of melting [e.g., *Yang et al.*, 2003], which may lead to significant changes in parent/daughter ratios, we used two sets of parent/daughter ratios for Hawaiian Rejuvenated-Stage lavas: EPR-MORB values for the orange solid line and Mauna Kea values for the black dashed line. Parent/daughter ratios are shown in Table 3.

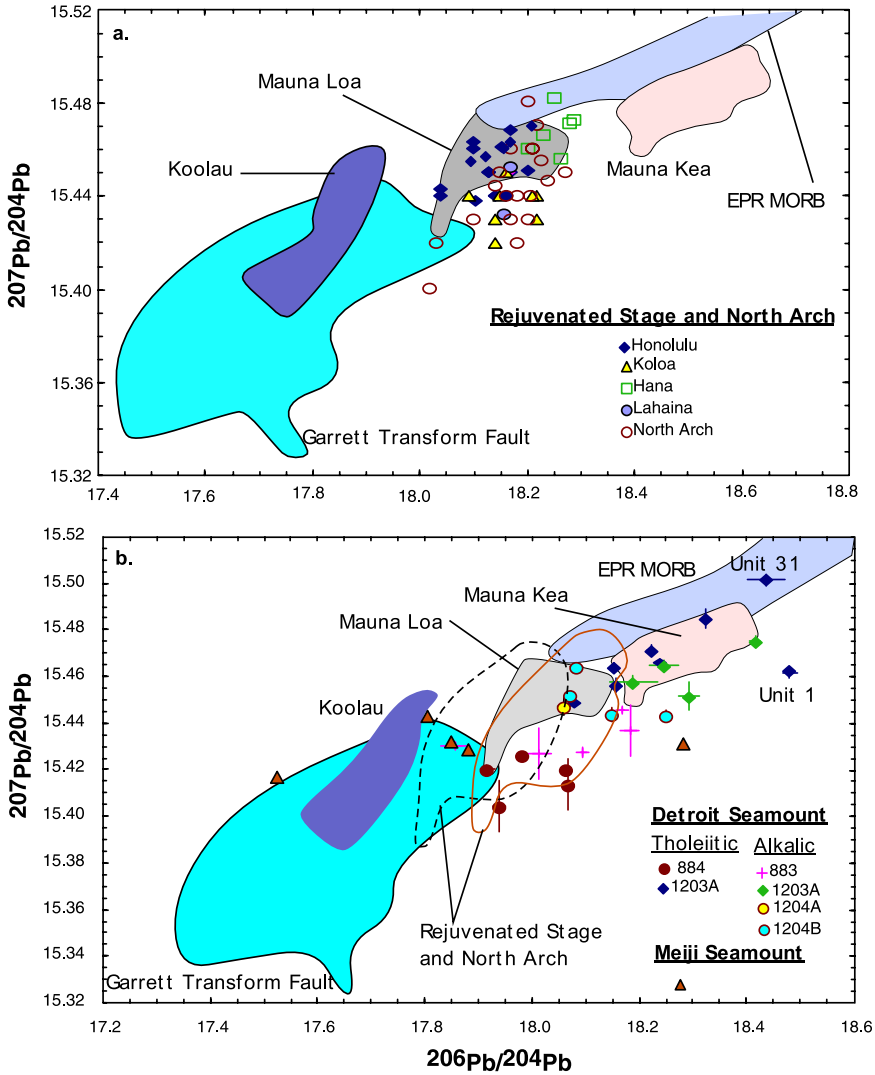

Figure 3. Values of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ showing fields for lavas from three Hawaiian shields, EPR MORB, and Garrett transform fault (see Figure 2 caption for GTF and Koolau data sources). Mauna Loa and Mauna Kea data are from *Abouchami et al.* [2000] and *Eisele et al.* [2003]. EPR MORB field in Figures 3a, 3b, 3c, and 3d is from *Regelous et al.* [2003] using unpublished triple-spike data of *Galer et al.* [1999]. This field is used because the data are more precise than literature data obtained in several laboratories over many years (see Figure 3e). (a and c) Data points for rejuvenated-stage and North Arch lavas (*Lassiter et al.* [2000], Kani et al. (submitted manuscript, 2004), and references in Figure 2 caption). (b and d) Data points for lavas from Detroit and Meiji Seamounts corrected to their eruption ages. See Figure 2 caption for data references and procedures used to calculate initial ratios. In subsequent plots we do not show Pb data for Meiji lavas because of uncertainty about age corrections (see section 4.2). (e) Values of $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ for young Pacific MORB. Data are downloaded from PET DB. Data for older Pacific MORB fall within this field [*Huang et al.*, 2005]. The red field, labeled "TS MORB," is the EPR MORB field shown in Figures 3a to 3d and is defined by data obtained using the high-precision triple-spike technique [*Galer et al.*, 1999]. This field is representative of Pacific MORB; however, it does not include the extreme ratios. The low $^{206}Pb/^{204}Pb$ (<18) end of the Pacific MORB field is dominated by Garrett transform fault lavas [*Wendt et al.*, 1999]; that is, 12 of the 25 MORB samples with $^{206}Pb/^{204}Pb < 18$ are from the spreading center within the Garrett transform fault. Of the remaining 13 MORB with $^{206}Pb/^{204}Pb < 18$, 10 are from atypical locations such as the Chile Ridge [*Sturm et al.*, 1999].

stage/North Arch lavas and Detroit Seamount lavas range to nonradiogenic ratios that are not typical of EPR MORB (Figures 3a–3e) [*Regelous et al.*, 2003; *Huang et al.*, 2005]. Such low ratios are characteristic of lavas erupted at a spreading center within the Garrett transform fault, but the rarity of such MORB (Figure 3e; see *Huang et al.* [2005] for a detailed discussion) have led to alternative

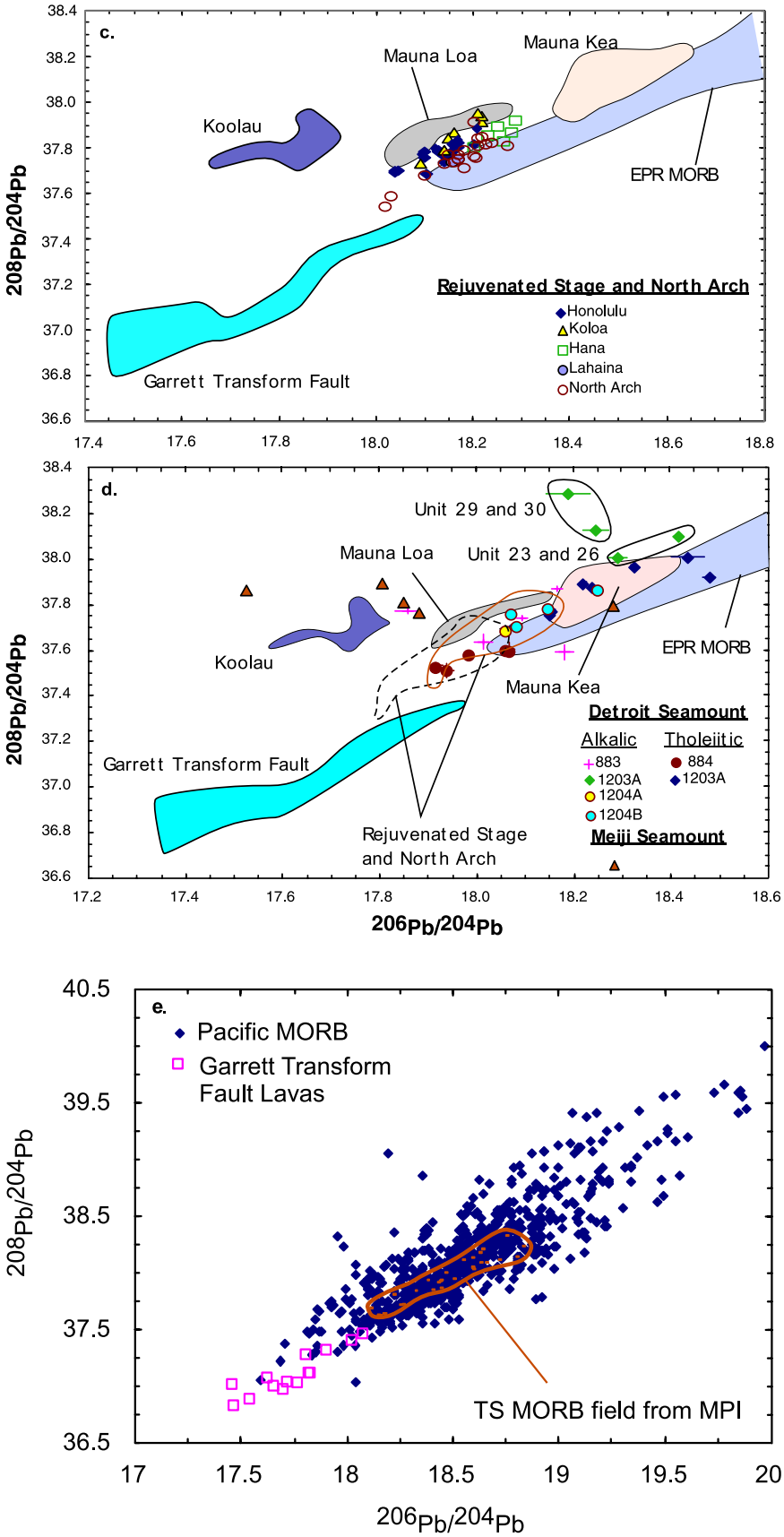

Figure 3. (continued)

