Melting of a complete section of recycled oceanic crust: Trace element and Pb isotopic evidence from Iceland

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[1] **Abstract:** We present new trace element and isotopic data on a selection of least evolved lavas in Iceland. Pb isotopic compositions are variable: $^{206}Pb/^{204}Pb$ ranges from 18.05 in picrites to 19.15 in alkali basalts. Large excesses of Sr and Pb and a deficiency of Hf and Zr relative to rare earth elements are characteristic of the picritic lavas (Ce/Pb ≈ 10, Sr/Nd ≈ 35, and Sm/Hf ≈ 1.75), whereas more normal ratios are observed in the alkali basalts (Ce/Pb ≈ 40, Sr/Nd ≈ 10, and Sm/Hf ≈ 1.4). These variations are correlated to systematic changes in Sr, Nd, and Pb isotopic compositions. Using these new data, the relationship between the Iceland plume and the Mid-Atlantic Ridge can be reexamined. The $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ relationship demonstrates clearly that all isotopic variations in Iceland have their origin in the plume source. In addition, the composition of both Reykjanes and Kolbeinsey Ridges results from contamination of the depleted mantle by the Iceland plume. Trace element and isotopic heterogeneities within Iceland are related to rock type and not to location in the island. This is contrary to what would be expected if a uniform plume mixed with surrounding mid-ocean ridge basalt (MORB), in which case the geochemical values would be more MORB-like at the perimeter. Instead, it suggests that the Iceland plume itself was highly heterogeneous. We propose that the source of the Iceland plume was old recycled oceanic crust that was stored in the mantle for a long time (potentially since the end of the Archean). Melting of the basaltic portion of this crust led to the formation of the alkali basalts, and melting of the clinopyroxene-plagioclase gabbroic portion of the same oceanic crust yielded the picritic basalts. In both cases, melting of the harzburgitic portion of the recycled lithosphere provided the necessary Mg and Ni. The tholeiites represent mixtures from the two sources. Iceland is therefore, together with Hawaii, a clear example of melting of a complete section of recycled oceanic lithosphere.

1. Introduction

[2] Iceland has the peculiarity of being formed by a deep mantle plume that interacts with a mid-ocean ridge and numerous studies have aimed at understanding its origin, mode of formation, and effect on the ridge location and chemical composition [e.g., *Fitton et al.*, 1997; *Hémond et al.*, 1993, 1988; *Schilling*, 1973; *Thirwall*, 1995]. Pioneering work by *Schilling* [1973] has shown that material from the Iceland plume invaded the mantle south of Iceland and changed its trace element and isotopic composition. Since this early study, various geochemical tools have been used to constrain the effect of the plume on the ridge, both south and north of the island. While general agreement has been reached on the contamination of the mid-ocean ridge along the Reykjanes Ridge in the south [*Hart et al.*, 1973; *Schilling*, 1973], the case is far less clear on the northern side of the island along the Kolbeinsey Ridge [*Devey et al.*, 1994; *Mertz et al.*, 1991]. *Mertz et al.* [1991], in particular, suggested not only that the ridge north of Iceland was not contaminated by the Iceland plume but also that the composition of the northern part of Iceland itself was strongly affected by the invasion of normal depleted mantle under the island. In a similar manner, the geochemical and isotopic heterogeneities reported for Icelandic lavas have been attributed either to heterogeneities in the plume source [*Kerr et al.*, 1995; *Fitton et al.*, 1997; *Thirwall*, 1995] or to mixing between a homogeneous plume and ordinary depleted mantle.

[3] In order to help understand these first-order issues we analyzed Pb isotopes and trace element concentrations for a selection of recent volcanics. These data provide new information that is complementary to previous constraints, which came primarily from Sr and Nd isotopic compositions.

2. Sample Selection

[4] Samples were selected from the collection studied by *Hémond et al.* [1988, 1993]. Although we concentrated on picrites and high-Mg basalts from the three main rift zones in Iceland, the East Rift Zone (ERZ), the Mid-Iceland Belt (MIL), and the West Rift Zone (WRZ) toward the Reykjanes Peninsula, we also analyzed a few alkaline volcanic rocks and several more common tholeiites. Our sample selection was aimed at investigating the source of the most primitive liquids in Iceland, and we avoided differentiated liquids in central volcanoes whose chemical composition are sometimes strongly affected by hydrothermal circulation. We focused instead on the more magnesian samples. Although some of these contain excess olivine, as in picrites D8-B1 and HEN5, the accumulation of olivine has no influence on the ratios of incompatible trace elements or isotopic compositions.

[5] Samples were also selected in order to cover most of the geographical locations. Their locations are shown on Figure 1.

[6] We concentrated primarily on the determination of Pb isotopic compositions because relatively few Pb isotopic analyses have previously been reported on Iceland lavas [*Elliot et al.*, 1991; *Furman et al.*, 1995; *Gee et al.*, 1998; *Hanan and Schilling*, 1997; *Hards et al.*, 1995; *Stecher et al.*, 1999; *Sun and Jahn*, 1975]. We also augmented the existing database by analyzing a large set of samples for an extended range of trace elements.

3. Analytical Techniques

[7] The trace element data reported in Table 1 were obtained using the inductively coupled plasma-mass spectometry (ICP-MS) at the University of Montreal. About 100 mg of powder was dissolved using a 4:1 mixture of 24 N HF
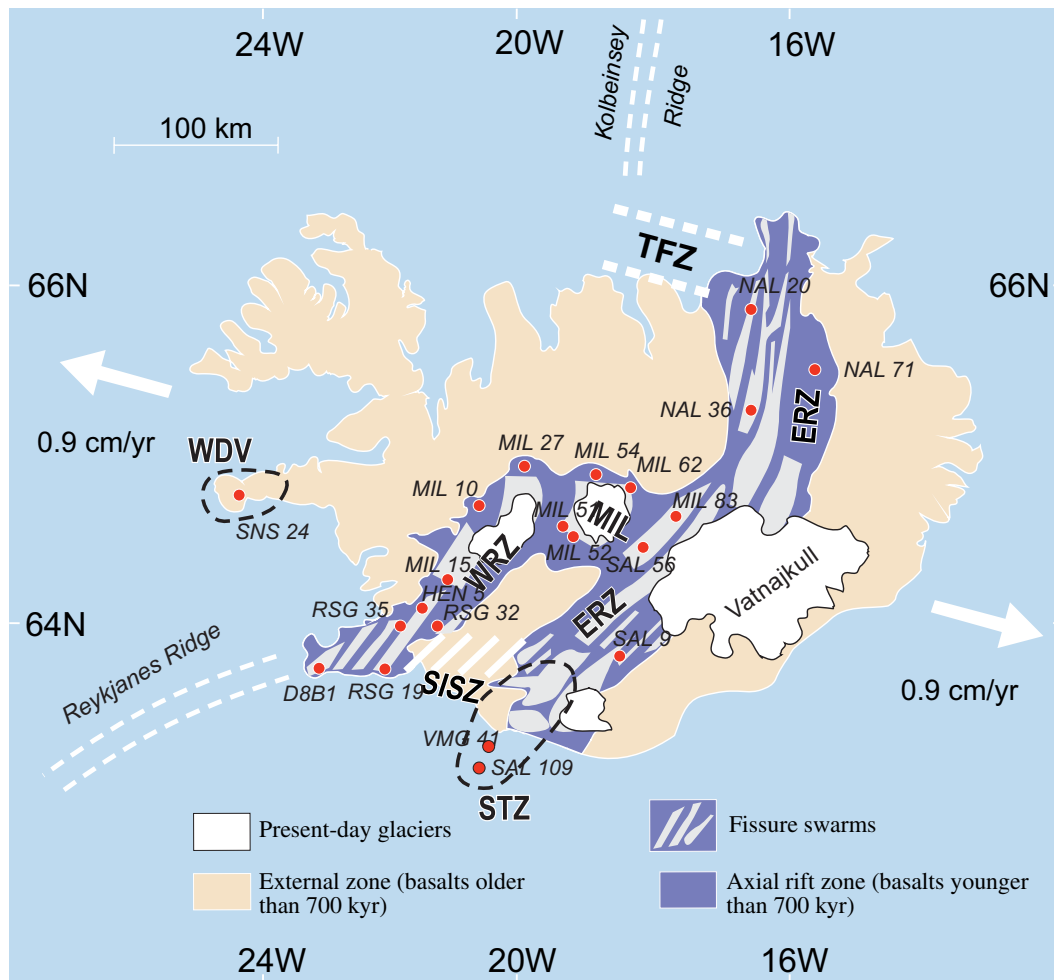
Figure 1. Map of Iceland showing sample locations. Abbreviations as follows: TFZ, Tjörness Fracture Zone; ERZ, East Rift Zone; MIL, Mid-Iceland Belt; WRZ, West Rift Zone; WDV, West Diverging Volcanism; STZ, South Transition Zone; SISZ, South Iceland Seismic Zone.

and 14 N HNO$_3$. After evaporation the residue was taken up several times in concentrated nitric acid and finally diluted in 200 mL of dilute nitric acid just before analysis on the machine. Data acquisition follows the method described by *Cheatham et al.* [1993].

[8] Pb isotopic compositions were obtained on rock chips at the University of Rennes. After a strong HCl leaching (1 hour in hot 6 N HCl), the chips were dissolved using HF and HNO$_3$,

and Pb was separated using the anion resin technique of *Manhès et al.* [1984]. During the course of analyses, blanks were always lower than 500 pg and were negligible relative to the amount of Pb in the samples. All samples were loaded and run twice in static mode on the mass spectrometer (Finnigan MAT 262). Values reported in Table 2 represent the average of the two independent runs and are corrected for fractionation using the average values measured for the standard NBS 981 and the