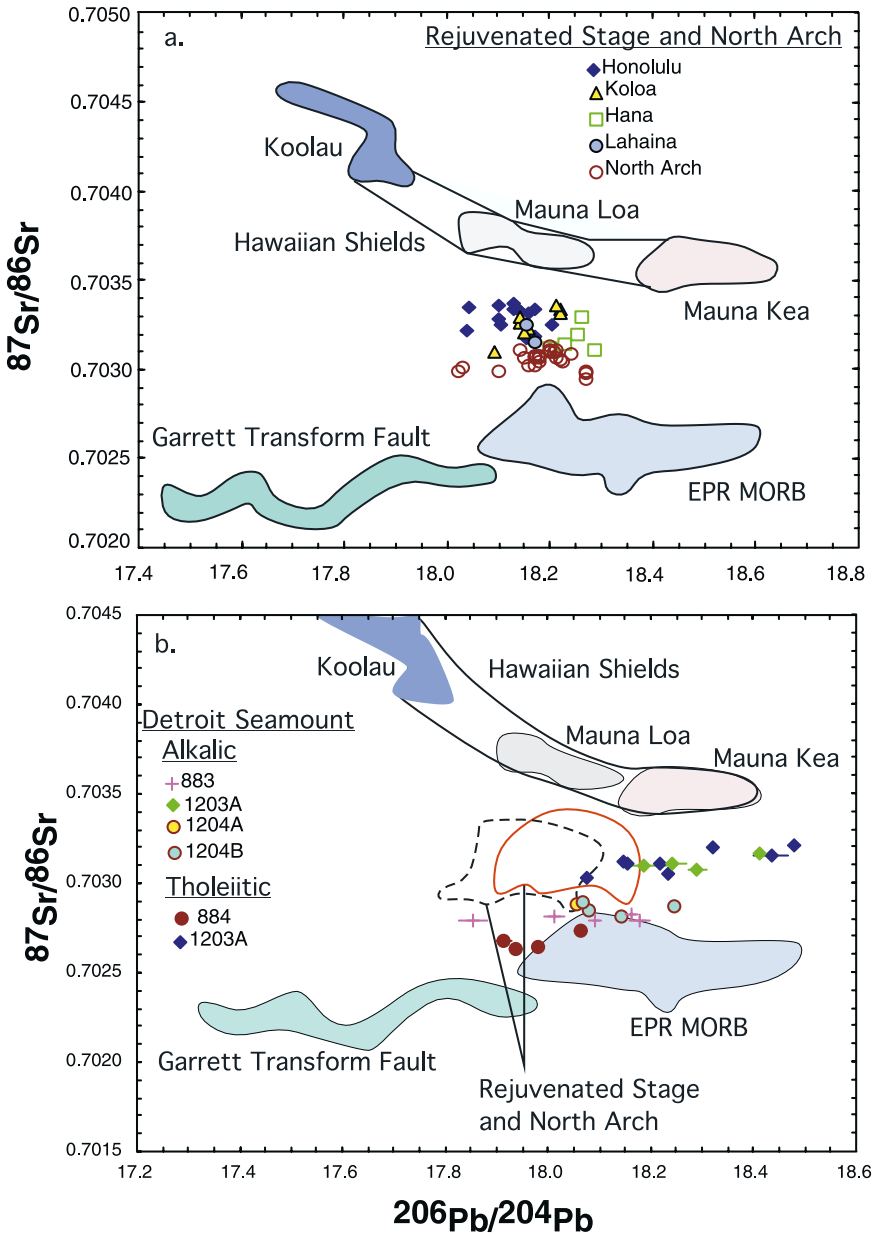

Figure 4. Values of $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ showing fields for lavas from Hawaiian shields, EPR MORB, and Garrett transform fault (for data references, see Figure 2 and Figures 3a–3e captions). (a) Data points for rejuvenated-stage and North Arch lavas. (b) Data points for lavas from Detroit Seamount corrected to their eruption age. See Figure 2 and Figures 3a–3e captions for data references and procedures used to calculate initial ratios.

proposals. For Detroit Seamount, *Regelous et al.* [2003] proposed that higher extents of melting below a young and thin oceanic lithosphere enabled sampling of a depleted plume component with relatively low Pb isotopic ratios. Similarly, the Pb isotopic trends for rejuvenated-stage and North Arch lavas have led to the conclusion that a MORB-related component is not the depleted component present in these lavas (*Fekiacova and Abouchami* [2003] and T. Kani et al. (Multiple components involved in North Arch volcanism, Hawaii: Evidence from Pb and Sr isotope compositions of submarine lavas, submitted to *Journal of Petrology*, 2004; hereinafter referred to as Kani et al., submitted manuscript, 2004), respectively).

[14] Tholeiitic basalt forming the Hawaiian shields defines a negative $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ trend (Figure 4). In contrast, *West et al.* [1987, Figure 3] noted that postshield alkalic lavas from Haleakala volcano define a positive $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ trend, and they inferred that these

alkalic lavas contain a depleted mantle component that is not present in shield lavas. Is this depleted mantle component related to EPR MORB? The field for rejuvenated-stage lavas shows variable $^{206}Pb/^{204}Pb$ at relatively uniform $^{87}Sr/^{86}Sr$; i.e., there is no trend toward the EPR MORB field (Figure 4a). The positive $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ trend defined by lavas from Detroit Seamount clearly extends to lower $^{206}Pb/^{204}Pb$ than the EPR MORB field (Figure 4b). As in Figures 3a–3e, Detroit Seamount lavas extend toward the field for lavas erupted within the Garrett transform fault.

[15] The $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$ trend has provided the strongest evidence that the depleted Icelandic component is unlike MORB [e.g., *Kempton et al.*, 2000; *Fitton et al.*, 2003]; namely depleted Icelandic basalt has higher $^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$ than the field for North Atlantic MORB (filtered to exclude Hf isotopic ratios whose within-run standard errors are >100 ppm [see *Fitton et al.*, 2003, Figure 4]). Although the Pacific MORB field for $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$ is large with numerous outlier points, it is not significantly decreased by using the data quality filter of *Fitton et al.* [2003] (see Figure 5a). In Figures 5a–5d, rejuvenated-stage Hawaiian lavas are within the broad positive trend defined by Hawaiian shield lavas and Pacific MORB. *Bizimis et al.* [2003a, p. 56] noted that data (six samples) for the Honolulu Volcanics from *Stille et al.* [1983] define a significantly steeper $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$ slope than the OIB/MORB array. However, our new and significantly more precise Hf data (9 samples) for the Honolulu Volcanics do not confirm this steep slope (Figure 5d). In general, however, rejuvenated-stage

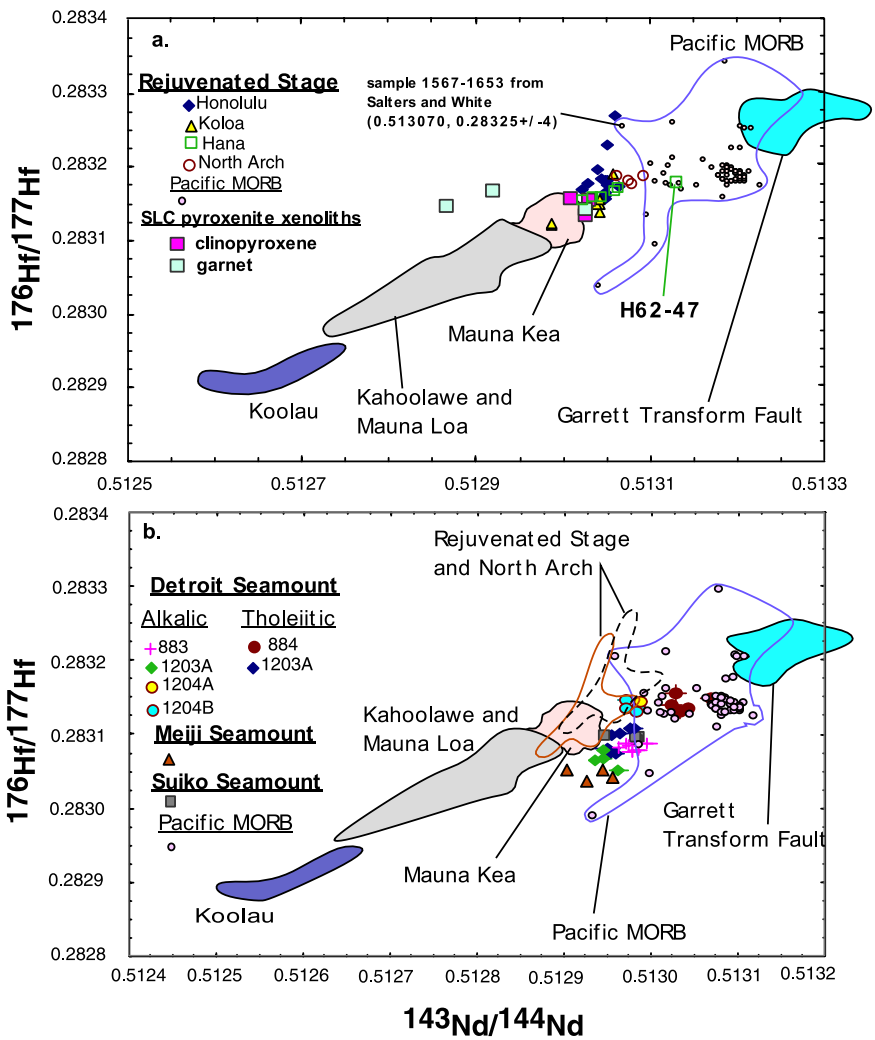

Figure 5

lavas overlap with the Pacific MORB field in $^{176}Hf/^{177}Hf$ but are offset to lower $^{143}Nd/^{144}Nd$ (Figures 5a–5d).

[16] Among Emperor Seamount lavas, Site 884 lavas are distinct in that they plot within the Pacific MORB field (Figure 5b). In contrast, samples from Sites 883, 1203 and 1204 on Detroit Seamount and Meiji and Suiko Seamounts are at the low $^{143}Nd/^{144}Nd$ boundary of the Pacific MORB field, and they define a steeper $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$ trend than the mantle array defined by most OIB and MORB (Figure 5b). Similarly steep Hf-Nd isotope ratio trends have been reported for Emperor Seamount lavas by *Kempton and Barry* [2001], *Kempton et al.* [2002], and *Thompson et al.* [2002]. A steep trend extrapolating to high $^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$ suggests that, like depleted Icelandic lavas [*Fitton et al.*, 2003, and references therein], these Emperor Seamount lavas sampled a depleted component that is geochemically distinct from the depleted MORB source. At the low $^{176}Hf/^{177}Hf$ end of the Emperor Seamount array, lavas from Meiji Seamount and Site 1203, especially the alkalic lavas, trend to lower $^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$ than the trend of Hawaiian shield lavas. Finally, compared to the field for rejuvenated-stage lavas, Emperor Seamount lavas, except those from Site 884 at Detroit Seamount, are offset to lower $^{176}Hf/^{177}Hf$ at similar $^{143}Nd/^{144}Nd$; this offset is not a result of age corrections (Figures 5c and 5d).

[17] *Blichert-Toft et al.* [1999] showed that Hawaiian shield lavas define a hyperbolic trend in plots of $^{176}Hf/^{177}Hf$ versus $^{206}Pb/^{204}Pb$, e.g., the trend defined by fields for Koolau, Kahoolawe, Mauna Loa and Mauna Kea in Figure 6a. Because the nearly uniform $^{176}Hf/^{177}Hf$ at the high $^{206}Pb/^{204}Pb$ end of this hyperbola is less than that of most MORB (Figure 6a), *Blichert-Toft et al.* [1999] concluded that the depleted component in Hawaiian shield lavas (e.g., Mauna Kea lavas with relatively low $^{87}Sr/^{86}Sr$, high $^{143}Nd/^{144}Nd$ and high