Table 1. New Trace Element Data Obtained by ICP-MS on Iceland Volcanics

	NAL20			NAL36			NAL71					SAL56		
	Others*	ICP-MS	% diff.	Others*	ICP-MS	% diff.	Others*	ICP-MS	ICP-MS	% diff.	% dupli.	Others*	ICP-MS	% diff.
Location	East Rift Zone			East Rift Zone			East Rift Zone					East Rift Zone		
Sublocation	Theistasreykjabunga			Keteldyngja			Sveinagja					Tröllahraun		
Rock type	olivine tholeiite			olivine tholeiite			quartz normative tholeiite					quartz normative tholeiite		
mg#		66.30			57.10			40.80					53.30	
La	1.82	1.87	2.9	5.19	5.37	3.3	9.55	15.43	15.50	38.1	0.4	9.03	10.12	10.8
Ce	5.09	5.44	6.4	14.03	14.49	3.1	23.32	37.54	37.92	37.9	1.0	16.98	19.16	11.4
Pr	0.83	0.90	8.2	1.99	2.26	11.8	3.08	5.43	5.45	43.3	0.3	2.48	2.93	15.5
Nd	4.39	4.72	6.9	10.36	10.85	4.5	14.45	23.86	24.36	39.4	2.0	11.82	13.91	15.0
Nd ID	4.60		2.4	10.60		2.3	23.70			2.7				
Sm	1.37	1.59	14.2	3.03	3.20	5.4	3.82	6.34	6.31	39.7	0.5	3.22	4.15	22.4
Eu	0.57	0.68	17.0	1.15	1.22	5.4	1.23	2.09	2.11	41.1	1.1	1.15	1.47	21.8
Gd	2.01	2.25	10.4	3.82	3.98	4.0	4.46	7.38	7.48	39.6	1.2	4.27	5.08	16.0
Tb	0.376	0.399	5.8	0.637	0.673	5.3	0.718	1.235	1.260	41.9	2.0	0.748	0.881	15.1
Dy		2.63			4.17			7.34	7.53		2.5		5.44	
Ho	0.57	0.56	1.8	0.88	0.85	3.3	1.72	1.49	1.52	15.1	1.6	1.08	1.12	3.5
Er	1.68	1.63	3.1	2.49	2.42	2.9	2.75	4.20	4.40	34.6	4.5	3.15	3.17	0.7
Tm	0.240	0.253	5.1	0.379	0.374	1.3	0.383	0.660	0.669	42.0	1.3	0.417	0.496	15.9
Yb	1.58	1.65	4.1	2.25	2.39	5.7	2.50	4.21	4.29	40.6	1.8	2.83	3.06	7.5
Lu	0.235	0.248	5.2	0.374	0.358	4.5	0.409	0.620	0.638	34.0	2.8	0.384	0.466	17.6
Pb†	0.299	0.298	0.3	0.478	0.490	2.4	1.210	1.232	1.258	1.8	2.1		0.549	
Th	0.106	0.097	9.3	0.298	0.287	3.8	1.430	1.368	1.437	4.5	4.8	0.612	0.601	1.8
U	0.035	0.032	9.4	0.095	0.094	1.1	0.420	0.421	0.439	0.2	4.1	0.177	0.183	3.3
Ba	16.2	16.4	1.5	39.3	40.0	1.7		113.1	115.1		1.8	40.5	43.1	5.9
Rb	2.00	0.90	123.2	2.08	2.62	20.5	11.60	11.75	11.67	1.2	0.6	3.94	4.27	7.7
Cs		.011			.029			.127	.130		2.3		.040	
Sr	96	125	23.0	174	181	4.0	189	186	189	1.8	1.7	168	170	1.0
Nb		2.1		7.8	7.6	3.2	21.2	19.3	19.2	9.8	0.9	11.0	10.9	0.8
Zr	55	34	63.3	83	70	18.0	193	187	190	3.1	1.3	105	112	6.1
Y	15.0	16.8	10.5	24.5	25.2	2.7	47.3	44.0	44.1	7.6	0.3	32.0	32.8	2.5
Hf		0.99			2.04			4.53	4.62		2.1		2.87	

Table 1. (continued)

	SAL9			MIL10					MIL15				
	Others*	ICP-MS	% diff.	Others*	ICP-MS	ICP-MS	% diff.	% dupli.	Others*	ICP-MS	ICP-MS	% diff.	% dupli.
Location	East Rift Zone			Mid-Iceland Belt					Mid-Iceland Belt				
Sublocation	Laki			Hallmundarhraun					Skjaldbreidur				
Rock Type	Quartz norm. tholeiite			Olivine tholeiite					Olivine tholeiite				
mg#		47.80			64.00					62.80			
La	13.46	14.07	4.4	3.77	3.92	3.94	3.7	0.6	1.64	3.77	3.66	56.6	3.0
Ce	33.12	35.36	6.3	9.55	10.09	10.26	5.4	1.6	4.12	10.58	10.17	61.1	4.0
Pr	4.68	5.28	11.3	1.39	1.54	1.59	9.7	3.0	0.62	1.70	1.68	63.3	0.9
Nd	21.24	23.63	10.1	7.09	7.38	7.53	3.9	1.9	2.89	8.44	8.27	65.8	2.0
Nd ID				7.20			4.3		8.28			0.1	
Sm	5.22	6.27	16.8	2.18	2.25	2.27	3.2	0.8	0.83	2.55	2.56	67.6	0.2
Eu	1.75	2.12	17.4	0.84	0.89	0.90	5.3	1.7	0.38	1.03	1.00	62.6	2.6
Gd	6.14	7.17	14.4	2.97	2.99	3.07	0.8	2.5	1.65	3.24	3.17	49.2	2.2
Tb	1.018	1.164	12.5	0.458	0.518	0.526	11.6	1.5	0.380	0.551	0.537	31.0	2.6
Dy		6.75		3.33	3.40	2.2	3.46	3.38	2.3				
Ho	1.30	1.36	4.5	0.80	0.70	0.70	13.4	0.0	0.61	0.70	0.68	12.9	3.2
Er	3.62	3.67	1.3	2.26	2.02	2.08	11.7	2.6	1.80	2.02	1.93	11.1	4.6
Tm	0.478	0.559	14.5	0.316	0.311	0.323	1.6	3.7	0.269	0.312	0.312	13.8	0.0
Yb	3.05	3.39	10.0	2.12	1.98	2.07	7.3	4.6	1.69	1.94	1.85	13.0	4.8
Lu	0.437	0.511	14.5	0.297	0.307	0.309	3.3	0.6	0.282	0.293	0.294	3.8	0.3
Pb*		1.318	3.94	0.460	0.479	0.472	4.0	1.5	0.339	0.403	0.262	15.9	53.8
Th	1.110	1.102	0.7	0.292	0.282	0.295	3.5	4.4	0.157	0.148	0.143	6.1	3.5
U	0.336	0.351	4.3	0.093	0.095	0.101	2.1	5.9	0.055	0.053	0.043	3.8	23.3
Ba	96.0	86.0	11.6	29.5	29.6	29.8		0.5	22.7	23.2	22.1	2.0	5.1
Rb	9.00	8.48	6.2	2.23	2.25	2.29	1.1	1.4	0.95	1.05	1.00	9.6	5.4
Cs	0.085	.026	.028		7.1	.011		.011		0.0			
Sr	252	237	6.3	133	137	138	2.8	0.7	159	164	158	2.8	3.8
Nb	21.0	18.3	15.0	5.0	5.1	5.1	1.2	1.0	5.7	5.7	5.5	0.7	2.1
Zr	186	194	3.9	59	57	51	2.8	11.3	65	64	62	1.9	3.5
Y	41.0	39.6	3.6	22.6	21.0	21.0	7.5	0.4	21.9	21.0	20.6	4.4	1.9
Hf		4.52			1.44	1.52		4.7		1.62	1.61		0.8

Table 1. (continued)

	MIL27			MIL51			MIL52			MIL54		
	Others*	ICP-MS	% diff.	Others*	ICP-MS	% diff.	Others*	ICP-MS	% diff.	Others*	ICP-MS	% diff.
Location	Mid-Iceland Belt			Mid-Iceland Belt			Mid-Iceland Belt			Mid-Iceland Belt		
Sublocation	Krokshraun						Illahraun			Lambarhraun		
Rock Type	Olivine tholeiite			Picritic Olivine tholeiite			Olivine tholeiite			Olivine tholeiite		
mg#		61.80			66.90			59.40			62.30	
La	3.73	3.81	2.0	1.60	1.66	3.8	3.57	2.74	30.4	2.04	2.39	14.8
Ce	9.88	10.23	3.4	4.59	4.87	5.8	8.59	7.60	13.0	5.57	6.69	16.8
Pr	1.49	1.60	6.9	0.76	0.83	8.3	1.32	1.23	7.8	0.88	1.09	19.7
Nd	7.65	7.82	2.2	4.23	4.37	3.3	6.54	6.22	5.2	4.80	5.60	14.3
Nd ID	7.53		3.7				6.13		1.4	5.32		5.1
Sm	2.40	2.40	0.1	1.44	1.55	7.1	2.14	2.09	2.5	1.66	1.90	12.8
Eu	0.92	0.96	3.5	0.60	0.66	8.8	0.82	0.87	6.1	0.69	0.80	13.6
Gd	3.18	3.12	1.8	2.18	2.25	3.1	2.89	2.91	0.6	2.37	2.65	10.4
Tb	0.500	0.540	7.4	0.396	0.410	3.4	0.504	0.511	1.4	0.409	0.470	13.0
Dy		3.41			2.70			3.35			3.04	
Ho	0.70	0.71	0.7	0.60	0.57	5.5	0.72	0.70	2.7	0.72	0.64	11.8
Er	2.16	2.04	6.1	1.80	1.68	7.3	2.02	2.05	1.5	1.80	1.89	4.7
Tm	0.311	0.313	0.6	0.258	0.265	2.6	0.300	0.322	6.8	0.249	0.295	15.6
Yb	2.00	2.00	0.1	1.69	1.72	1.7	1.83	2.06	11.1	1.71	1.89	9.5
Lu	0.324	0.299	8.4	0.248	0.259	4.2	0.291	0.308	5.5	0.270	0.283	4.6
Pb*	0.336	0.353	4.8	0.311	0.382	18.6	0.367	0.387	5.2	0.332	0.347	4.3
Th	0.210	0.199	5.5	0.078	0.096	18.5	0.185	0.177	4.5	0.144	0.131	9.9
U	0.068	0.067	1.5	0.029	0.035	18.3	0.060	0.064	6.3	0.048	0.050	4.0
Ba	25.0	24.9	0.3		11.0		20.1	19.9	1.1	16.5	17.6	6.1
Rb	1.27	1.34	5.5		0.68		1.36	1.35	1.0	0.89	1.04	14.1
Cs		0.013			0.008			0.015			0.011	
Sr	147	153	3.8		118		133	135	1.1	133	139	4.3
Nb	5.3	4.9	7.2		1.7		3.1	3.1	0.5	2.6	2.7	4.4
Zr	59	59	0.2		36		52	48	7.7	44	42	6.7
Y	22.0	21.2	3.7		17.2		21.9	20.9	4.7	20.6	19.5	5.8
Hf		1.51			0.99			1.29			1.19	

Table 1. (continued)

	MIL62			MIL83					VMG41			SNS24		
	Others*	ICP-MS	% diff.	Others*	ICP-MS	ICP-MS	% diff.	% dupli.	Others*	ICP-MS	% diff.	Others*	ICP-MS	% diff.
Location	Mid-Iceland Belt			Mid-Iceland Belt					South Transition Zone			West Diverging Volcanism		
Sublocation	Illvidrahnjukahraun			Dvergar					Heimaey			Budarhraun		
Rock Type	Picrite			Picrite					Hawaiite			Alkali Olivine Basalt		
mg#	70.60			69.70					40.40			58.00		
La	1.06	1.07	1.1	0.89	0.88	0.91	0.8	3.0	26.77	27.45	2.5	28.38	28.10	1.0
Ce	3.11	3.29	5.4	2.79	2.77	2.86	0.6	3.1	59.28	61.82	4.1	57.92	62.26	7.0
Pr	0.53	0.58	8.0	0.50	0.52	0.52	2.9	0.8	7.90	8.71	9.3	7.87	8.13	3.2
Nd	3.03	3.23	6.0	2.90	2.94	3.00	1.5	1.8	35.44	36.93	4.0	31.13	32.76	5.0
Nd ID	3.09		4.2	2.94				1.9						
Sm	1.16	1.22	5.0	1.20	1.19	1.21	0.6	1.0	8.46	8.87	4.6	6.42	6.64	3.3
Eu	0.51	0.54	5.3	0.53	0.55	0.55	4.3	1.1	2.78	2.92	4.8	2.20	2.29	4.1
Gd	1.84	1.86	1.3	1.85	1.92	1.92	3.4	0.3	9.05	9.32	2.9	6.00	6.12	1.9
Tb	0.337	0.344	2.0	0.338	0.354	0.356	4.5	0.6	1.40	1.526	8.3	0.849	0.924	8.1
Dy		2.33			2.39	2.43		1.6		8.47			4.86	
Ho	0.56	0.50	12.4	0.50	0.52	0.53	2.1	3.0	1.65	1.67	1.4	0.90	0.90	0.3
Er	1.58	1.50	5.5	1.37	1.55	1.57	11.4	1.5	4.56	4.61	1.0	2.39	2.48	3.6
Tm	0.231	0.237	2.5	0.194	0.240	0.247	19.2	2.8	0.646	0.714	9.5	0.319	0.364	12.4
Yb	1.54	1.53	0.9	1.18	1.60	1.62	26.0	1.4	3.90	4.27	8.6	1.69	2.29	26.0
Lu	0.214	0.233	8.2	0.180	0.243	0.247	25.9	1.6	0.529	0.658	19.6	0.203	0.329	38.3
Pb*	0.446	0.683	34.7	0.182	0.230	0.187	20.9	23.0		1.823			3.202	
Th	0.062	0.050	24.0	0.052	0.046	0.046	13.0	0.0	2.16	2.177	0.8	2.030	2.064	1.6
U	0.021	0.020	5.0	0.017	0.018	0.015	5.6	20.0	0.70	0.740	6.1	0.597	0.637	6.3
Ba	7.4	7.3	0.8	5.6	5.8	6.0	3.6	3.0	248.0	238.0	4.2	357.0	341.8	4.5
Rb	0.38	0.43	10.8	0.31	0.34	0.36	8.0	6.6	22.0	21.81	0.9	18.00	19.08	5.7
Cs		0.004			0.004	.004		0.0		.264			.200	
Sr	106	111	4.9	101	103	106	2.0	3.1	384	369	4.0	495	485	2.0
Nb	1.1	1.0	13.5	0.8	0.8	0.8	1.8	1.5	35.0	32.8	6.7	47.0	41.4	13.5
Zr	27	24	11.1	25	21	22	16.8	0.6	273	290	5.8	174	181	3.8
Y	14.0	15.3	8.7	14.5	15.6	16.0	6.8	2.9	51.0	49.2	3.7	28.0	26.2	6.9
Hf		0.74			0.72	0.72		0.0		6.41			3.93	

Table 1. (continued)

	D8B-1			HEN5			RSG19					RSG32		
	Others*	ICP-MS	% diff.	Others*	ICP-MS	% diff.	Others*	ICP-MS	ICP-MS	% diff.	% dupli.	Others*	ICP-MS	% diff.
Location	West Rift Zone			West Rift Zone			West Rift Zone					West Rift Zone		
Sublocation	Vatnsheidi			Hengill			Selvogsheidi					Seydisholar		
Rock Type	Picrite			Picrite			Olivine tholeiite					Olivine tholeiite		
mg#	79.70			75.30			60.80					60.20		
La	1.02	1.09	7.0	0.81	0.92	12.2	1.96	2.07	2.17	5.4	4.6	11.50	12.26	6.2
Ce	2.78	3.02	7.9	2.43	2.79	12.7	5.29	5.74	5.87	7.9	2.1	27.20	29.64	8.2
Pr	0.45	0.51	11.4	0.44	0.52	14.9	0.85	0.97	0.99	12.3	1.9	3.66	4.19	12.6
Nd	2.46	2.71	9.4	2.55	2.98	14.4	4.57	4.98	5.19	8.4	4.0	15.86	18.37	13.6
Nd ID							4.83			6.9		17.10		6.9
Sm	0.88	1.02	14.3	0.87	1.16	24.7	1.50	1.71	1.82	12.3	6.1	3.39	4.46	24.0
Eu	0.38	0.45	14.6	0.37	0.48	23.3	0.63	0.73	0.75	14.1	2.8	1.16	1.52	23.8
Gd	1.42	1.59	10.5	1.36	1.71	20.6	2.21	2.45	2.53	10.0	3.0	3.83	4.68	18.2
Tb	0.278	0.291	4.5	0.263	0.315	16.5	0.404	0.430	0.447	6.0	3.8	0.625	0.754	17.1
Dy		2.03			2.05			2.86	2.99		4.2		4.16	
Ho	0.44	0.43	3.0	0.39	0.43	9.0	0.61	0.60	0.64	1.7	6.1	0.78	0.78	0.6
Er	1.35	1.27	6.3	1.15	1.26	9.0	1.78	1.77	1.84	0.6	4.0	2.12	2.13	0.4
Tm	0.195	0.204	4.4	0.165	0.205	19.5	0.264	0.276	0.295	4.3	6.4	0.313	0.312	0.3
Yb	1.26	1.31	3.7	1.13	1.22	7.2	1.72	1.78	1.83	3.1	2.6	1.81	1.89	4.1
Lu	0.190	0.196	3.1	0.158	0.183	13.7	0.244	0.266	0.277	8.3	4.0	0.249	0.266	6.4
Pb*		0.521			0.195		0.341	0.364	0.321	6.3	13.4	0.966	1.023	5.6
Th	0.056	0.058	3.8	0.034	0.043	21.9	0.131	0.120	0.124	9.2	3.2	0.940	0.893	5.3
U	0.020	0.011	77.3	0.012	0.007	75.7	0.043	0.044	0.030	2.3	46.7	0.299	0.301	0.7
Ba	8.4	7.8	7.5	6.3	6.9	8.8	16.9	17.2	17.0	1.7	1.5		93.5	
Rb	0.57	0.48	18.3	0.32	0.28	13.1	0.96	0.98	0.98	2.4	0.4	7.00	6.70	4.5
Cs		.003			.002			.013	.011		18.2		.074	
Sr	72	71	0.8	87	91	4.1	127	133	133	4.2	0.3	278	303	8.2
Nb	1.0	1.3	20.4	0.9	0.8	8.3	2.2	2.4	2.5	8.5	2.6	16.6	16.3	1.9
Zr	22	20	8.3	22	22	0.2	35	29	34	19.3	13.9	124	129	3.5
Y	11.0	12.7	13.6	10.0	13.1	23.5	18.7	17.8	18.7	5.2	5.0	21.6	23.2	6.8
Hf		0.59			0.66			1.00	1.06		5.3		3.08	

Here % diff. corresponds to the percent difference between ICP-MS data and data obtained using other methods; % dupli. corresponds to the percent difference between two independent ICP-MS measurements.

*Data published by *Hémond et al.* [1993].

†Pb concentrations measured by ID (in the "others") or ICP-MS on rock powders.

Table 2. Pb Concentrations and Isotopic Compositions of Iceland Volcanics

Sample	Sublocation	Rock Type	Lat (North)	Long (West)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb, ppm
			East Rift Zone					
NAL20	Theistasreykjabunga	qz thol	65° 52′ 34″	16° 50′ 32″	18.054	15.427	37.708	0.279
NAL20*								0.290
NAL36	Keteldyngja	qz thol	65° 25′ 16″	16° 40′ 26″	18.387	15.470	38.104	0.382
NAL36*					18.389	15.475	38.089	0.393
NAL71	Sveinagja	qz thol	65° 39′ 19″	16° 25′ 26″	18.484	15.483	38.229	1.223
SAL56	Tröllahraun	qz thol	64° 26′ 53″	18° 08′ 07″	18.586	15.577	38.537	0.550
SAL9	Laki	qz thol	63° 51′ 53″	17° 48′ 26″	18.514	15.529	38.397	0.966
			Mid-Iceland Belt					
MIL10	Hallmundarhraun	ol thol	64° 46′ 29″	20° 42′ 54″	18.603	15.463	38.158	0.332
MIL10*					18.607	15.452	38.124	0.335
MIL10*								0.330
MIL15	Skjaldbreidur	ol thol	64° 23′ 47″	20° 45′ 18″	18.513	15.474	38.182	0.393
MIL15*								0.317
MIL15*								0.321
MIL27	Krokshraun	ol thol	65° 02′ 01″	19° 45′ 09″	18.623	15.481	38.234	0.304
MIL27*								0.305
MIL 51		ol thol	64° 42′ 17″	19° 14′ 30″	18.281	15.455	37.971	0.205
MIL 51*					18.276	15.432	37.902	
MIL52	Illahraun	ol thol	64° 40′ 16″	19° 09′ 21″	18.443	15.454	38.064	0.313
MIL54	Lambarhraun	ol thol	65° 02′ 34″	18° 54′ 30″	18.394	15.436	38.010	0.296
MIL62	Illvidrahnjukahraun	picrite	65° 00′ 24″	18° 41′ 17″	18.179	15.418	37.790	0.269
MIL62*								0.306
MIL83	Dvergar	picrite	64° 44′ 43″	17° 38′ 03″	18.155	15.466	37.979	0.122
MIL83*								0.119
			South Transition Zone					
SAL109	Surtsey	alk ol bas	63° 16′ 53″	20° 37′ 34″	19.164	15.647	39.007	1.055
SAL109*								1.047
VMG41	Heimaey	Hawaiite	63° 26′ 29″	20° 16′ 52″	19.140	15.636	38.973	1.849
			West Rift Zone					
D8B-1	Vatnsheidi	picrite	63° 50′ 32″	22° 25′ 56″	18.553	15.510	38.326	0.171
D8B-1*								0.170
HEN5	Hengill	picrite	64° 05′ 48″	21° 12′ 30″	18.323	15.554	38.138	0.161
HEN5*								0.160

Table 2. (continued)

Sample	Sublocation	Rock Type	Lat (North)	Long (West)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb, ppm
			West Rift Zone					
RSG19	Selvogsheidi	ol thol	63° 52′ 25″	21° 35′ 18″	18.554	15.476	38.162	0.408
RSG19*					18.559	15.487	38.205	0.390
RSG32	Seydisholar	ol thol	64° 02′ 25″	20° 54′ 41″	18.879	15.520	38.438	0.764
RSG32*								0.743
RSG35	Nesjahraun	ol thol	64° 07′ 17″	21° 15′ 56″				0.625
			West Diverging Volcanism					
SNS24	Budarhraun	alk ol bas	64° 48′ 30″	23° 25′ 37″	18.989	15.592	38.819	1.532
SNS24*								1.330

*Duplicate analysis.

All Pb concentrations were obtained on rock chips (crushed by hand in agat mortar) by isotopic dilution. All Pb isotopic compositions are averages of two independent runs on the mass spectrometer. They were corrected for fractionation using average values measured for NBS 981 and the recommended values of *Todt et al.* [1996]. Rock types are qz, quartz; thol, tholeiite; ol, olivine; alk, alkali; bas, basalt.

recommended values of *Todt et al.* [1996]. Complete duplicate analyses, including dissolution and chemistry, were performed for four samples (see Table 2).

[9] Pb concentrations were obtained by three different methods: ICP-MS on powders and isotopic dilution mass spectrometry on both powders and chips. The isotopic dilution data were obtained in Brest using a ^{206}Pb spike, the classical anion resin technique and a Finnigan MAT 261 mass spectrometer. Pb concentrations measured by ICP-MS and isotopic dilution on rock powders are given in Table 1, and concentrations obtained by the same method on carefully hand-crushed rock chips are reported in Table 2.

4. New Results and Comparison of Trace Element Data From Various Methods

[10] New trace element data obtained by ICP-MS are, with few exceptions, consistent with the XRF, irotopic dilution (ID) and high-performance liquid chromatography (HPLC) data reported by *Hémond et al.* [1993]. The precision on the new ICP-MS data can be evaluated using the duplicate analyses of samples NAL71, MIL10, MIL15, MIL83, and RSG19 (see Table 1). For all samples, measured values differ by <5 %. The only element that is not measured with the same accuracy is U on the extremely depleted samples MIL15, MIL83, and RSG19. In these particular cases, U concentrations are too low to be measured accurately by ICP-MS.

[11] New rare earth element (REE) data are comparable with values reported by *Hémond et al.* [1993] with the exception of NAL71, SAL56, SAL9, MIL15, MIL54, and SNS24. For all these samples, the new data are higher than values obtained by HPLC but comparable

with available Nd concentrations measured by isotopic dilution. This suggests that a portion of the REE was lost during the HPLC procedure. For this reason, we prefer to use the new ICP-MS data for the following discussion. Although elements measured previously by XRF (Ba, Rb, Sr, Nb, Zr, and Y) are also well reproduced by the ICP-MS measurements, the new Rb data are probably better than the old XRF data, which were close to detection limits for this instrument. In contrast, Th and U data previously measured by isotopic dilution by *Hémond et al.* [1988] are probably more reliable than the ICP-MS data, particularly on the very poor samples.