Figure 5. Values of $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$ showing fields for Hawaiian shields, EPR MORB, and Garrett fracture zone lavas. See Figure 2 caption for sources of Nd data, except for two new analyses of Site 883 samples (145-5 and 145-6) by Regelous. The measured $^{143}Nd/^{144}Nd$ values in these two samples (unleached whole rock) are 0.513056 and 0.513066, respectively. Hf data for Hawaiian lavas are from *Blichert-Toft et al.* [1999, 2003], plus data from *Stille et al.* [1983] and *Stracke et al.* [1999], both adjusted to a JMC-475 Hf standard value of $^{176}Hf/^{177}Hf$ = 0.282160. Hf data for Pacific MORB are from *Nowell et al.* [1998], *Salters and White* [1998], *Chauvel and Blichert-Toft* [2001], and *Sims et al.* [2002, 2003]. The MORB sample (1567–1653) with the largest uncertainty in $^{176}Hf/^{177}Hf$ is labeled. Field for Garrett transform fault in Figures 5 and 6 is defined by 14 samples (one each from *Nowell et al.* [1998] and *Chauvel and Blichert-Toft* [2001] and 12 unpublished $^{176}Hf/^{177}Hf$ from Blichert-Toft for samples analyzed by *Wendt et al.* [1999]). (a) Data points for rejuvenated-stage and North Arch lavas (all Hf data from Table 1 plus data for 5 Hana samples from *Stracke et al.* [1999] and 6 Honolulu Volcanics samples from *Stille et al.* [1983]). Garnet and clinopyroxene data for SLC garnet pyroxenite xenoliths from Table 2. (b) Data points for lavas from Detroit and Meiji Seamounts corrected to their eruption ages. See Figure 2 caption for procedures used to calculate initial ratios. All Hf data from Table 1. (c) In order to avoid uncertainties in age corrections resulting from estimated parent/daughter ratios for rejuvenated-stage lavas, in this panel we age-correct old Detroit Seamount data to present-day. If we assume that the melting process did not fractionate Sm/Nd and Lu/Hf and that these two isotopic systems were not affected by alteration processes, the present-day values of Nd-Hf isotopic ratios in the sources should be the same as that in the unleached whole rocks. Hf data for all Emperor Seamount lavas and Nd data for Suiko, Detroit Seamount Sites 883 and 884, and Meiji lavas were obtained on unleached whole rocks; consequently, measured data are plotted in this panel. Because Nd data for Sites 1203 and 1204 lavas were obtained on acid-leached samples, we use the calculated initial $^{143}Nd/^{144}Nd$, based on measured $^{143}Nd/^{144}Nd$ and Sm/Nd of acid-leached samples [*Huang et al.*, 2005], and the Sm/Nd of unleached whole rocks to calculate present-day unleached whole rock values. Both measured and age-corrected data for Site 884 lavas are well within the Pacific MORB field. Relative to the field for rejuvenated-stage/North Arch lavas, at a given $^{143}Nd/^{144}Nd$, most Detroit and all Meiji lavas are offset to lower $^{176}Hf/^{177}Hf$. Given that the measured isotopic ratios of Emperor Seamount lavas are minimum estimates of the present-day source, i.e., partial melting of peridotite decreases Sm/Nd and Lu/Hf, this mismatch may be an artifact. (d) In this panel with an expanded scale, we evaluate the effects of age corrections in calculating the present-day source estimates for Emperor Seamount lavas. The data points for Emperor Seamount lavas are the same as in Figure 5c, where we assumed that partial melting did not fractionate Sm/Nd and Lu/Hf. In this panel, we evaluate the effect of partial melting on these ratios. If we assume that partial melting reduces the source parent/daughter ratios by factors of 0.5 and 0.8 for Lu/Hf and Sm/Nd, respectively, the present-day values are indicated by vertical and horizontal lines emanating from each data point for Emperor Seamount lavas. Clearly, the offset of Emperor Seamount lavas to lower $^{176}Hf/^{177}Hf$ seen in Figure 5c remains. Note that the data for the Honolulu Volcanics from *Stille et al.* [1983] define a steeper trend than our data.

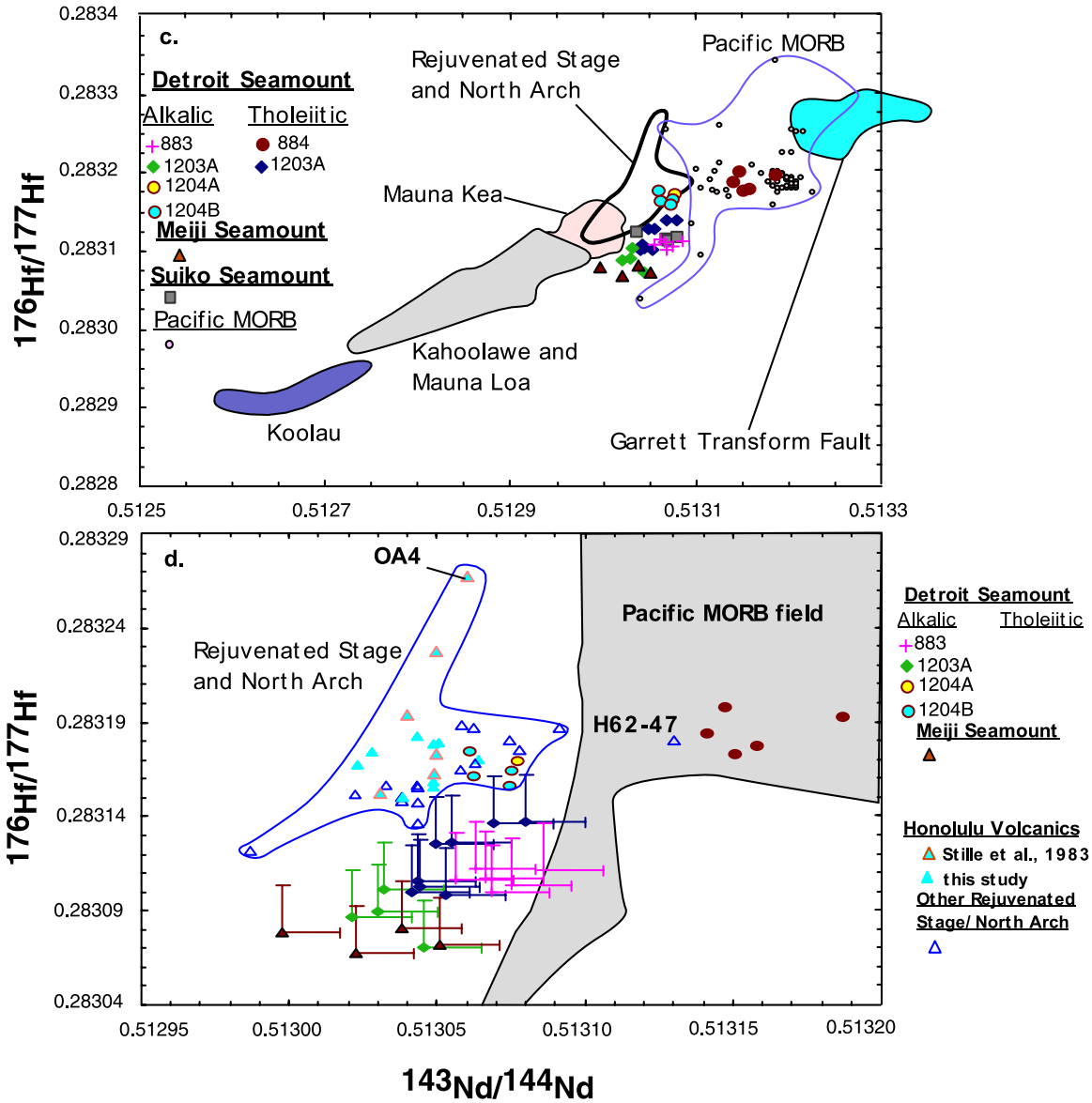

Figure 5. (continued)

$^{176}Hf/^{177}Hf$ (Figures 2 and Figures 5a–5d) is not related to MORB. This inference has been questioned by *Wang et al.* [2003], but Figure 6 of *Blichert-Toft et al.* [2003] shows that relatively depleted Hawaiian shield lavas, such as Mauna Kea, have lower $^{176}Hf/^{177}Hf$ than most Pacific MORB. The conclusion that oceanic lithosphere or MORB-related asthenosphere does not contribute to Hawaiian shield lavas has also been reached by *Lassiter and Hauri* [1998] and *Abouchami et al.* [2000].

[18] In a $^{176}Hf/^{177}Hf$ versus $^{206}Pb/^{204}Pb$ plot it is evident that rejuvenated-stage lavas are not on the hyperbola defined by shield lavas (Figure 6a); consequently isotopically distinct depleted components have contributed to these two lava groups. Specifically, for shield lavas the high $^{176}Hf/^{177}Hf$ component has high $^{206}Pb/^{204}Pb$ whereas rejuvenated lavas with high $^{176}Hf/^{177}Hf$ have lower $^{206}Pb/^{204}Pb$ (Figure 6a). In contrast to the positive trend defined by Hawaiian shield lavas, lavas from Detroit Seamount, like MORB, form an elongated negative trend ranging from Site 1203 lavas, which in large part overlap the field for the Mauna Kea shield, to Site 884 lavas which overlap with the age-corrected field for rejuvenated-stage lavas (Figure 6b). This negative trend extends toward the low $^{206}Pb/^{204}Pb$ end of the Pacific MORB field, which, as in Figures 3b

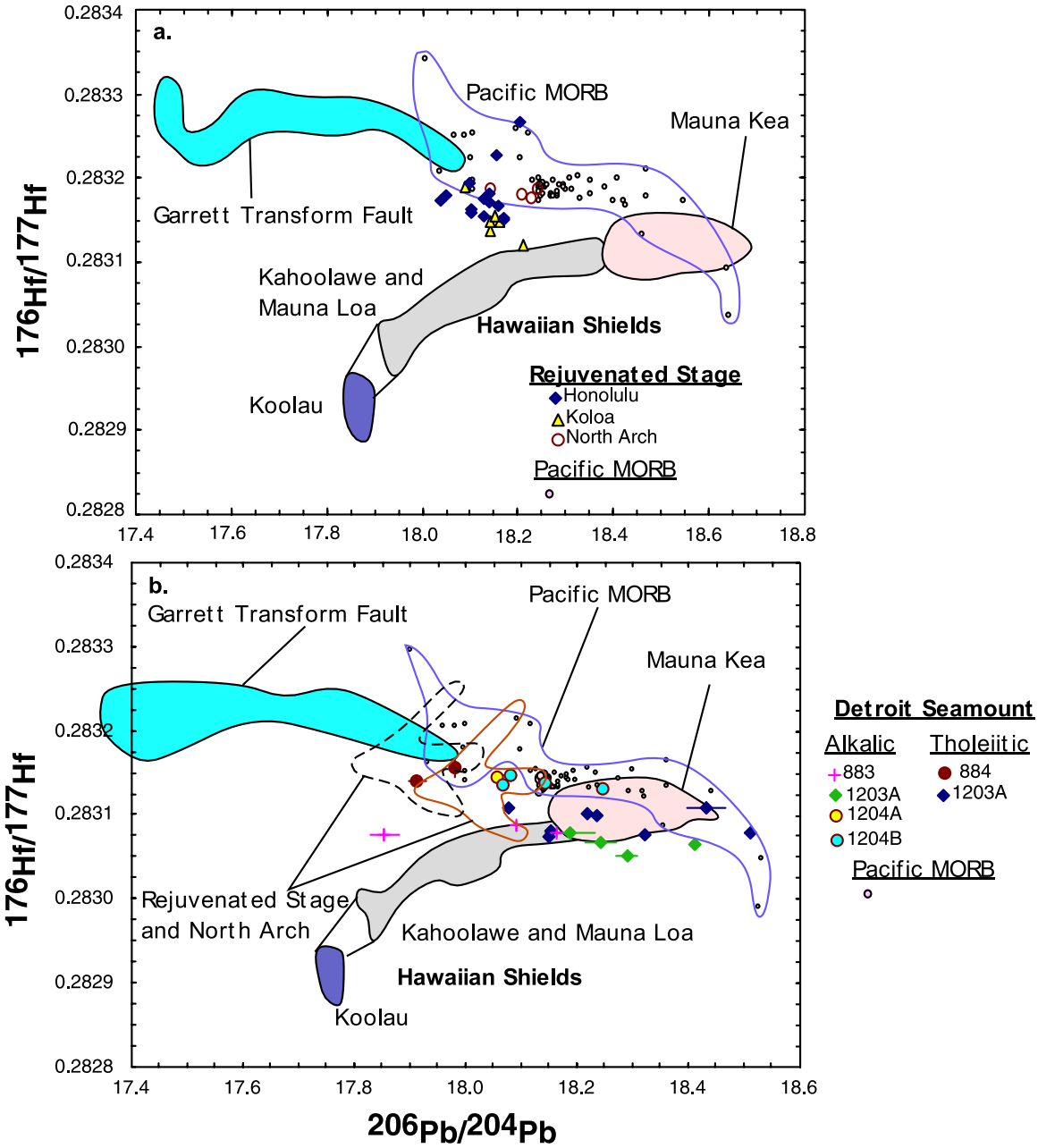

Figure 6. Values of $^{176}Hf/^{177}Hf$ versus $^{206}Pb/^{204}Pb$ showing fields for Hawaiian shields, EPR MORB, and Garrett fracture zone lavas. Data sources for Pb are in the caption for Figures 3a–3e, and data sources for Hf are in the caption for Figures 5a–5d. (a) Data points for rejuvenated-stage and North Arch lavas. (b) Data points for lavas from Detroit Seamount corrected to their eruption ages. See Figure 2 caption for procedures used to calculate initial ratios.

and 3d, is defined by lavas erupted within the Garrett transform fault.