[12] Cs contents were not reported by *Hémond et al.* [1993], and the new data, even for the very depleted samples, seem to be generally of high quality, judging from the duplicate analyses and the constancy of the Rb/Cs (91 ± 8) ratio among the various samples. The only exceptions are samples D8B-1 and HEN5, for which the Cs concentrations are too low to be
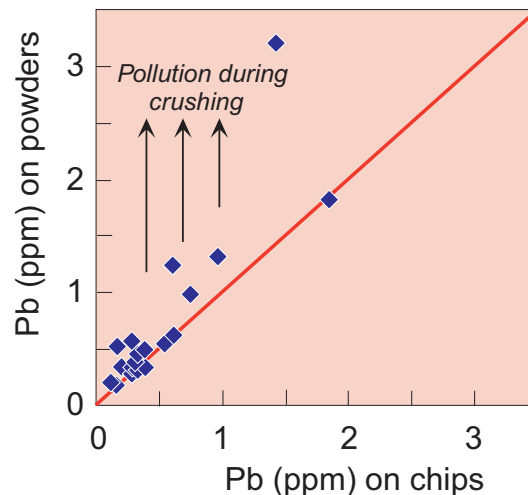
Figure 2. Comparison of Pb concentrations measured on powders and rock chips showing that concentrations measured on powders are always higher than those obtained on chips. It suggests that powdered samples were highly contaminated during the crushing procedure.
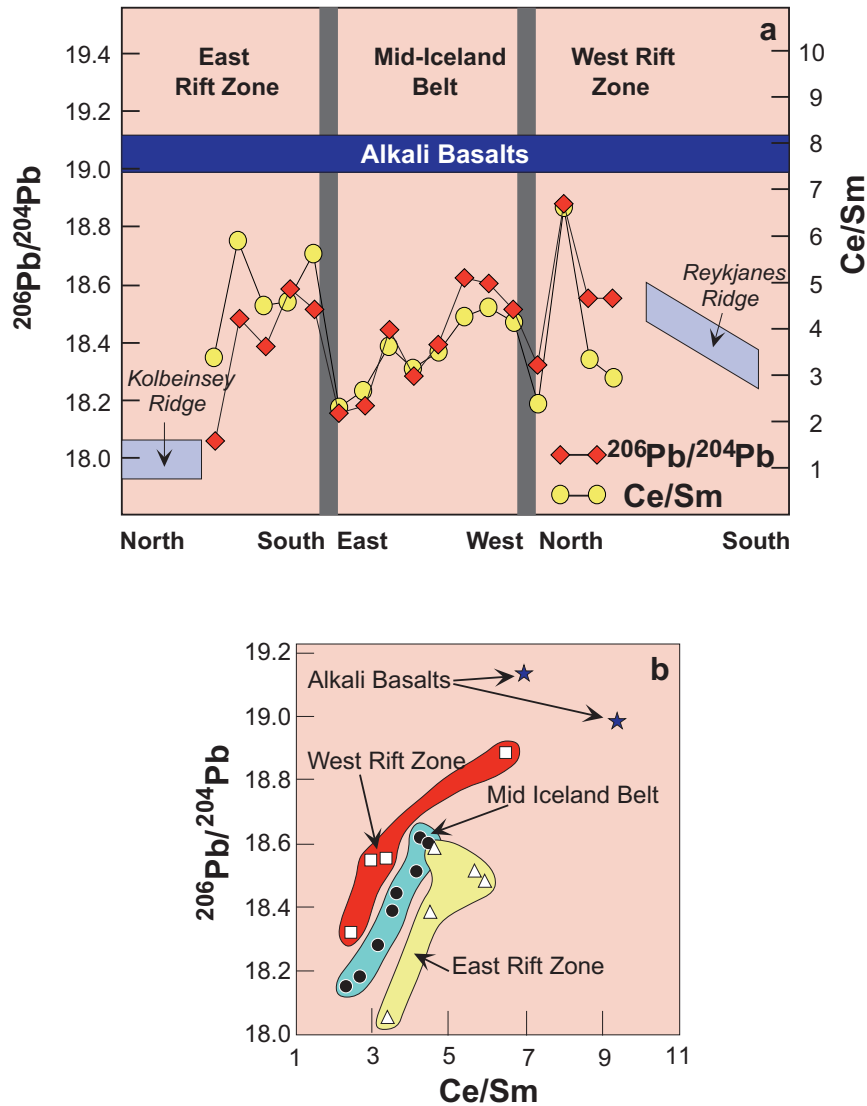
Figure 3. (a) Variation of ^{206}Pb/^{204}Pb (left axis and lozenges) and Ce/Sm (right axis and circles) as a function of sample position along the three ridge segments in Iceland. (b) Ce/Sm versus ^{206}Pb/^{204}Pb. Ce/Sm is chosen as a measure of the degree of depletion or enrichment of the liquids. Figures 3a and 3b both show that changes in Pb isotopic compositions are related to rock type and not to location in the island. The lowest Pb isotopic compositions are not restricted to samples located in the edge of Iceland. In contrast, the presence of very unradiogenic values in the center of the island suggests that the plume source is heterogeneous with both radiogenic and unradiogenic Pb components.

accurately measured, as can be seen from their elevated Rb/Cs ratios. Pb concentrations were measured on both powdered samples and rock chips. In the case of powders, most samples were analyzed both by ICP-MS and by isotopic dilution. Rock chips were only analyzed by isotopic dilution. The results reported in Figure 2 show clearly that concentrations obtained on the two types of samples are generally not identical. Pb concentrations obtained on pow-

Table 3. Isotopic analysis of Sample I48 Provided by S.-S. Sun

Ratios	Published Values	New Values	
		Leached Powder	Unleached Powder
$^{206}Pb/^{204}Pb$	19.260 19.249	19.256	19.228
$^{207}Pb/^{204}Pb$	15.558 15.551	15.544	15.524
$^{208}Pb/^{204}Pb$	38.925 38.908	38.918	38.857
$^{87}Sr/^{86}Sr$	0.70336	0.703329 ± 6	0.703323 ± 6
$^{143}Nd/^{144}Nd$		0.512989 ± 22	0.512956 ± 7

No rock chips were available, and we had to perform the isotopic analyses on rock powders.

Two aliquots were taken. The first aliquot was severely leached (see section 3 on analytical techniques), while the second one was not leached at all. Results show that slight differences exist between *Sun and Jahn*'s [1975] Pb results and our results on both leached and unleached powders. However, these differences are not significant.

ders are systematically higher than those of rock chips, suggesting that Pb was added to the sample during the crushing procedure. A similar observation for samples from Rurutu Island was interpreted by *McDonough and Chauvel* [1991] in terms of pollution during sample preparation. We suspect that the Iceland rock powders were contaminated during crushing, which was done in 1981 using a tungsten carbide mill. We will not use these data and will base our discussion of lava petrogenesis on Pb contents obtained on rock chips.

[13] Pb isotopic compositions obtained for the whole range of rock types are variable: $^{206}Pb/^{204}Pb$ ranges from 18.05 to 19.16 and the variation overlaps with previously reported values [*Elliott et al.*, 1991; *Furman et al.*, 1995; *Gee et al.*, 1998; *Hanan and Schilling*, 1997; *Hards et al.*, 1995; *Stecher et al.*, 1999; *Sun and Jahn*, 1975]. The changes in Pb isotopic composition appear to be independent of sample location in the island (see Figures 1 and 3a) but correlate with rock type. The lowest Pb isotopic ratios are obtained on the most magnesian lavas, which have the most depleted trace element patterns, and the highest values

are found for the alkali basalts (Figures 3a and 3b). We noticed a slight systematic difference between our Pb isotopic results and those reported by *Sun and Jahn* [1975] and suspected that the difference could be due to differences in analytical procedure. To test this, a sample with radiogenic Pb isotopic composition originally published by *Sun and Jahn* [1975] was reanalyzed and complementary Sr and Nd isotopic compositions were also determined. Results given in Table 3 show that we obtained values similar to those published. We conclude therefore that the difference between samples collected by Sun and Jahn and by ourselves is real and might have a geological significance.

5. Discussion

[14] As mentioned in section 1, various models have been proposed to explain the effect of the Iceland plume on the two neighboring ridges, the Reykjanes Ridge to the south and the Kolbeinsey Ridge to the north [*Elliot et al.*, 1991; *Fitton et al.*, 1997; *Hémond et al.*, 1993; *Mertz et al.*, 1991]. The Iceland plume clearly influences the composition of basalts along the

ridge, as has been demonstrated along the Reykjanes Ridge where *Hart et al.* [1973], *Schilling* [1973], and *Sun et al.* [1975] showed that La/Sm ratios and Sr and Pb isotopic compositions increase as Iceland is approached. In contrast, as Iceland is approached from the north along the Kolbeinsey Ridge, the situation is quite different [*Mertz et al.*, 1991]. Sr isotopic compositions increase slightly, while Pb isotopic compositions remain almost constant with low values comparable to those reported by *Elliot et al.* [1991] for the Theistareykir picrites, which are located in the northernmost part of the rift in Iceland. *Mertz et al.* [1991] used the lack of Pb isotopic variation along the ridge and the similarity with values reported for the Theistareykir picrites to conclude that the Iceland plume had no influence on the composition of the Kolbeinsey Ridge. They also suggested that material from the depleted upper mantle source of Kolbeinsey Ridge basalts invaded the region beneath northern Iceland and formed the source of the Theistareykir picrites which erupted along the Northern Rift Zone.

[15] The difference in isotope compositions between the Reykjanes and the Kolbeinsey Ridges raises an important question about the composition of the Iceland plume and its influence on both sides of the island. Namely, if the Iceland plume has a composition that is uniform both in terms of trace elements and isotopes, mixing between ambient mantle and the plume should lead to simple binary mixing relationships. In this case, the progressive change in isotopic ratios as Iceland is approached from the south along the Reykjanes Ridge would reflect mixing between the two sources, and the lack of similar isotopic variation along the Kolbeinsey Ridge would suggest, as proposed by *Mertz et al.* [1991], that normal upper mantle invades the region located in the northern part of the Iceland rift. In contrast, if the Iceland plume is heterogeneous at a scale smaller than that of the island and if

the plume material contaminated the adjacent ridges, this process could affect the composition of ridges on opposite sides of the island in different ways. In this case, it might be expected that distinctive isotopic compositions, such as the very unradiogenic values reported for the Theistareykir picrites and the Kolbeinsey basalts, would exist at other parts of the island.

[16] Sr and Nd isotopic compositions alone do not distinguish clearly between the two possibilities because the composition of the depleted upper mantle is similar to that of the most depleted volcanic rocks sampled in Iceland. In contrast, Pb isotopic compositions can provide new information if used in conjunction with trace elements and other isotopic data. This is the issue that we address in the discussion using our new Pb isotope results and trace element data.

5.1. Does the Iceland Plume Affect the Atlantic Ridge on Both Sides of the Island?

[17] It is commonly thought that plumes have relatively enriched isotopic compositions like those used to characterize the mantle end-members enriched mantle 1 (EM1), EM2, and high μ (μ = $^{238}Pb/^{204}Pb$) (HIMU). On this basis, it might be assumed that the composition of the Iceland plume is best represented by that of the alkali volcanoes located at various parts of the island. This interpretation would, however, be difficult to justify in view of the small proportion of these alkaline lavas in relation to the entire range of magmas produced all over Iceland. The majority of primary volcanics erupted on Iceland are tholeiites, and liquid compositions vary from picrites to olivine tholeiites, quartz tholeiites, and alkali basalts. More differentiated liquids are also found in central volcanoes along the rift but their origin is complex and probably involves crustal con-

tamination [*Nicholson et al.*, 1991]. These lavas should therefore be excluded when considering the composition of the plume source. The different types of primitive lavas define a range of Nd and Sr isotopic compositions that has been considered by *Hémond et al.* [1993] to represent that of the plume source. The amplitude of variations observed both in terms of Sr and Nd isotopes is equivalent to other plume-related oceanic islands such as Hawaii [*Stille et al.*, 1983; *Lassiter et al.*, 1996; *Hauri et al.*, 1996].

[18] In the new Pb isotopic compositions reported in Table 2 and plotted in Figures 3 and 4, $^{206}Pb/^{204}Pb$ varies from 18.05 to 19.16 and correlates with rock type. The most magnesian lavas have the lowest $^{206}Pb/^{204}Pb$, while the highest ratios are obtained on the alkali basalts from Surtsey and Heimaey (Vestman islands) and Budarhraun from the West Diverging Volcanism. The total range does not extend to the extremely low values reported by *Elliott et al.* [1991] for the Theistareykir picrites. However, our values are similar to values reported by *Hanan and Schilling* [1997], who showed that Elliot et al.'s extremely low values resulted from inadequate mass fractionation correction; our highest Pb isotopic compositions are comparable to the highest values reported by *Sun and Jahn* [1975]. No systematic correlation between geographical location in the island and isotopic compositions can be established (see Figure 3a). Rather, the Pb isotope compositions seem to be evenly distributed throughout the island. For example, low Pb isotopic ratios were obtained for sample NAL20 located in the northern part of the East Rift Zone, for samples MIL83 and MIL51 located in the Mid-Iceland Belt, and, to a lesser extent, for sample HEN5 located on the Reykjanes Peninsula. The lack of a systematic relationship suggests that the Pb isotopic composition of the source of the lavas is not uniform but

varies considerably and has little relationship to the geographic location of the lavas relative to the center of the island and distance to the Mid-Atlantic Ridge. The lack of relationship between geographical position in the island and Pb isotopic compositions suggests therefore that the isotopic variation is not due to simple mixing between uniform plume source and ambient depleted mantle at the edge of the plume. It appears, instead, that the Iceland plume was heterogeneous and that the unradiogenic $^{206}Pb/^{204}Pb$ reported for the picrites are as representative of the plume source as the radiogenic values found in the most alkaline basalts.

[19] Figure 4 shows the relationship between $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ in Iceland as well as on the two adjacent ridge segments, the Kolbeinsey and the Reykjanes Ridges. Figure 4 demonstrates that both Kolbeinsey and Reykjanes Ridges have compositions that deviate from that of the Mid-Atlantic Ridge farther away from Iceland: as Iceland is approached from the south along the Reykjanes Ridge, both $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ increase; in contrast, as Iceland is approached from the north along the Kolbeinsey Ridge, $^{206}Pb/^{204}Pb$ remains constant while $^{87}Sr/^{86}Sr$ increases. The plume materials tapped on the two ridges are therefore isotopically distinct, but they both coexist within Iceland itself.

[20] Kolbeinsey and Reykjanes Ridges define two distinct trends in Figure 4. These two trends are not parallel but converge on a composition with $^{87}Sr/^{86}Sr \approx 0.7024$ and $^{206}Pb/^{204}Pb \approx 17.9$. This composition could be considered that of the Atlantic depleted mantle before contamination by the Iceland plume. Such Sr and Pb isotopic ratios are very unradiogenic in comparison with the majority of published values for the North Atlantic mid-ocean ridge basalt (MORB) (see Figure 4) but are similar to average values compiled
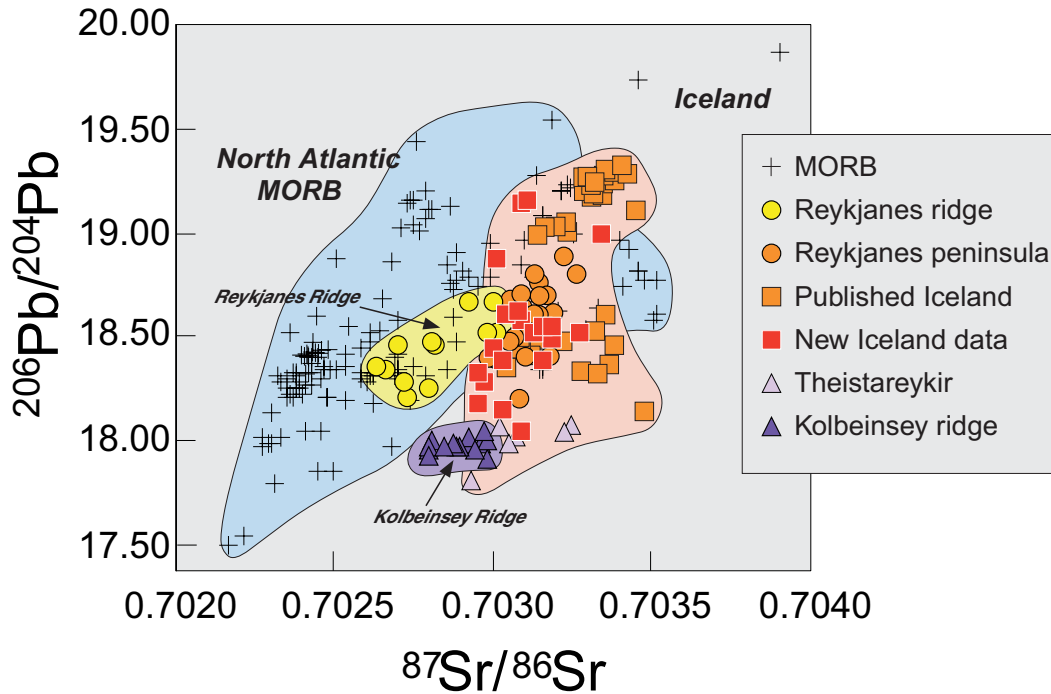
Figure 4. The ratio $^{206}Pb/^{204}Pb$ versus $^{87}Sr/^{86}Sr$ showing the isotopic variations within Iceland and the effect of the Iceland plume on both the Reykjanes and the Kolbeinsey Ridges. Data sources for Iceland, Kolbeinsey, and Reykjanes Ridges are *Cohen and O'Nions* [1982], *Elliott et al.* [1991], *Furman et al.* [1991], *Gee et al.* [1998], *Hards et al.* [1995], *Hart et al.* [1973], *Hémond et al.* [1993], *Hémond et al.* [1988], *Mertz et al.* [1991], *Park* [1990], *Stecher et al.* [1999], *Sun and Jahn* [1975], *Sun et al.* [1975], and this work. Data sources for North Atlantic MORB are *Cohen et al.* [1980], *Cohen and O'Nions* [1982], *Dosso et al.* [1993], *Dupré and Allègre* [1980], *Hamelin and Allègre* [1985], *Hamelin et al.* [1984], *Hofmann et al.* [1986], *Ito et al.* [1987], *O'Nions et al.* [1977], *Shirey et al.* [1987], *White and Hofmann* [1982], *White and Schilling* [1978], and C. Hémond (unpublished data, 1999).

for Pacific MORB ($^{87}Sr/^{86}Sr \approx 0.7024$ and $^{206}Pb/^{204}Pb \approx 18.0$) [*Chauvel and White*, 1998]. This suggests that the depleted mantle below the North Atlantic upper mantle could have a composition similar to that underlying the Pacific Ocean but that its composition has been highly modified by interaction with numerous plumes all along the ridge.

5.2. Characteristics and Origin of the Iceland Plume

[21] New trace element data reported in Table 1 provide additional strong constraints on the

composition and makeup of the Iceland plume. Of special interest are the Cs, Rb, Ba, Sr, Hf, and Pb concentrations, which show peculiar variations relative to other trace elements and isotopic compositions.

[22] *Hémond et al.* [1993] showed that the more magnesian lavas in Iceland are characterized by large excesses of Sr, Ba, and Rb relative to trace elements with similar geochemical behavior (see Figure 5). They suggested that these positive anomalies could be explained by the digestion of fluid-derived veins by magmas deep in the Iceland

crust. The new trace element data cast some doubt on this interpretation for the following reasons:

[23] The new Cs concentrations obtained for samples with compositions ranging from picrite to alkali basalt show a coherent
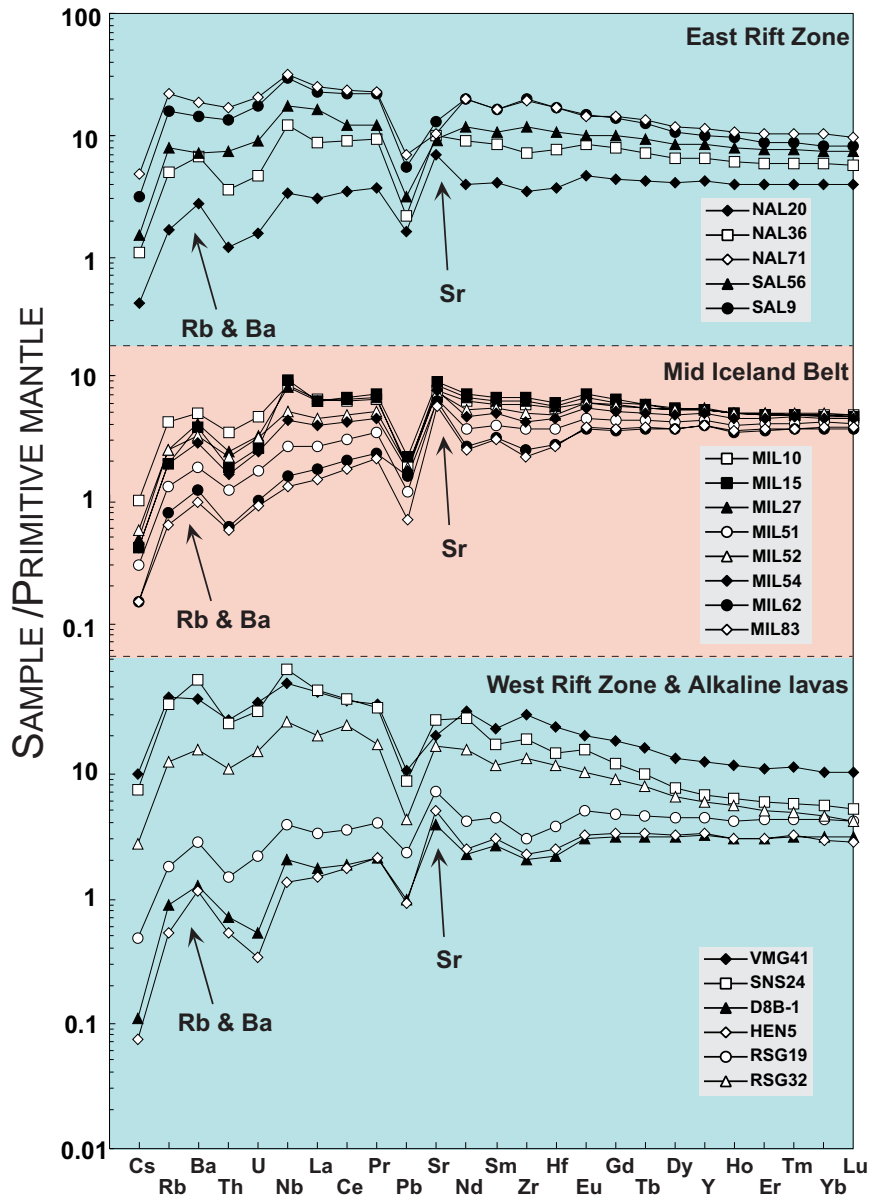
Figure 5. Trace element patterns for the Iceland lavas normalized to primitive mantle values [*Hofmann*, 1988]. Samples are grouped by geographical location. In the three areas, patterns are similar. The most depleted lavas have sharp positive Rb, Ba, and Sr anomalies and smaller but significant negative Zr and Hf anomalies. As the overall trace element concentrations increase, both negative and positive anomalies vanish.

behavior with Rb concentrations. While Rb/Cs might be expected to vary quite widely in fluid-derived deposits, all samples have constant Rb/Cs with an average of 91 ± 8. This value is similar to that compiled for mantle-derived volcanics by *McDonough et al.* [1992] and significantly different from that of continental crust (25) [*McDonough et al.*, 1992], river waters (43) [*Chester*, 1990], seawater (42) [*Von Damm*, 1990], and hydrothermal fluids (≈60) [*James et al.*, 1995; *Von Damm*, 1990]. The excess Rb observed in the picrites and more magnesian tholeiites is therefore more likely to have its origin in the source of the volcanics or it might result from peculiar melting conditions during the formation of the lavas.