4.2. Meiji Seamount

[19] Meiji Seamount is the most northerly Emperor Seamount that has been sampled (Figure 1). Drilling on DSDP Leg 19 recovered ~13m of pillow basalt. The altered whole rock compositions are alkalic [*Stewart et al.*, 1973], but subsequent analysis of a glassy sample by *Dalrymple et al.* [1980] showed that the samples may be altered tholeiitic basalt. An age of 85 Ma was inferred by *Keller et al.* [2000], but no reliable radiometric ages are available. The minimum age is 68–70 Ma on the basis of fossils in overlying sediments [*Worsley*, 1973].

[20] Meiji samples have $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ similar to basalt from Site 1203 at Detroit Sea-

mount (Figure 2b), but they range to lower $^{176}Hf/^{177}Hf$ (Figure 5b). Although the Sr-Nd-Hf isotopic data for Meiji samples lie within or close to fields for Detroit Seamount lavas, the age-corrected Pb isotopic data do not (Figures 3a–3e). The anomalously low $^{206}Pb/^{204}Pb$ of the 4 samples analyzed by *Regelous et al.* [2003] arises from the high parent/daughter ratios (U/Pb > 1.08; also, U/Th > 1 is anomalously high [see *Regelous et al.*, 2003, Table 4]). The plagioclase phenocrysts in Meiji samples have been variably replaced by potassium feldspar [*Dalrymple et al.*, 1980]. Therefore it is likely that the anomalously high U/Pb of the leached Meiji samples reflect the fluids that converted plagioclase to potassium feldspar. Since this alteration event was relatively young, <38 Ma [*Dalrymple et al.*, 1980; *Duncan and Keller*, 2004], the use of measured U/Pb to correct to an inferred age of 85 Ma leads to overestimates of the age corrections for $^{206}Pb/^{204}Pb$. In contrast, the single Meiji sample studied by *Keller et al.* [2000] has lower U/Pb (0.5); consequently, it has much higher age corrected $^{206}Pb/^{204}Pb$ (Figure 3b). Given the difficulty in calculating initial Pb isotope ratios, Meiji samples are not plotted in Figures 4 and 6. Sample 145-2 from Detroit Seamount Site 883 also has anomalously high U/Pb (0.74 [*Regelous et al.*, 2003, Table 4]), and its anomalous location in Figure 3d, i.e., relatively low $^{206}Pb/^{204}Pb$ and high $^{208}Pb/^{204}Pb$, probably reflects an overestimated age correction.

4.3. Garnet Pyroxenite Xenoliths From Salt Lake Crater

[21] Previous studies have shown that Sr, Nd, Pb and Os isotopic ratios of whole rock garnet pyroxenite xenoliths from Salt Lake Crater, a vent of the rejuvenated-stage Honolulu Volcanics, overlap with the range of ratios in the Honolulu Volcanics [e.g., *Okano and Tatsumoto*, 1996; *Lassiter et al.*, 2000]. Hence a genetic relationship is inferred. *Frey* [1980] inferred that these pyroxenites formed as high-pressure cumulate rocks derived from the Honolulu Volcanics, whereas *Lassiter et al.* [2000] suggested that these pyroxenites formed at a spreading ridge at ~100 Ma and subsequently were an important source component for the Honolulu Volcanics.

[22] Our Nd and Hf isotopic data for clinopyroxene and garnet bear on these interpretations (Figure 5a). Firstly, the Hf isotopic data overlap with the range of the Honolulu Volcanics. Secondly, Hf isotopic ratios are similar in the clinopyroxenes and garnets indicating that these phases are equilibrated (Table 2). Nd isotopic data are, however, more complex. Sample 3B15 has equilibrated clinopyroxene and garnet with $^{143}Nd/^{144}Nd$ also overlapping with the field for the Honolulu Volcanics. However, garnet in the other two samples has lower $^{143}Nd/^{144}Nd$ than both the coexisting clinopyroxene and the Honolulu Volcanics. Since $(Sm/Nd)_{gt} > (Sm/Nd)_{cpx}$, the two-point isochron has a negative slope indicating recent mixing with a low $^{143}Nd/^{144}Nd$ component. In this case the lower $^{143}Nd/^{144}Nd$ in garnet relative to clinopyroxene is consistent with the higher diffusion coefficient of Nd in garnet relative to clinopyroxene [*Van Orman et al.*, 2002]. Furthermore, in a study of garnet peridotite xenoliths from kimberlites *Bedini et al.* [2004] find "that Hf is far more resistant to diffusional loss and metasomatism than Nd."

5. Temporal Evolution of Sr, Nd, and Hf Isotope Ratios Along the Emperor Seamount Chain

[23] *Keller et al.* [2000] showed that the measured $^{87}Sr/^{86}Sr$ of tholeiitic basalt decrease from Suiko Seamount (65 Ma) to Detroit Seamount (76–81 Ma). Assuming that age corrections are unimportant, they proposed an increasing proportion of a MORB-related component as the age difference between the seamount and underlying oceanic crust decreased. This interpretation was questioned by *Regelous et al.* [2003] who noted that given the 25 Myr difference between eruption ages of Suiko lavas and the underlying oceanic crust, "it is therefore unlikely that a ridge could influence the chemistry of hot spot lavas over such a distance." *Regelous et al.* [2003] plotted ε_{Sr} and ε_{Nd} versus age along the Hawaiian-Emperor hot spot track. They found decreasing initial ε_{Sr} with increasing age, but there is a reversal in this trend from the ~81 Ma Site 884 lavas at Detroit Seamount to presumably older lavas from Meiji Seamount (see Figure 7a). There is no corresponding age trend for ε_{Nd}; except for Site 884 lavas, there is considerable overlap in ε_{Nd} for lavas erupted from 43 to 81 Ma [*Regelous et al.*, 2003, Figure 8d]. This result is also apparent in Figure 2b, where, except for Site 884 lavas from Detroit Seamount, lavas from Meiji and Detroit Seamounts define a shallow slope, i.e., significant variation in $^{87}Sr/^{86}Sr$ but overlap in $^{143}Nd/^{144}Nd$. Given the strong correlation between $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$, it is not surprising

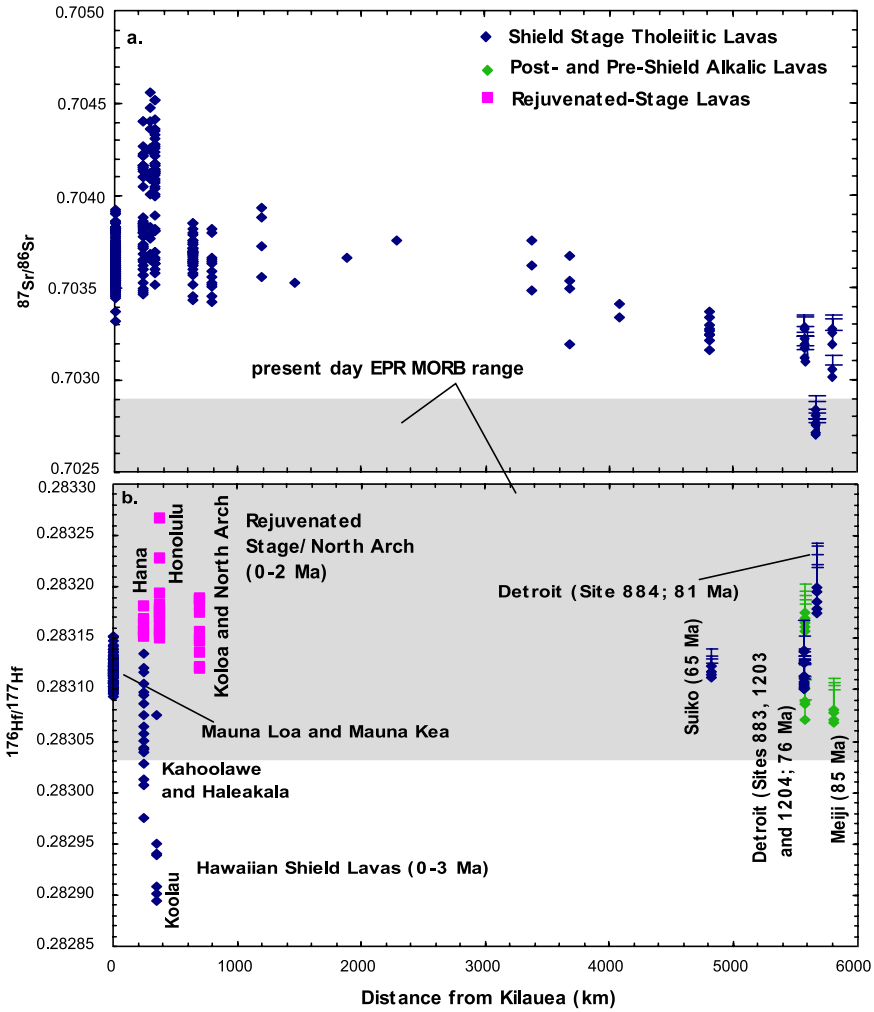

Figure 7. Values of $^{87}Sr/^{86}Sr$ and $^{176}Hf/^{177}Hf$ in young Hawaiian lavas and older Emperor Seamount lavas as a function of distance from Kilauea volcano. Our objective is to compare present-day ratios for the sources of recent Hawaiian lavas and older Emperor Seamount lavas. For Hawaiian lavas we assume that the source ratios are those measured in the relatively young lavas. Estimating present-day source ratios of Emperor Seamount lavas is more complex. (a) For $^{87}Sr/^{86}Sr$ we use measured Rb/Sr and $^{87}Sr/^{86}Sr$ values for acid-leached powders to calculate initial ratios for each lava from Detroit and Meiji Seamounts. As minimal estimates of present-day source $^{87}Sr/^{86}Sr$, the data points are the initial values calculated for each lava. For calculating maximum values (vertical lines with horizontal bars) we assumed a source Rb/Sr = 0.024, the typical value for unaltered Kilauea lavas [*Hofmann et al.*, 1984]. Present-day source ratios were then calculated by forward correcting to the present. These are maximum estimates because $(Rb/Sr)_{Emperor\ source} < (Rb/Sr)_{Kilauea\ lava}$. For <65 Ma Emperor lavas measured $^{87}Sr/^{86}Sr$ are plotted since the age correction (typically, <0.00003) is less than the $^{87}Sr/^{86}Sr$ variation at the seamount. Our results show that even with consideration of uncertainties arising from age corrections, the sources of Detroit Seamount lavas had lower $^{87}Sr/^{86}Sr$ than the sources of Hawaiian lavas. Data sources: Modern Hawaiian shields from GEOROC database; Emperor Seamounts from *Lanphere et al.* [1980], *Basu and Faggart* [1996], *Keller et al.* [2000], *Regelous et al.* [2003], and *Huang et al.* [2005]. (b) For $^{176}Hf/^{177}Hf$ the minimal estimates (data points) of present-day source ratios are measured $^{176}Hf/^{177}Hf$. Procedures for calculating maximum estimates (indicated by vertical lines with horizontal bars) are in the caption for Figure 5d. The important result is that there is no systematic temporal trend defined by sources of Hawaiian and Emperor Seamount lavas. Data sources: *Blichert-Toft et al.* [1999, 2003], *Stracke et al.* [1999], and *Stille et al.* [1983].

that there is also no systematic temporal trend for $^{176}Hf/^{177}Hf$ (Figure 7b).