[24] The new Hf and Zr concentrations obtained for the same set of samples correlate systematically with Sm concentrations. The Sm/Hf ratio decreases from 1.7 in the picritic tholeiites to 1.4 in the more alkali lavas and correlates with the size of the positive Sr anomalies. The process that led to the formation of the Sr anomalies also produced a deficiency of Hf and Zr in the liquids. It is difficult to explain the low concentrations of these high field strength elements in the picrites by addition of both alkali and REE elements coming from a fluid-derived deposit. More probably, the source of the various lavas in Iceland had these characteristics, or they were acquired during the melting event.

[25] To further constrain the conditions that led to the formation of the positive Sr, Ba, and Rb anomalies and the negative Hf anomalies, we consider the behavior of Pb relative to Sr and the neighboring REE, Ce, and Nd. Ce/Pb ratios vary widely among the analyzed Iceland lavas (from 10 to 46) and the changes in Ce/Pb are correlated to the size of the Sr anomaly, as seen in Figure 6 where a strong correlation

exists between Ce/Pb and Sr/Nd. This correlation suggests that the process that created the positive Sr anomalies is also responsible for the excess Pb concentrations that led to low Ce/Pb in the most magnesian lavas. Figure 6 also shows that (1) the more alkaline lavas with high Ce/Pb have low Sr/Nd and (2) the trends defined by Iceland lavas barely overlap the fields representative of average Ce/Pb, Sr/Nd, and Sm/Hf ratios in MORB and OIB [*Hofmann et al.*, 1986; *Sun and McDonough*, 1989].

[26] It appears therefore that variations in Sr/Nd are related to changes in Ce/Pb and Sm/Hf. A continuous trend between two end-members can be identified. A first end-member with almost normal Sr/Nd, relatively high Ce/Pb, and normal Sm/Hf is found in the alkaline rocks. This component has chemical characteristics quite similar to most ocean island basalts (OIB). The second end-member is more peculiar and has high Sr/Nd and Sm/Hf and low Ce/Pb. This component is sampled primarily by the picritic tholeiites.

[27] The unusual changes in trace element ratios correlate not only with rock type, but also with systematic changes in isotopic compositions (Figure 6). The picrites have very depleted isotopic signatures (low $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ and high $^{143}Nd/^{144}Nd$), while the more alkaline lavas have contrasting isotopic characteristics (higher $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ and lower $^{143}Nd/^{144}Nd$). Because isotopic compositions are not affected by melting processes, the correlation between rock type, isotopic compositions and Ce/Pb, Sr/Nd, and Sm/Hf ratios must be attributed to differences in source compositions. It suggests therefore that parts of the plume with differing trace element and isotopic compositions melted under different conditions to produce picrites with low Ce/Pb and unradiogenic Pb isotopes, olivine and quartz tholeiites with
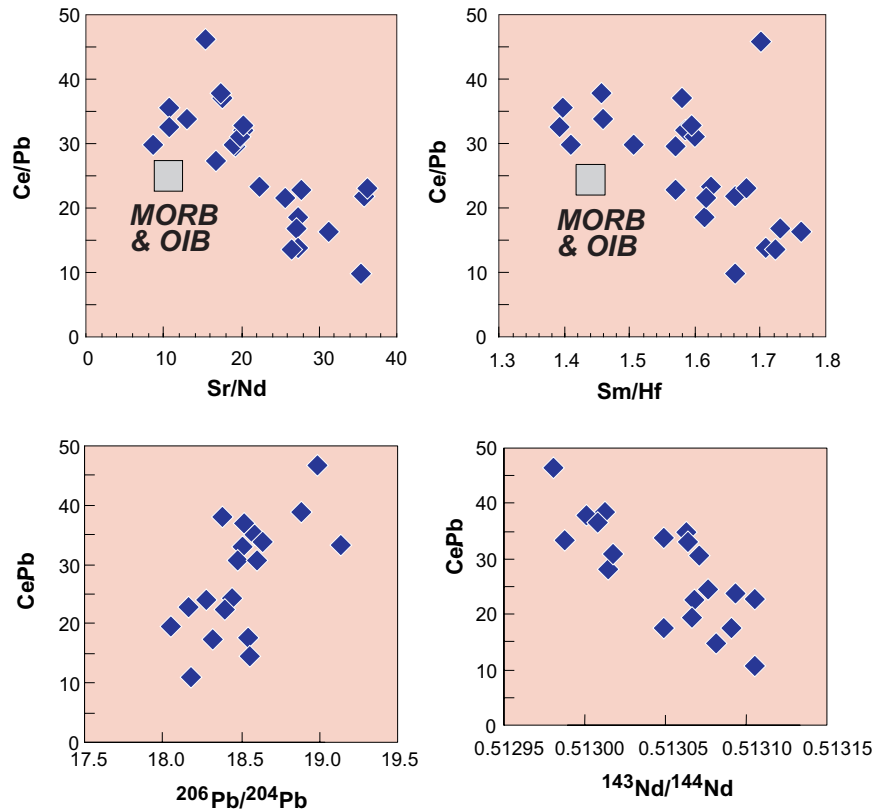
Figure 6. Ce/Pb versus Sr/Nd, Sm/Hf, ^{206}Pb/^{204}Pb, and ^{143}Nd/^{144}Nd. The remarkable correlation between Ce/Pb ratio and isotopic compositions suggests that the large range of Ce/Pb has its origin in the plume source region.

intermediate compositions, and more alkaline lavas with high Ce/Pb and more radiogenic Pb ratios.

5.2.1. Effects of Fractional Crystallization and Crustal Assimilation

[28] Before conclusions can be reached about the nature and origin of the source of Iceland lavas, the potential effects of crustal assimilation and fractional crystallization need to be evaluated. In order to minimize such effects, we concentrated on samples with high MgO contents because they are less likely to have interacted with the Icelandic crust on their way to the surface. However, three samples with relatively low MgO contents were ana-

lyzed, two quartz-normative tholeiites (Nal71 and SAL9) and a hawaiite (VMG41). The two tholeiites show signs of interaction with the Icelandic crust (low δ^{18}O, for example), but their isotopic compositions are similar to those of other tholeiites and do not define one of the end-member compositions. Nevertheless, we will not use these samples in the discussion of the source of Iceland. The hawaiite has a normal δ^{18}O value (5.8) and Sr, Nd, and Pb isotopic compositions similar to those of the alkali basalt SAL109. However, its trace element composition might have changed during fractionation processes, and it will not be considered when trace element ratios of the Iceland source are discussed.

[29] The composition of the most magnesian lavas could also have been affected by processes occurring after segregation of the melts from the source region. In particular, picritic basalts with elevated MgO contents could have accumulated olivine phenocrysts through the digestion of oceanic lithosphere. It could then be argued that the composition of the highly magnesian lavas is not representative of their mantle source. Such a case has been made for certain Hawaiian picrites [i.e., *Eiler et al.*, 1996; *Rhodes*, 1996] whose compositions are thought to have been influenced by digestion of the oceanic lithosphere. The main argument is that picrites in Hawaii have Nd, Sr, and Pb isotopic compositions intermediate between those of common Hawaiian lavas and those of MORB. This is not the case in Iceland. We emphasize that in contrast, the Iceland picrites have Sr, Nd, and Pb isotopic compositions that resemble neither that of the alkali lavas nor that of the Atlantic MORB. They are an end-member by themselves (see Figures 4 and 6). We suggest therefore that the isotopic compositions measured on the picritic basalts are as representative of the plume source as those of the more alkaline lavas. If the picrites acquired their characteristic isotopic signature from digested crust, this crust must have had a composition unlike that of MORB and that of the alkaline Iceland lavas. In this case, the distinctive signature would still have come from the plume, though perhaps not from the magma parental to the erupted picrites. Furthermore, if mantle-derived magmas were to digest a significant proportion of oceanic lithosphere, they must themselves have been highly magnesian. We are confident therefore that the Iceland picrites represent magnesian magmas from a mantle source with a distinct isotopic composition.

[30] We recognize that incorporation of olivine xenocrysts in the liquid can increase significantly the concentration of elements such as Ni or MgO in the picrites and decrease the overall concentrations of incompatible trace elements. This is most probably the case for samples D8-B1 and HEN5. However, given the extremely low concentrations of incompatible elements in olivine, we think that this process does not affect significantly ratios of trace elements such as Ce/Pb, Sr/Nd, and Sm/Hf, and we consider that these ratios are also representative of the primary liquid produced in the plume source.

5.2.2. Trace Element and Isotopic Characteristics of the Source of Alkali Basalts

[31] The overall characteristics of the source of alkali basalts in Iceland have been described in detail by several authors [e.g., *Furman et al.*, 1995, 1991; *Hards et al.*, 1995; *Hémond et al.*, 1993; *Stecher et al.*, 1999]. The new trace element data and isotopic compositions provide few new constraints on the source composition, but we can summarize the main characteristics as follows: (1) The source has relatively unradiogenic $^{143}Nd/^{144}Nd$ and radiogenic $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ isotopic compositions. (2) Its trace element characteristics are comparable to typical OIB.