[24] The implication is that the processes that led to isotopic variation among lavas from different Emperor Seamounts created more variability in Rb/Sr than in Sm/Nd and Lu/Hf. Given the relatively higher incompatibility, mobility and volatility of Rb relative to Sr, Sm, Nd, Lu and Hf, there are well known examples of decoupling between $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ or $^{176}Hf/^{177}Hf$; for example both lower continental crust and HIMU OIB are offset from the field defined by MORB and most OIB to low $^{87}Sr/^{86}Sr$ for their $^{143}Nd/^{144}Nd$ (e.g., *Halliday et al.* [1993] and *Hart* [1988], respectively). Specifically for Hawaiian lavas, *Basu and Faggart* [1996] proposed that the offset from the MORB trend to high $^{87}Sr/^{86}Sr$ (Figure 2a) indicates that an ancient lithospheric component that was subjected to seawater alteration is in the source of Hawaiian magmas. In this case, the proportion of such a component in Hawaiian lavas has increased with decreasing age (Figure 7a).

6. Definition and Origin of Depleted Components in Lavas Associated With the Hawaiian Plume

[25] Firstly, trends defined by Detroit Seamount lavas in $^{206}Pb/^{204}Pb$ versus $^{87}Sr/^{86}Sr$ and $^{176}Hf/^{177}Hf$ show the following: (1) At one extreme, Site 1203 lavas trend to (Figure 6b) or beyond (Figure 4b) the low $^{87}Sr/^{86}Sr$, high $^{176}Hf/^{177}Hf$ and high $^{206}Pb/^{204}Pb$ end of the array defined by Hawaiian shield lavas. This end is commonly defined as the Kea end-member [e.g., *Mukhopadhyay et al.*, 2003]. (2) At the other extreme, relative to Hawaiian shield lavas, lavas from Sites 883 and 884 have low $^{87}Sr/^{86}Sr$ and high $^{176}Hf/^{177}Hf$ accompanied by relatively low $^{206}Pb/^{204}Pb$. Such a depleted component is not expressed in Hawaiian shield lavas. Our discussion focuses on the significance of this component in lavas from Detroit Seamount and the surprisingly similar component expressed in isotopic ratios of rejuvenated-stage/North Arch lavas. The abundance of major and incompatible trace elements in the highly alkalic rejuvenated-stage/North Arch lavas differs substantially from those of the mildly alkalic to tholeiitic lavas from Detroit Seamount [*Yang et al.*, 2003; *Huang et al.*, 2005]. Therefore any similarity in radiogenic isotope ratios (Sr, Nd, Hf and Pb) and their trends in these two suites of lavas is surprising (Figures 2 to 6). In particular, both groups trend to very nonradiogenic Pb isotopic ratios which are lower than those of most recent and ancient Pacific MORB (Figures 3a–3e). This trend could reflect the influence of a component similar to that of the atypical ocean floor lavas erupted in the Garrett transform fault; however, this inference is weakened by the rarity of such MORB (Figure 3e). It is possible, however, that depleted asthenospheric mantle with unradiogenic Pb isotope ratios is accessed only under unusual tectonic conditions; for example, the two-stage melting of a MORB source proposed for lavas erupted within the Garrett transform fault [*Wendt et al.*, 1999], the proximity of the plume and spreading ridge when Detroit Seamount formed, and the second pulse of volcanism forming rejuvenated-stage lavas at Hawaiian volcanoes [*Ribe and Christensen*, 1999].

[26] Evidence against the involvement of a depleted component like that expressed in the Garrett transform fault lavas is the steep $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$ trends defined by most Emperor Seamount lavas. This trend extrapolates toward a depleted component unlike that expressed in lavas from the Garrett transform fault (Figure 5b). Site 884 lavas from Detroit Seamount are an exception since they are within the MORB field (Figures 5b, 5c, and 5d). What is the significance of the steep $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$ trend (Figure 5d)? One possibility is that aged mantle lithosphere with relatively high Lu/Hf, reflecting residual garnet, is offset to high $^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$ [see *Salters and Zindler*, 1995, Figure 3], and in unusual circumstances this material is a magma source. This is the model proposed by *Fitton et al.* [2003] to explain Hf-Nd isotopic systematics in Icelandic lavas.

[27] The atypically high Hf isotopic ratios, up to $\varepsilon_{Hf} = 65$, in clinopyroxene from peridotite xenoliths at Salt Lake Crater, a Honolulu Volcanics vent, may be relevant for understanding rejuvenated-stage lavas [*Salters and Zindler*, 1995; *Bizimis et al.*, 2003a]. Because these clinopyroxenes are relatively enriched in incompatible elements, their high Hf isotopic ratios require processes more complex than aging of residual material. The simplest model proposed by *Bizimis et al.* [2003a] is mixing of an old, >1 Ga, depleted peridotite that has relatively high $^{176}Hf/^{177}Hf$ (and $^{143}Nd/^{144}Nd$) with small amounts, <5%, of melt with high Nd/Hf ratio, such as lavas forming the Honolulu Volcanics. As shown in Figure 7 of *Bizimis et al.* [2003a], the mixing lines are highly hyperbolic and result in peridotite with high

$^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$. An alternative and favored model of *Bizimis et al.* [2003a] is melt-peridotite reaction. Specifically, they propose that a magma, similar to the Honolulu Volcanics lavas reacted with 100 Ma depleted oceanic lithosphere mantle [*Bizimis et al.*, 2003a, Table 3]. Although these models were created to explain anomalously high $^{176}Hf/^{177}Hf$ in clinopyroxene of peridotite xenoliths at Salt Lake Crater, *Bizimis et al.* [2003a] suggest that the steep $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$ trend of the Honolulu Volcanics (data of *Stille et al.* [1983] in Figure 5d) indicates the importance of such reacted melts in forming the Honolulu Volcanics. The validity of this inference is weakened by the absence of Nd-Hf isotope ratio correlation shown by our new data for the Honolulu Volcanics (Figure 5d). Regardless, models involving melts enriched in highly incompatible elements are unlikely explanations for the steep Hf-Nd isotope ratio trends defined by Emperor Seamount lavas with their relatively low abundance of incompatible elements [*Huang et al.*, 2005]. Ancient depleted lithospheric mantle is a more appropriate explanation.

[28] In summary, we suggest that the trends to unradiogenic Pb isotope ratios and $^{143}Nd/^{144}Nd$-$^{176}Hf/^{177}Hf$ systematics in lavas from Detroit Seamount and rejuvenated-stage/North Arch lavas indicate involvement of an aged depleted component that is intrinsic to the Hawaiian plume. Despite the marked compositional differences between these two groups of lavas, their Sr, Nd, Hf and Pb isotopic characteristics are surprisingly similar.

[29] There are also similarities in abundance ratios of some incompatible elements. Specifically, high Ba/Th, relative to the primitive mantle estimate of 83, is characteristic of all Hawaiian lavas, including rejuvenated-stage lavas [*Yang et al.*, 2003, Figure 10a]. Glasses from Detroit Seamount also have high Ba/Th; in fact among Detroit Seamount samples, Site 884 glasses have the highest Ba/Th, approximately a factor of two greater than the Ba/Th of lavas from the Garrett fracture zone [*Huang et al.*, 2005, Figure 17c].

[30] *Fitton et al.* [1997] used a Nb/Y versus Zr/Y plot to distinguish a depleted component in the Iceland plume from MORB. The pros and cons of this approach are discussed by *Hanan et al.* [2000] and *Fitton et al.* [2003]. For Hawaiian shield lavas this approach is less useful because Hawaiian shield lavas plot at the boundary between Icelandic lavas and MORB (Figure 8) [see also *Yang et al.*, 2003, Figure 10b]. However, within the context of a MORB-related or plume-related source for the depleted component it is notable that (1) rejuvenated-stage lavas plot farthest from the MORB field and (2) Site 884 lavas do not overlap with lavas from the Garrett transform fault (Figure 8).

[31] If a depleted component in the Hawaiian plume was sampled at Detroit Seamount and in the rejuvenated-stage lavas of the Hawaiian Islands, there are important implications. Despite considerable short-term geochemical variability expressed among lavas forming the Hawaiian Islands there is also long-term homogeneity, specifically a depleted component intrinsic to the plume that has been available for 80 Ma. This component has not been sampled randomly, as might be expected of a variably metasomatized source, but is available only under specific conditions that enable melting of a depleted source with relatively low $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ coupled with high $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$.

[32] What is the mechanism for sampling a depleted component intrinsic to the plume? For Detroit Seamount, *Regelous et al.* [2003, Figure 11] proposed that an intrinsic depleted refractory component within the Hawaiian plume was accessed as a result of the relatively higher extent of melting achieved when the plume ascended below thin oceanic lithosphere. Additional studies of recently acquired samples from Detroit Seamount, indicating relatively low pressures of melt segregation, are consistent with this hypothesis [*Huang et al.*, 2005].

[33] For rejuvenated-stage/North Arch lavas, the depleted component has typically been inferred to be depleted oceanic lithosphere [e.g., *Yang et al.*, 2003, Figure 12]. However, numerical models of melting dynamics during plume ascent by *Ribe and Christensen* [1999] suggest that rejuvenated-stage volcanism results from a secondary melting zone (see their Figures 5a–5d) whereby plume material is initially melted in a primary melting zone above the plume stem followed by a secondary melting zone 300–500 km downstream. They proposed that rejuvenated-stage, but not North Arch, magmas result from this second-stage melting of the plume.

[34] There are two obvious problems with the hypothesis that rejuvenated-stage lavas arise from a secondary melting zone where melts are derived from the plume-related residue of the initial melting event. Firstly, the very high abundances of

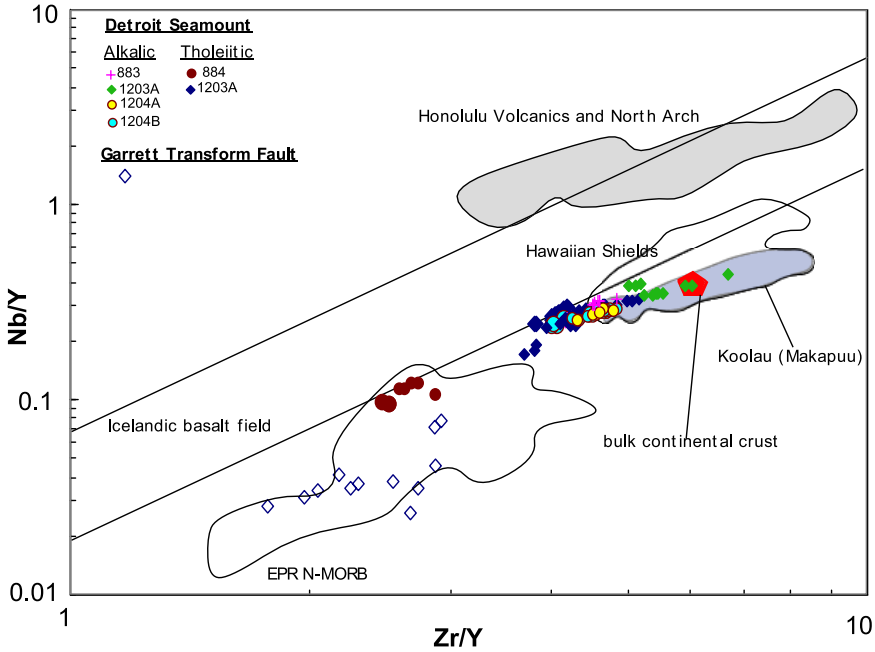

Figure 8. Nb/Y versus Zr/Y. This plot was used by *Fitton et al.* [2003, and references therein] to distinguish Icelandic lavas, including depleted samples with relatively low Nb/Y and Zr/Y from N-MORB. Trends of melts derived by variable extents of melting parallel the boundary lines of the Icelandic field [*Fitton et al.*, 1997]. As shown here and by *Yang et al.* [2003], Hawaiian shield lavas overlap the lower boundary of the Iceland field and extend into the MORB field, perhaps reflecting a sedimentary component (see bulk continental crust location) in Hawaiian lavas, such as the uppermost Koolau (Makapuu) shield [*Blichert-Toft et al.*, 1999]. Detroit Seamount lavas largely overlap with Hawaiian shield lavas and extend to lower ratios (e.g., Site 884) along a trend parallel to the boundary line. Note that Site 884 lavas are distinct from Garrett transform fault lavas. As shown by *Yang et al.* [2003], rejuvenated-stage/North Arch overlap the upper boundary of the Icelandic field. Data sources: Hawaiian shields and rejuvenated/North Arch [see *Yang et al.*, 2003, Figure 10]; Garrett transform fault [*Wendt et al.*, 1999]; EPR N-MORB [*Niu and Batiza*, 1997; *Regelous et al.*, 1999].

incompatible elements in rejuvenated-stage and North Arch lavas suggests a source enriched in these elements relative to primitive mantle [e.g., *Clague and Frey*, 1982; *Frey et al.*, 2000; *Yang et al.*, 2003]. An incompatible element-rich source with depleted isotopic characteristics could be created by metasomatism during the time gap between the shield and rejuvenated-stage volcanism [e.g., *Roden et al.*, 1984]. Alternatively, derivation of incompatible element-rich magma from a source depleted in incompatible elements is only possible if extents of melting are very low. For example, the most SiO_2-undersaturated, nephelinite and nepheline melilitite, lavas of the Honolulu Volcanics are enriched in incompatible elements relative to primitive mantle by factors of 100 to 200 [*Yang et al.*, 2003, Figure 3]. Extents of melting therefore must be <1% and even lower if the residue from the initial melting event had lower abundances of incompatible elements than primitive mantle. The alkalic posterosional (rejuvenated-stage) lavas associated with the Madeira hot spot also have depleted isotopic ratios compared to shield lavas and relative enrichment in highly incompatible elements. *Geldmacher and Hoernle* [2000] proposed that these posterosional lavas were derived by low degrees of melting of a depleted recycled peridotite intrinsic to the Madeira plume.

[35] Secondly, *Lassiter et al.* [2000] found that rejuvenated-stage lavas have higher $^{187}Os/^{188}Os$ than Hawaiian shield lavas, and most samples of mantle peridotite. A source with relatively high Re/Os is required and a likely explanation is pyroxenite veins in the source of rejuvenated-stage lavas [*Lassiter et al.*, 2000; see also *Yang et al.*, 2003, Figure 13]. Garnet pyroxenite xenoliths from Salt Lake Crater have variable and relatively high $^{187}Os/^{188}Os$ that overlap with the range for the Honolulu Volcanics [*Lassiter et al.*, 2000]. We also find that Hf isotope ratios of garnet and clinopyroxene from these xenoliths overlap with the range for the Honolulu Volcanics. Moreover, in another study of garnet pyroxenite xenoliths from Salt Lake Crater, *Bizimis et al.* [2003b] also found that

Sr, Nd and Hf isotope ratios in garnet and clinopyroxene overlap with those of the Honolulu Volcanics. Clearly, the Honolulu Volcanics and garnet pyroxenites are genetically related. *Frey* [1980] proposed that the garnet pyroxenites formed as high-pressure cumulates in rejuvenated-stage magmas. In contrast, *Lassiter et al.* [2000] proposed that these xenoliths formed from MORB at ~100 Ma. On the basis of the similar $^{176}Hf/^{177}Hf$ of garnet and clinopyroxene in these xenoliths (Table 2) [see also *Bizimis et al.*, 2003b], this hypothesis requires that garnet and clinopyroxene were at sufficiently high temperature to maintain Hf isotopic equilibrium.

[36] Since pyroxenites typically have lower solidi than peridotites [e.g., *Hirschmann and Stolper*, 1996], it is unlikely that pyroxenites could remain in the residue of the initial melting event. However, pyroxenites within the mantle are likely to have diverse mineral proportions and a wide range of compositions [*Hirschmann and Stolper*, 1996]. As a result their solidus temperatures are variable. In fact some pyroxenites, such as the silica-deficient Salt Lake Crater garnet pyroxenites, have solidi close to that of mantle peridotite [*Kogiso et al.*, 2003]. Another possible alternative is that some peridotites have high $^{187}Os/^{188}Os$ [*Stracke et al.*, 1999, 2003], but a recent assessment of Os isotopic ratios in mantle rocks [*Chesley et al.*, 2004] notes that mantle peridotites do not have $^{187}Os/^{188}Os > 0.15$ whereas rejuvenated lavas and pyroxenites commonly reach values of 0.16 [*Lassiter et al.*, 2000].

7. Summary

[37] Isotopic ratios of Sr, Nd, Hf and Pb indicate that 76 to 81 Ma lavas forming Detroit Seamount contain a depleted component which is unlike that expressed in young Hawaiian shields, such as Mauna Kea. Distinguishing characteristics of most Detroit lavas are relatively unradiogenic Pb isotope ratios, a negative $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ trend, a steep positive $^{143}Nd/^{144}Nd$ versus $^{176}Hf/^{177}Hf$ trend, and a negative $^{176}Hf/^{177}Hf$ versus $^{206}Pb/^{204}Pb$ trend (Figures 3a–3e–6). A MORB-related component is a suitable end-member for some of these trends but most young and ancient Pacific MORB do not have sufficiently unradiogenic Pb isotope ratios. Lavas erupted within the Garrett transform fault on the EPR have suitably unradiogenic Pb isotope ratios, but they do not lie on the trend of $^{143}Nd/^{144}Nd$ versus $^{176}Hf/^{177}Hf$ defined by most lavas from Detroit Seamount and Emperor Seamounts in general. Also lavas from the Garrett transform fault differ from Hawaiian lavas in diagnostic incompatible element abundance ratios, such as Ba/Th and Nb/Y at a given Zr/Y.

[38] Although the alkalic rejuvenated-stage and North Arch lavas erupted in the Hawaiian Islands are substantially different from Detroit Seamount lavas in major element composition and abundance of incompatible elements, these lava suites have surprisingly similar Sr, Nd, Hf and Pb isotopic ratios, and they define similar trends among these ratios. A possible explanation is that these young and old lavas related to the Hawaiian hot spot sampled a depleted component intrinsic to a long-lived source. This component can be accessed only under special conditions, such as (1) the second-stage melting for rejuvenated-stage lavas proposed for Hawaii by *Ribe and Christensen* [1999] and for the Madeira hot spot track in the eastern North Atlantic by *Geldmacher and Hoernle* [2000, Figure 9] or (2) under thin lithosphere resulting from the proximity of the Hawaiian plume to a spreading ridge axis [*Regelous et al.*, 2003]. If this inference is correct, the magma source has contained such a depleted component for ~80 Myr. Although the geochemical heterogeneity of the Hawaiian plume is well established, a long-term role for a depleted component argues against models invoking sources involving random incorporation of geochemical heterogeneities within the shallow mantle. A long-lived geochemically heterogeneous plume with well-defined and spatially coherent geochemical heterogeneities is inferred [see also *Abouchami et al.*, 2004].

[39] Supporting evidence for a long-lived plume source also arises from high $^{3}He/^{4}He$ and Ba/Th ratios. Relatively high $^{3}He/^{4}He$ are typical of Hawaiian shield lavas and *Keller et al.* [2004] report R/R_A ($^{3}He/^{4}He$ in lava relative to atmospheric ratio) >10 for lavas at Site 1203 on Detroit Seamount. All lavas related to the Hawaiian hot spot, including tholeiitic basalt forming the young shields, the Cretaceous lavas forming Detroit Seamount and alkalic lavas erupted during rejuvenated-stage volcanism and forming the North Arch volcanic field, share a common feature of relatively high Ba/Th [e.g., *Yang et al.*, 2003; *Huang et al.*, 2005]. High Ba/Th distinguishes lavas derived from the Hawaiian hot spot from MORB and most other OIB [*Hofmann and Jochum*, 1996].

Acknowledgments

[40] We thank the editors, R. Duncan and W. White, and reviewers, G. Fitton and K. Hoernle, for their constructive

review comments. We also thank J. Lassiter, P. Reiners, and D. Weis for discussion. The garnet pyroxenite xenoliths were provided by D. Velde. This research used samples provided by the Ocean Drilling Program (ODP). The ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under the management of Joint Oceanographic Institutions, Inc. Funding for this research was provided by the U.S. Science Support Program and NSF grant EAR-0105557. J.B.T. acknowledges financial support from the French Institut National des Sciences de l'Univers.

References

Abouchami, W., S. J. G. Galer, and A. W. Hofmann (2000), High precision lead isotope systematics of lavas from the Hawaiian Scientific Drilling Project, *Chem. Geol.*, *169*, 187–209.