[32] However, there are some remarkable trace element features that should be highlighted: Ce/Pb and Nb/La tend to be higher than average mantle values (>25 and >1.1, respectively) while Sr/Nd and Sm/Hf display normal mantle values (see Figure 7). These characteristics suggest a possible genetic link with HIMU sources, which have elevated Ce/Pb and Nb/La [*Weaver*, 1991a, b; *Chauvel et al.*, 1992]. However, the source of alkaline lavas in Iceland does not have the Pb isotopic composition of the HIMU component.
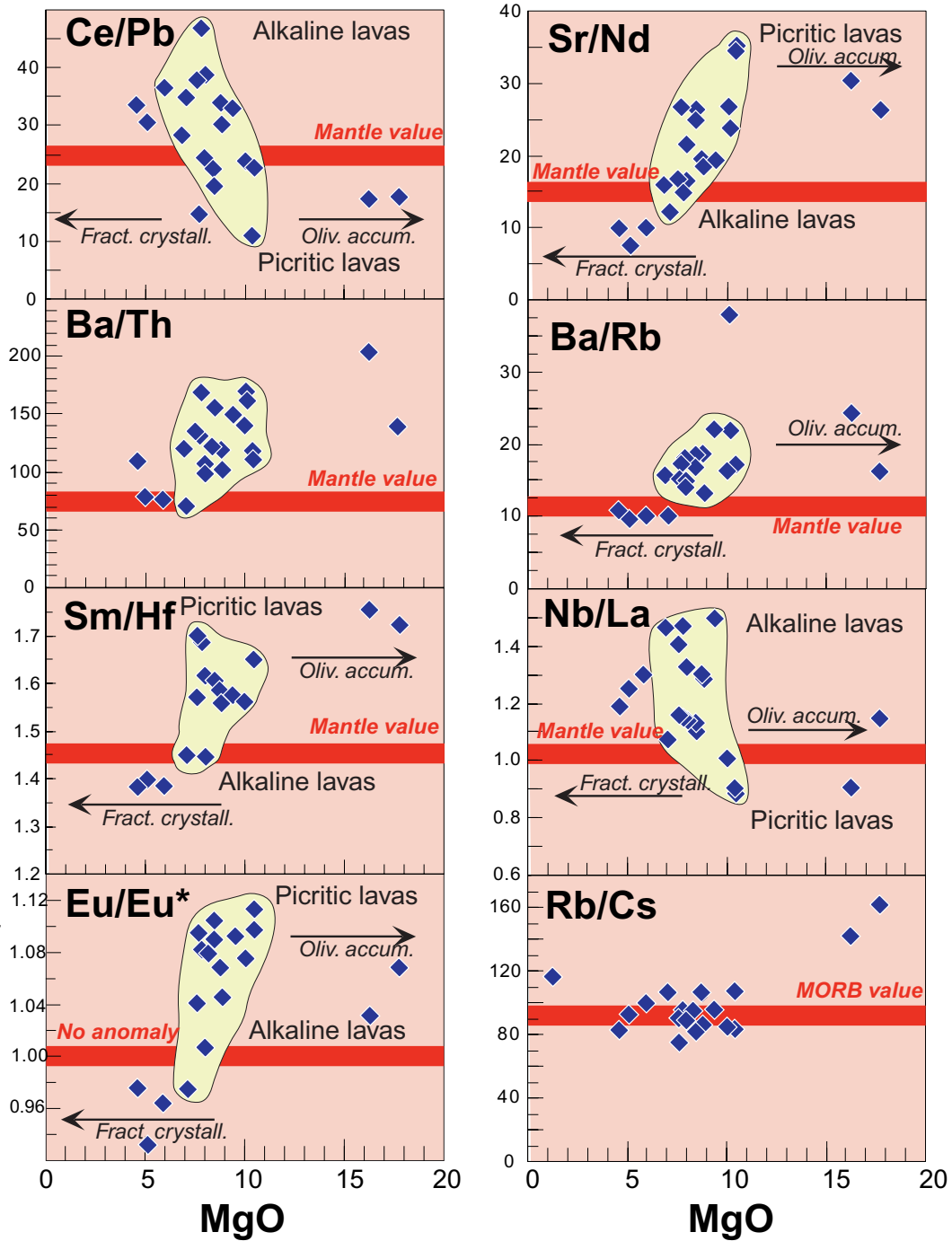
Figure 7. MgO contents plotted as a function of ratios of similarly incompatible elements (Ce/Pb, Sr/Nd, Ba/Th, Ba/Rb, Sm/Hf, Nb/La, and Rb/Cs) and Eu anomaly. Mantle values, where available, are shown for reference. The various diagrams show clearly the systematic differences between picritic lavas, tholeiites, and alkaline lavas.

5.2.3. Trace Element and Isotopic Characteristics of the Source of Picritic Tholeiites

[33] The picritic lavas have very unusual characteristics: (1) They are isotopically depleted with elevated $^{143}Nd/^{144}Nd$ and low $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$. Their compositions differ from those of Atlantic MORB (see Figure 4). (2) The main peculiarity lies in the unusual ratios of trace elements with similar compatibilities. Ce/Pb is lower than averages mantle value ($\approx$10 versus 25) while Sr/Nd, Ba/Th, and Sm/Hf are far above average mantle values (see Figure 7).

[34] These geochemical characteristics cannot be explained by residual phases during melting processes: No mantle phase is known to significantly fractionate neither Ce from Pb nor Sm from Hf. In addition, the trace element anomalies correlate with isotopic variations, suggesting that the anomalies did not arise during melting but are long-lived features of the source region.

5.2.4. Relationship Between the Two Components in the Plume

[35] In terms of both trace element ratios and isotopic compositions (Figures 6 and 7) a continuum of compositions characterizes Iceland lavas. The two end-members must be closely related and are not independent reservoirs that were accidentally tapped by melting in the plume. Recycling of oceanic crust to form the source of plume volcanism, as proposed by *Hofmann and White* [1982], is now a popular explanation for the composition of tholeiitic to alkali basalts in oceanic islands. Hofmann and coworkers [*Hofmann and Jochum*, 1996, *Abouchami and Hofmann*, 1998; A. W. Hofmann, manuscript in preparation, 1999] have extended the model and propose

that the isotope and trace element characteristics of Hawaiian basalts with different compositions are consistent with melting in different parts of recycled oceanic crust. We now apply this model to Icelandic volcanic rocks.

[36] The Iceland plume is a long-lived and strong plume that has operated for ~63 Ma [*White*, 1988] and is associated with the opening of the North Atlantic Ocean. Recent seismic data have been interpreted to indicate that the plume originated at the core-mantle boundary and that the material erupted at the surface might have traversed the whole mantle [*Helmberger et al.*, 1998]. The Iceland plume is also characterized by high production rates of a variety of lava compositions, ranging from alkali basalts to picritic basalts. It is commonly accepted that alkali basalts are produced by low degrees of melting at depths sufficient for garnet to be stable as a residual phase [*Gast*, 1968]. The melting processes responsible for the existence of picritic basalts are more controversial, but all models require high-degree melting at shallow levels in the mantle. In section 5.1 we showed that the source of both alkali and picritic lavas is to be found in the plume and that the surrounding depleted upper mantle is involved neither in the genesis of alkali basalts nor in that of the picritic basalts. Parts of the plume with enriched compositions melted to give the alkali basalts and depleted parts melted to give the picrites. The presence of basalts with intermediate compositions suggests the involvement of mixtures between the enriched and depleted portions of the plume source.

[37] We suggest that the range of lava compositions can be explained by melting of a complete section of old recycled oceanic crust. The more alkaline lavas result mainly of melting of the basaltic portion, as already suggested for ocean island basalts by numerous authors [e.g., *Hofmann and White*, 1982; *Weaver*,

1991a, b; *Chauvel et al.*, 1992], while picritic basalts represent melting of the more depleted gabbroic cumulates, as suggested for Hawaii by *Hofmann and Jochum* [1996], *Lassiter and Hauri* [1998], and *Sobolev et al.* [1999]. For all lavas a contribution of the harzburgitic part of the old recycled oceanic lithosphere is also required to account for the high Mg and Ni concentrations in the various types of lavas. This interpretation provides an explanation for the correlations between isotopic compositions, trace element variations, and rock type in Iceland. It also takes into account the fact that the depleted mantle (MORB source) is not involved in the genesis of Iceland lavas, as shown in section 5.1.

[38]   We tried to quantify the characteristics of the various parts of the recycled oceanic crust that produced the various liquids in the plume. The source region for picritic basalts has highly depleted isotopic compositions, excess Sr, Ba, and Pb and a deficiency of Hf (and Zr) relative to the REE. The lavas are also characterized by significant positive Eu anomalies whose size correlates with the Sr excess (see Figure 7). These characteristics are quite uncommon and resemble those of plagioclase-clinopyroxene-rich gabbros. Few trace element data exist for such rocks, but analyses available in the literature for ophiolites display these anomalies [*Zimmer et al.*, 1995; *Benoit*, 1997; *Benoit et al.*, 1996; C. J. Garrido and P. B. Kelemen, Composition of gabbros and parental melts in the Wadi Tayin massif, southern Oman ophiolite, manuscript in preparation, 1999]. In addition, experimental data on trace element concentrations in plagioclase and clinopyroxene [*Blundy et al.*, 1998; *Dunn and Sen*, 1994; *Hart and Dunn*, 1993; *Johnson*, 1998; *Hauri et al.*, 1994; *Salters and Longhi*, 1999] show (1) that plagioclase accepts Sr, Pb, and Sm more easily than Nd, Ce, and Hf, respectively, and (2) that for clinopyroxene, partition coefficients (K_d) of Sr and Pb are lower than

Nd and Ce, whereas that of Sm is higher than Hf. The original proportions of plagioclase and clinopyroxene in the source can be evaluated using published partition coefficients and the Sr/Nd, Ce/Pb, and Sm/Hf ratios of the lavas. In order to use a coherent set of partition coefficients for the six elements in both clinopyroxene and plagioclase, we chose *Blundy et al.*'s [1998] values even though we realize that these values are high compared to other published K_d. Partition coefficients for Pb are the values recommended by *White* [1999]. To perform the calculation, we make three major assumptions: (1) Sr/Nd, Ce/Pb, and Sm/Hf ratios of Iceland lavas represent those of their source regions. (2) Sr/Nd, Ce/Pb, and Sm/Hf ratios of the picritic basalts represent the composition of a plagioclase-clinopyroxene-rich cumulate that formed in equilibrium with liquids with the composition of oceanic basalts. The cumulate retained its trace element characteristics while going through phase changes during subduction and storage in the deep mantle. (3) Concentrations of Sr, Pb, Hf, Ce, Nd, and Sm in both olivine and orthopyroxene are considered negligible relative to those in clinopyroxene and plagioclase and are taken as zero in the mass balance calculation.

[39]   Calculations were performed using the K_d values and Sr/Nd, Ce/Pb, and Sm/Hf ratios given in Table 4. No absolute concentrations are required to calculate the original relative proportions of clinopyroxene and plagioclase, and we assume that olivine and orthopyroxene had no effect on the ratios. Details about the procedure are given in the appendix. We calculate only the ratio of plagioclase to clinopyroxene in the source and not its total mineralogy. The proportions of olivine and orthopyroxene are not constrained by the calculation.

[40]   Using the three trace element ratios, we obtain three independent constraints on the

Table 4. Proportions of Plagioclase and Clinopyroxene Calculated for the Source of Picritic Basalts

	Hf	Sm	Nd	Sr	Ce	Pb
D^{Cpx}	0.55	0.67	0.36	0.062	0.16	0.01
D^{Plagio}	0.010	0.053	0.081	2.21	0.117	1.07

	Alkali Basalts		Picritic Basalts	% Plag. Calculated for the Source of Picritic Basalts	% Cpx Calculated for the Source of Picritic Basalts
Sm/Hf	1.4		1.75	30%	70%
Ce/Pb	40		10	51%	49%
Sr/Nd	10		35	38%	62%

D^{Cpx} (or D^{Plag}) is the partition coefficient between clinopyroxene (or plagioclase) and liquid for the various elements listed. Partition coefficients used for clinopyroxene and plagioclase are from *Blundy et al.* [1998] and *White* [1999]. The Sm/Hf, Ce/Pb, and Sr/Nd values for alkali and picritic lavas are from this work. Calculations were performed using the method given in the appendix.

relative proportions of clinopyroxene and plagioclase in the source of picritic basalts. Sm/Hf and Sr/Nd ratios provide similar values of ∼35 % plagioclase and 65 % clinopyroxene, while Ce/Pb gives a slightly higher proportion of plagioclase. For the Ce/Pb ratio to give 35 % plagioclase, the K_d value of Pb in plagioclase must be around 1.5, instead of the 1.07 value given by *White* [1999]. The difference is relatively small and most likely within an acceptable range, given the precision with which partition coefficients are known.

[41] The consistency of the three estimates therefore supports our interpretation for the source of picrites. However, we acknowledge that the calculated clinopyroxene/plagioclase ratios depend strongly on the choice of partition coefficients used for the calculation and that the ratio itself is poorly constrained. The persistence of positive Eu anomalies in picritic samples (Figure 7) independently supports the concept that plagioclase was a significant component of the source of these rocks. Furthermore, the proportion of plagioclase to clinopyroxene resembles measured proportions in gabbros both in present oceanic crust [e.g., *Ross and Elthon*, 1997] and in ophiolites [e.g., *Benoit et al.*, 1996].