Abouchami, W., A. W. Hofmann, S. J. G. Galer, F. Frey, J. Eisele, and M. Feigenson (2004), Lead isotopes reveal bilateral asymmetry and vertical continuity in the Hawaiian mantle plume, *Nature*, in press.

Basu, A. R., and B. E. Faggart (1996), Temporal isotopic variations in the Hawaiian mantle plume: The Lanai anomaly, the Molokai fracture zone and a seawater-altered lithospheric component, in *Earth Processes: Reading the Isotopic Code*, *Geophys. Monogr. Ser.*, vol. 95, edited by A. Basu and S. Hart, pp. 149–159, AGU, Washington, D. C.

Bedini, R.-M., J. Blichert-Toft, M. Boyet, and F. Albarede (2004), Isotopic constraints on the cooling of the continental lithosphere, *Earth Planet. Sci. Lett.*, *223*, 99–112.

Bizimis, M., G. Sen, and V. J. M. Salters (2003a), Hf-Nd isotope decoupling in the oceanic lithosphere: Constraints from spinel peridotites from Oahu, Hawaii, *Earth Planet. Sci. Lett.*, *217*, 43–58.

Bizimis, M., G. Sen, and V. J. Salters (2003b), Volatile-rich mineral phases in the Hawaiian lithosphere: Phlogopites, and carbonates in 0-age garnet pyroxenite xenoliths from Salt Lake Crater, Oahu, Hawaii, *Eos Trans. AGU*, *84*(46), Fall Meet. Suppl., Abstract V42H-04.

Blichert-Toft, J. (2001), On the Lu-Hf isotope geochemistry of silicate rocks, *Geostand. Newsl.*, *25*, 41–56.

Blichert-Toft, J., and W. M. White (2001), Hf isotope geochemistry of the Galapagos Islands, *Geochem. Geophys. Geosyst.*, *2*, doi:10.1029/2000GC000138.

Blichert-Toft, J., C. Chauvel, and F. Albarede (1997), Separation of Hf and Lu for high-precision isotope analysis of rock samples by magnetic sector-multiple collector ICP-MS, *Contrib. Mineral. Petrol.*, *127*, 248–260.

Blichert-Toft, J., F. A. Frey, and F. Albarède (1999), Hf isotope evidence for pelagic sediments in the source of Hawaiian basalts, *Science*, *285*, 879–882.

Blichert-Toft, J., M. Boyet, Télouk, and F. Albarède (2002), $^{147}Sm/^{143}Nd$ and $^{176}Lu/^{176}Hf$ in eucrites and the differentiation of the HED parent body, *Earth Planet. Sci. Lett.*, *204*, 167–181.

Blichert-Toft, J., D. Weis, C. Maerschalk, A. Agranier, and F. Albarède (2003), Hawaiian hot spot dynamics as inferred from the Hf and Pb isotope evolution of Mauna Kea volcano, *Geochem. Geophys. Geosyst.*, *4*(2), 8704, doi:10.1029/2002GC000340.

Castillo, P. R., E. Klein, J. Bender, C. Langmuir, S. Shirey, R. Batiza, and W. White (2000), Petrology and Sr, Nd, and Pb isotope geochemistry of mid-ocean ridge basalt glasses from the 11°45′N to 15°00′N segment of the East Pacific Rise, *Geochem. Geophys. Geosyst.*, *1*, doi:10.1029/1999GC000024.

Chauvel, C., and J. Blichert-Toft (2001), A hafnium and trace element perspective on melting of depleted mantle, *Earth Planet. Sci. Lett.*, *190*, 137–151.

Chauvel, C., and C. Hémond (2000), Melting of a complete section of recycled oceanic crust: Trace element and Pb isotopic evidence from Iceland, *Geochem. Geophys. Geosyst.*, *1*, doi:10.1029/1999GC000002.

Chen, C.-Y., and F. A. Frey (1985), Trace element and isotope geochemistry of lavas from Haleakala Volcano, East Maui: Implications for the origin of Hawaiian basalts, *J. Geophys. Res.*, *90*(B10), 8743–8768.

Chen, C.-Y., F. A. Frey, and M. O. Garcia (1990), Evolution of alkalic lavas at Haleakala Volcano, East Maui, Hawaii: Major, trace element and isotopic constraints, *Contrib. Mineral. Petrol.*, *105*, 197–218.

Chesley, J., K. Righter, and J. Ruiz (2004), Large-scale mantle metasomatism: A Re-Os perspective, *Earth Planet. Sci. Lett.*, *219*, 49–60.

Clague, D. A., and F. A. Frey (1980), Trace-element geochemistry of tholeiitic basalts from Site 433C, Suiko Seamount, *Initial Rep. Deep Sea Drill. Proj.*, *55*, 559–569.

Clague, D. A., and F. A. Frey (1982), Petrology and trace element geochemistry of the Honolulu Volcanics, Oahu: Implications for the oceanic mantle below Hawaii, *J. Petrol.*, *23*, 447–504.

Clague, D. A., R. T. Holcomb, J. M. Sinton, R. S. Detrick, and M. E. Torresan (1990), Pliocene and Pleistocene alkalic flood basalts on the seafloor north of the Hawaiian Islands, *Earth Planet. Sci. Lett.*, *98*, 175–191.

Dalrymple, G. B., M. A. Lanphere, and D. A. Clague (1980), Conventional and $^{40}Ar/^{39}Ar$ K-Ar ages of volcanic rocks from Ojin (Site 430), Nintoku (Site 432), and Suiko (Site 433) seamounts and the chronology of volcanic propagation along the Hawaiian-Emperor chain, *Initial Rep. Deep Sea Drill. Proj.*, *55*, 659–676.

Dixon, J. E., and D. A. Clague (2001), Volatiles in basaltic glasses from Loihi Seamount: Evidence for a relatively dry plume component, *J. Petrol.*, *42*(3), 627–654.

Duncan, R. A., and R. A. Keller (2004), Radiometric ages for basement rocks from the Emperor Seamounts, ODP Leg 197, *Geochem. Geophys. Geosyst.*, *5*, Q08L03, doi:10.1029/2004GC000704.

Eisele, J., W. Abouchami, S. J. G. Galer, and A. W. Hofmann (2003), The 320 kyr Pb isotope evolution of Mauna Kea lavas recorded in the HSDP-2 drill core, *Geochem. Geophys. Geosyst.*, *4*(5), 8710, doi:10.1029/2002GC000339.

Fekiacova, Z., and W. Abouchami (2003), Pb isotopic evolution of Koolau volcano (Oahu, Hawaii), *Eos Trans. AGU*, *84*(46), Fall Meet. Suppl., Abstract V32A-0991.

Fitton, J. G., A. D. Saunders, M. J. Norry, B. S. Hardarson, and R. N. Taylor (1997), Thermal and chemical structure of the Iceland plume, *Earth Planet. Sci. Lett.*, *153*, 197–208.

Fitton, J. G., A. D. Saunders, P. D. Kempton, and B. S. Hardarson (2003), Does depleted mantle form an intrinsic part of the Iceland plume?, *Geochem. Geophys. Geosyst.*, *4*(3), 1032, doi:10.1029/2002GC000424.

Frey, F. A. (1980), The origin of pyroxenites and garnet pyroxenites from Salt Lake Crater, Oahu, Hawaii: Trace element evidence, *Am. J. Sci.*, *280A*, 427–444.

Frey, F. A., M. O. Garcia, and M. F. Roden (1994), Geochemical characteristics of Koolau volcano: Implications of intershield geochemical differences among Hawaiian volcanoes, *Geochim. Cosmochim. Acta*, *58*, 1441–1462.

Frey, F. A., D. Clague, J. J. Mahoney, and J. M. Sinton (2000), Volcanism at the edge of the Hawaiian plume: Petrogenesis of submarine alkalic lavas from the North Arch volcanic field, *J. Petrol.*, *41*(5), 667–691.

Galer, S. J. G., W. Abouchami, and J. D. Macdougall (1999), East Pacific Rise MORB through the Pb isotope looking-glass, *Eos Trans AGU*, *80*(46), Fall Meet. Suppl., F1086.

Geldmacher, J., and K. Hoernle (2000), The 72 Ma geochemical evolution of the Madeira hotspot (eastern North Atlantic); recycling of Paleozoic (≤500 Ma) oceanic lithosphere, *Earth Planet. Sci. Lett.*, *183*, 73–92.

Halliday, A. N., A. P. Dickin, R. N. Hunter, G. R. Davies, T. T. Dempster, J. Hamilton, and B. J. Upton (1993), Formation and composition of lower continental crust: Evidence from Scottish xenolith suites, *J. Geophys. Res.*, *98*, 581–607.

Hanan, B. B., J. Blichert-Toft, R. Kingsley, and J. Schilling (2000), Depleted Iceland mantle plume geochemical signature: Artifact of multicomponent mixing?, *Geochem. Geophys. Geosyst.*, *1*, doi:10.1029/1999GC000009.

Hart, S. R. (1988), Heterogeneous mantle domains: Signatures, genesis and mixing chronologies, *Earth Planet. Sci. Lett.*, *90*, 273–296.

Hirschmann, M. M., and E. M. Stolper (1996), A possible role for garnet pyroxenite in the origin of the "garnet" signature in MORB, *Contrib. Mineral. Petrol.*, *124*, 185–208.

Hoernle, K., R. Werner, J. Phipps-Morgan, D. Garbe-Schönberg, J. Bryce, and J. Mrazek (2000), Existence of complex spatial zonation in the Galapagos plume for at least 14 m. y., *Geology*, *28*, 435–438.

Hofmann, A. W. (1997), Mantle geochemistry: The message from oceanic volcanism, *Nature*, *385*, 219–229.

Hofmann, A. W., and K. P. Jochum (1996), Source characteristics derived from very incompatible trace elements in Mauna Loa and Mauna Kea basalts (Hawaiian Scientific Drilling Project), *J. Geophys. Res.*, *101*, 11,831–11,839.

Hofmann, A. W., M. D. Feigenson, and I. Raczek (1984), Case studies on the origin of basalt: III. Petrogenesis of the Mauna Ulu eruption, Kilauea, 1969–1971, *Contrib. Mineral. Petrol.*, *88*, 24–35.

Huang, S., and F. A. Frey (2003), Trace element abundances of Mauna Kea basalt from phase 2 of the Hawaii Scientific Drilling Project: Petrogenetic implications of correlations with major element content and isotopic ratios, *Geochem. Geophys. Geosyst.*, *4*(6), 8711, doi:10.1029/2002GC000322.

Huang, S., M. Regelous, T. Thordarson, and F. A. Frey (2005), Petrogenesis of lavas from Detroit Seamount: Geochemical differences between Emperor Chain and Hawaiian volcanoes, *Geochem. Geophys. Geosyst.*, *6*, Q01L06, doi:10.1029/2004GC000756.

Keller, R. A., M. R. Fisk, and W. M. White (2000), Isotopic evidence for Late Cretaceous plume-ridge interaction at the Hawaiian hotspot, *Nature*, *405*, 673–676.

Keller, R. A., D. W. Graham, K. A. Farley, R. A. Duncan, and J. E. Lupton (2004), Cretaceous-to-recent record of elevated $^{3}He/^{4}He$ along the Hawaiian-Emperor volcanic chain, *Geochem. Geophys. Geosyst.*, *5*, Q12L05, doi:10.1029/2004GC000739.

Kempton, P. D., and T. L. Barry (2001), Did the Hawaiian Plume interact with a mid-ocean ridge in the Late Cretaceous?, *J. Conf. Abstr.*, *6*, 466.

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

Kempton, P. D., P. M. E. Thompson, and A. D. Saunders (2002), Did the ancestral Hawaiian plume interact with a mid-ocean ridge? The isotopic evidence, *Geochim. Cosmochim. Acta.*, *66*(15A), suppl., A392–A392.

Kerr, A. C., A. D. Saunders, J. Tarney, N. H. Berry, and V. L. Hards (1995), Depleted mantle-plume geochemical signature: No paradox for plume theories, *Geology*, *23*, 843–846.

Kirkpatrick, R. J., D. A. Clague, and W. Freisen (1980), Petrology and geochemistry of volcanic rocks, DSDP Leg 55, Emperor seamount chain, *Initial Rep. Deep Sea Drill. Proj.*, *55*, 509–557.

Kogiso, T., M. M. Hirschmann, and D. J. Frost (2003), High-pressure partial melting of garnet pyroxenite: Possible mafic lithologies in the source of ocean island basalts, *Earth Planet. Sci. Lett.*, *216*, 603–617.

Lanphere, M. A., G. B. Dalrymple, and D. A. Clague (1980), Rb-Sr systematics of basalts from the Hawaiian-Emperor volcanic chain, *Initial Rep. Deep Sea Drill. Proj.*, *55*, 695–706.

Lassiter, J. C., and E. H. Hauri (1998), Osmium-isotope variations in Hawaiian lavas: Evidence for recycled oceanic lithosphere in the Hawaiian plume, *Earth Planet Sci Lett.*, *164*, 483–496.

Lassiter, J. C., D. J. DePaolo, and M. Tatsumoto (1996), Isotopic evolution of Mauna Kea volcano: Results from the initial phase of the Hawaiian Scientific Drilling Project, *J. Geophys. Res.*, *101*, 11,769–11,780.

Lassiter, J. C., E. H. Hauri, P. W. Reiners, and M. O. Garcia (2000), Generation of Hawaiian post-erosional lavas by melting of a mixed lherzolite/pyroxenite source, *Earth Planet Sci Lett.*, *178*(3–4), 269–284.

Mukhopadhyay, S., J. C. Lassiter, K. A. Farley, and S. W. Bogue (2003), Geochemistry of Kauai shield-stage lavas: Implications for the chemical evolution of the Hawaiian plume, *Geochem. Geophys. Geosyst.*, *4*(1), 1009, doi:10.1029/2002GC000342.

Niu, Y., and R. Batiza (1997), Trace element evidence from seamounts for recycled oceanic crust in the eastern Pacific mantle, *Earth Planet Sci Lett.*, *148*(3–4), 471–483.

Niu, Y., and M. J. O'Hara (2003), Origin of ocean island basalts: A new perspective from petrology, geochemistry, and mineral physics considerations, *J. Geophys. Res.*, *108*(B4), 2209, doi:10.1029/2002JB002048.

Niu, Y., K. D. Collerson, R. Batiza, J. I. Wendt, and M. Regelous (1999), Origin of enriched-type mid-ocean ridge basalt at ridges far from mantle plumes: The East Pacific Rise at 11°20′N, *J. Geophys. Res.*, *104*(4), 7067–7087.

Nowell, G. M., P. D. Kempton, S. R. Noble, J. G. Fitton, A. D. Saunders, J. J. Mahoney, and R. N. Taylor (1998), High precision Hf isotope measurements of MORB and OIB by thermal ionization mass spectrometry; insights into the depleted mantle, *Chem. Geol.*, *149*(3–4), 211–233.

Okano, O., and M. Tatsumoto (1996), Petrogenesis of ultramafic xenoliths from Hawaii inferred from Sr, Nd, and Pb isotopes, in *Earth Processes: Reading the Isotopic Code*, *Geophys. Monogr. Ser.*, vol. 95, edited by A. Basu and S. Hart, pp. 135–147, AGU, Washington, D. C.

Regelous, M., Y. Niu, J. I. Wendt, R. Batiza, A. Greig, and K. D. Collerson (1999), Variations in the geochemistry of magmatism on the East Pacific Rise at 10 degrees 30′N since 800 ka, *Earth Planet. Sci. Lett.*, *168*(1–2), 45–63.

Regelous, M., A. W. Hofmann, W. Abouchami, and S. J. G. Galer (2003), Geochemistry of lavas from the Emperor Seamounts, and the geochemical evolution of Hawaiian magmatism from 85 to 42 Ma, *J. Petrol.*, *44*, 113–140.

Reiners, P. W., and B. K. Nelson (1998), Temporal-compositional-isotopic trends in rejuvenated-stage magmas of Kauai,

Hawaii, and implications for mantle melting processes, *Geochim. Cosmochim. Acta*, *62*(13), 2347–2368.

Ribe, N. M., and U. R. Christensen (1999), The dynamical origin of Hawaiian volcanism, *Earth Planet. Sci. Lett.*, *171*, 517–531.

Roden, M. F., F. A. Frey, and D. A. Clague (1984), Geochemistry of tholeiitic and alkalic lavas from the Koolau Range, Oahu, Hawaii: Implications for Hawaiian volcanism, *Earth Planet. Sci. Lett.*, *69*, 141–158.

Roden, M. F., T. Trull, S. R. Hart, and F. A. Frey (1994), New He, Sr, Nd and Pb isotopic constraints on the constitution of the Hawaiian plume: Results from Koolau Volcano, Oahu, Hawaii, *Geochim. Cosmochim. Acta.*, *58*, 1431–1440.

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

Salters, V. J. M., and A. Zindler (1995), Extreme $^{176}Hf/^{177}Hf$ in the sub-oceanic mantle, *Earth Planet. Sci. Lett.*, *129*, 13–30.

Sharp, W. D., and D. A. Clague (2002), An older, slower Hawaii-Emperor bend, *Eos Trans. AGU*, *83*(47), Fall Meet. Suppl., Abstract T61C-04.

Sherrod, D. R., Y. Nishimitsu, and T. Tagami (2003), New K-Ar ages and geologic evidence against rejuvenated-stage volcanism at Haleakala, East Maui, a postshield-stage volcano of the Hawaiian island chain, *Geol. Soc. Am. Bull.*, *115*, 683–694.

Sims, K. W. W., et al. (2002), Chemical and isotopic constraints on the generation and transport of magma beneath the East Pacific Rise, *Geochim. Cosmochim. Acta.*, *66*(19), 3481–3504.

Sims, K. W. W., et al. (2003), Aberrant youth: Chemical and isotopic constraints on the origin of off-axis lavas from the East Pacific Rise, 9°–10°N, *Geochem. Geophys. Geosyst.*, *4*(10), 8621, doi:10.1029/2002GC000443.

Skovgaard, A. C., M. Storey, J. Baker, J. Blusztajn, and S. R. Hart (2001), Osmium-oxygen isotope evidence for a recycled and strongly depleted component in the Iceland mantle plume, *Earth Planet. Sci. Lett.*, *194*, 254–275.

Stewart, R. J., J. H. Natland, and W. R. Glassley (1973), Petrology of volcanic rocks recovered on DSDP Leg 19 from the North Pacific Ocean and the Bering Sea, *Initial Rep. Deep Sea Drill. Proj.*, *19*, 615–627.

Stille, P., D. M. Unruh, and M. Tatsumoto (1983), Pb, Sr, Nd and Hf isotopic evidence of multiple sources for Oahu, Hawaii basalts, *Nature*, *304*(5921), 25–29.

Stracke, A., V. J. M. Salters, and K. W. W. Sims (1999), Assessing the presence of garnet-pyroxenite in the mantle sources of basalts through combined hafnium-neodymium-thorium isotope systematics, *Geochem. Geophys. Geosyst.*, *1*, doi:10.1029/1999GC000013.

Stracke, A., M. Bizimis, and V. J. M. Salters (2003), Recycling oceanic crust: Quantitative constraints, *Geochem. Geophys. Geosyst.*, *4*(3), 8003, doi:10.1029/2001GC000223.

Sturm, M. E., E. M. Klein, D. W. Graham, and J. Karsten (1999), Age constraints on crustal recycling to the mantle beneath the southern Chile Ridge: He-Pb-Sr-Nd isotope systematics, *J. Geophys. Res.*, *104*, 5097–5114.

Sun, S.-S., and W. F. McDonough (1989), Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes, in *Magmatism of the Ocean Basins*, edited by A. D. Saunders and M. J. Norry, *Geol. Soc. Spec. Publ.*, *42*, 313–345.

Tatsumoto, M., E. Hegner, and D. M. Unruh (1987), Origin of the West Maui volcanic rocks inferred from Pb, Sr, and Nd isotopes and a multicomponent model for oceanic basalt, in *Volcanism in Hawaii*, edited by R. W. Decker, T. L. Wright, and P. H. Stauffer, *U.S. Geol. Surv. Prof. Pap.*, *1350-II*, 723–744.

Thirlwall, M. F. (1995), Generation of the Pb isotopic characteristics of the Iceland plume, *J. Geol. Soc. London*, *152*, 991–996.

Thirlwall, M. F., M. A. M. Gee, R. N. Taylor, and B. J. Murton (2004), Mantle components in Iceland and adjacent ridges investigated using double-spike Pb isotope ratios, *Geochim. Cosmochim. Acta*, *68*(2), 361–386.

Thompson, P. M. E., P. D. Kempton, and A. D. Saunders (2002), The 48 Ma Koko Guyot: Early indications of temporal changes in the composition of the Hawaiian plume, *Eos Trans. AGU*, *83*(47), Fall Meet. Suppl., Abstract T61C-09.

Van Orman, J. A., T. L. Grove, N. Shimizu, and G. D. Layne (2002), Rare earth element diffusion in natural pyrope single crystal at 2.8 Gpa, *Contrib. Mineral. Petrol.*, *142*, 416–424.

Wang, Z., N. E. Kitchen, and J. M. Eiler (2003), Oxygen isotope geochemistry of the second HSDP core, *Geochem. Geophys. Geosyst.*, *4*(8), 8712, doi:10.1029/2002GC000406.

Wendt, J. I., M. Regelous, Y. Niu, R. Hekinian, and K. D. Collerson (1999), Geochemistry of lavas from the Garrett Transform Fault: Insights into mantle heterogeneity beneath the eastern Pacific, *Earth Planet. Sci. Lett.*, *173*, 271–284.

West, H. B., D. C. Gerlach, W. P. Leeman, and M. O. Garcia (1987), Isotopic constraints on the origin of Hawaiian lavas from the Maui Volcanic Complex, Hawaii, *Nature*, *330*, 216–219.

Worsley, J. R. (1973), Calcareous nannofossils: Leg 19 of DSDP, *Initial Rep. Deep Sea Drill. Proj.*, *19*, 741–750.

Yang, H.-J., F. A. Frey, and D. A. Clague (2003), Constraints on the source components of lavas forming the Hawaiian North Arch and Honolulu Volcanoes, *J. Petrol.*, *44*, 603–627.

Zindler, A., and S. R. Hart (1986), Chemical geodynamics, *Annu. Rev. Earth Planet. Sci.*, *14*, 443–571.