[42] If we accept the model of partial melting of different parts of recycled oceanic crust, the trend observed in the $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ space can be taken as having an age significance. If the U-Pb system has not been significantly disturbed since the formation and subduction of the old recycled oceanic crust, the correlation between the two Pb isotopic ratios provides an Archean age (≈2.6–2.9 Ga.) for the source of the Iceland plume. We realize that this age might have little significance, but it highlights the ancient origin of the source of the Iceland plume.

[43] Our interpretation also provides an explanation for the distinct Nb/Y versus Zr/Y relationships in oceanic basalts discussed by *Fitton et al.* [1997]. They show that Iceland lavas define a trend that is distinct from that of mid-ocean ridge basalts (see Figure 8a). They interpret the systematic difference between Iceland and MORB in terms of relative depletion and/or enrichment in Nb in the source and variable fractional melting. On the basis of our own data, we argue that the difference between Iceland and MORB is primarily due to the presence of negative Zr and Hf anomalies in the most depleted picritic lavas from Iceland. Figure 8 shows the relationships between Nb/Y, Zr/Y, La/Yb, and Sm/Yb ratios. Nb is about as
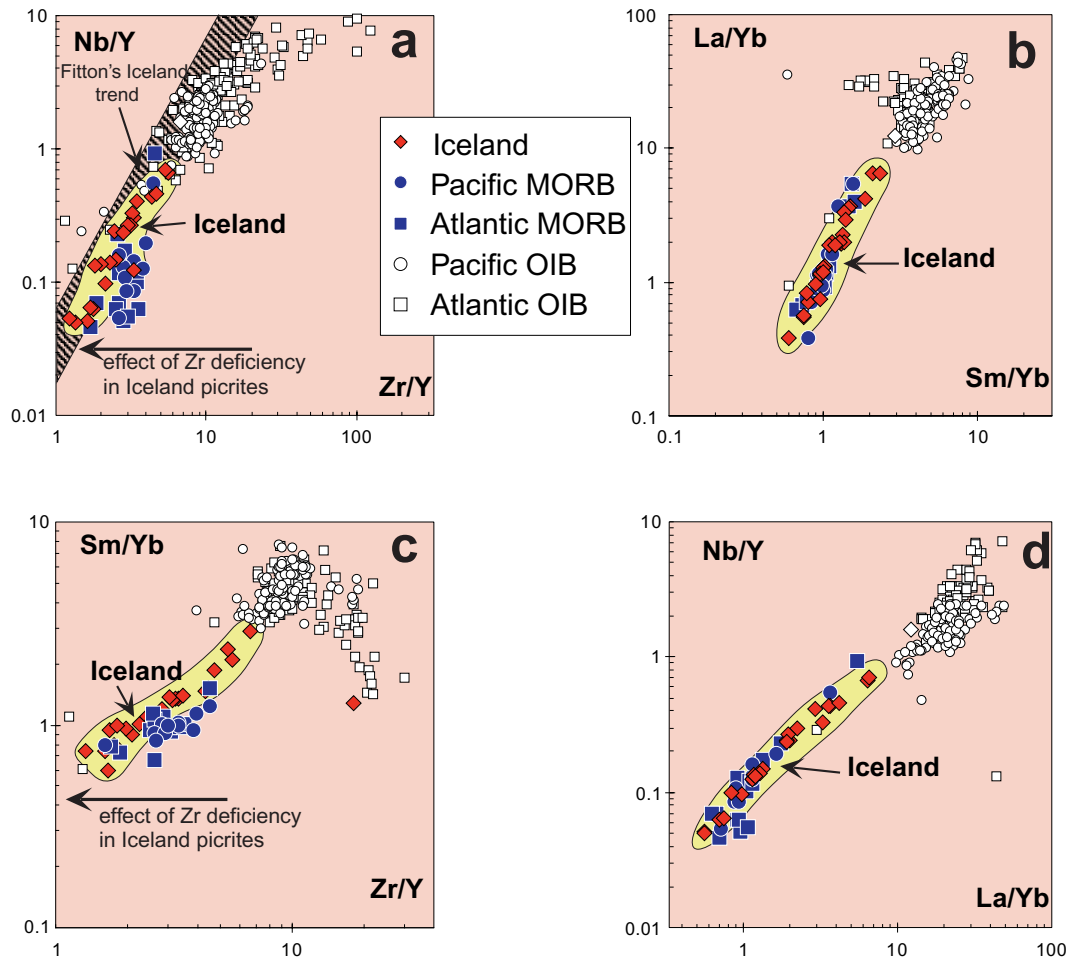
Figure 8. Relationships between (a) Nb/Y and Zr/Y, (b) La/Yb and Sm/Yb, (c) Sm/Yb and Zr/Y, and (d) Nb/Y and La/Yb for Atlantic and Pacific MORB, OIB, and Iceland. The difference between Iceland and MORB demonstrated by *Fitton et al.* [1997] is shown in Figure 8a where the striped field represents their Iceland trend while the dark symbols correspond to MORB and the light field highlights our new Iceland data. However, the same shift is not seen for La/Yb versus Sm/Yb (Figure 8b), suggesting that the difference in Figure 8a is not due to melting. The perfect collinearity between Nb/Y and La/Yb rules out an enrichment in Nb to explain the shift in Figure 8a, while the distinct Iceland trend in Figure 8c demonstrates that the most depleted lavas in Iceland have lower Zr/Y than MORB. Data sources are too numerous to be given.

incompatible as La, Sm behaves like Zr, and Y behaves like Yb during melting processes. Figure 8b shows clearly that the distinct Iceland trend defined by *Fitton et al.* [1997] does not exist when La/Yb is plotted versus Sm/Yb. This suggests that element fractionation during melting is not responsible for the peculiar Nb-

Zr-Y relationship in Iceland. Comparing the trends in Figure 8c and 8d shows clearly that the displacement of Iceland data in Figure 8a is due to too low Zr/Y ratios in the most depleted Icelandic picrites. In our opinion, their particular compositions are derived from their source, recycled plagioclase-clinopyroxene cumulate.

[44] The exact melting process that leads to the formation of picritic tholeiites in Iceland is more difficult to evaluate. As shown above, the major characteristics of the picrites are not due to the melting process but to the source composition. The problem is then to explain why such a source is not sampled more often in oceanic islands. The answer might be found in the refractory nature of such gabbros, which do not melt under normal circumstances. To produce magmas from such a source requires that all other components in the source region have already melted. Otherwise, the trace element signature of the lavas would be totally dominated by the contribution from the other components. Such a scenario is possible in Iceland because the Icelandic plume is a strong and long-lived plume that has operated over tens of millions of years. It is located at a ridge where lithosphere is absent, and it is also characterized by long-term excess heat that led to the formation of this large and active island. All these conditions result in high-degree melting.

6. Conclusions

[45] New trace element and isotopic data obtained on a wide range of magnesian lavas in Iceland exhibit large variations. Excess Sr, Eu, and Pb contents as well as a small but significant deficiency of Hf in the picrites are source characteristics. Variations in Ce/Pb, Sm/Hf, and Sr/Nd between picrites and alkali basalts correlate with Pb, Sr, and Nd isotopic ratios.

[46] Our preferred interpretation is as follows:

[47] 1. The Iceland plume is not contaminated by the surrounding depleted mantle. Instead, the composition of the Mid-Atlantic Ridge is affected by the invasion of plume material along both the Reykjanes Ridge and the Kolbeinsey Ridge.

[48] 2. The Iceland plume is chemically and isotopically heterogeneous. Melting of the plagioclase-clinopyroxene-rich gabbroic part of old oceanic crust that had been recycled and stored in the mantle for long periods of time can explain the composition of the picritic basalts in Iceland.

[49] This interpretation provides an explanation for the unusual Ce/Pb, Sm/Hf, and Sr/Nd ratios in picrites. The continuum of lava composition and the systematic changes in Ce/Pb, Sm/Hf, and Sr/Nd ratios, as well as Nd, Sr, and Pb isotopic compositions, within alkali basalts, tholeiites, and picritic basalts, are also explained by the model. The alkali basalts inherit their trace element signature from the basaltic part of the recycled slab, whereas tholeiites have compositions derived from a mixture of both end-members. For all types of basalts the harzburgitic part of the oceanic lithosphere must also been involved to provide a source of Ni and Mg.

Appendix

[50] The relative proportions of plagioclase and clinopyroxene were calculated using data given in Table 4 and the following procedure:

$$D_{Sm}^{Cpx/liq} = C_{Sm}^{Cpx}/C_{Sm}^{liq}, \tag{1}$$

where $D_{Sm}^{Cpx/liq}$ is the partition coefficient for Sm between clinopyroxene and liquid, C_{Sm}^{Cpx} the Sm concentration in clinopyroxene and C_{Sm}^{liq} is the Sm concentration in the liquid. Similarly, for plagioclase,

$$D_{Sm}^{Plag/liq} = C_{Sm}^{Plag}/C_{Sm}^{liq}. \tag{2}$$

Combining (1) and (2) gives

$$D_{Sm}^{Cpx/Plag} = D_{Sm}^{Cpx/liq}/D_{Sm}^{Plag/liq} = C_{Sm}^{Cpx}C_{Sm}^{Plag}. \tag{3}$$

The same relationship can be written for Hf between clinopyroxene and plagioclase:

$$D_{Hf}^{Cpx/Plag} = D_{Hf}^{Cpx/liq}/D_{Hf}^{Plag/liq} = C_{Hf}^{Cpx}/C_{Hf}^{Plag} \tag{4}$$

Considering that Sm/Hf ratios are identical in the Iceland lavas and in their source, the following approximations can be made:

$$C_{Sm}^{liq}/C_{Hf}^{liq} = C_{Sm}^{Alkalibasalts}/C_{Hf}^{Alkalibasalts} \tag{5}$$

with C_{Elt}^{liq} representing the concentration of the element of interest in the basaltic portion of the recycled crust that formed the source of the Iceland alkali basalts, and $C_{Elt}^{Alkalibasalts}$ representing that of the element in Iceland alkali basalts;

$$C_{Sm}^{Cum}/C_{Hf}^{Cum} = C_{Sm}^{Picriticbasalts}/C_{Hf}^{Picriticbasalts} \tag{6}$$

with C_{Elt}^{Cum} representing the concentration of the element of interest in the gabbroic cumulate portion of the recycled crust that formed the source of the Iceland picritic basalts and $C_{Elt}^{Picriticbasalts}$ representing that of the element in Iceland picritic basalts.

[51] Combining (1) and its equivalent for Hf gives

$$C_{Sm}^{Cpx}/C_{Hf}^{Cpx} = D_{Sm}^{Cpx/liq}/D_{Hf}^{Cpx/liq} \, C_{Sm}^{liq}/C_{Hf}^{liq} \tag{7}$$

which can be rearranged in the following way:

$$C_{Hf}^{Cpx} = C_{Sm}^{Cpx} D_{Hf}^{Cpx/liq}/D_{Sm}^{Cpx/liq} \, C_{Hf}^{liq}/C_{Sm}^{liq}. \tag{8}$$

The overall trace element concentrations in the gabbroic cumulate can be described in a simple manner. For Hf, for example, we can write the following relationship:

$$C_{Hf}^{Cum} = C_{Hf}^{Cpx} W^{Cpx} + C_{Hf}^{Plag} W^{Plag} + C_{Hf}^{Ol} W^{Ol} + C_{Hf}^{Opx} W^{Opx} \tag{9}$$

with W^{Cpx}, W^{Plag}, W^{Ol} and W^{Opx} representing fractions of clinopyroxene, plagioclase, olivine, and orthopyroxene.

[52] Since the source mineralogy is defined by

$$W^{Cpx} + W^{Plag} + W^{Ol} + W^{Opx} = 1, \tag{10}$$

we can define y as the sum of the olivine and orthopyroxene fractions in the source:

$$y = W^{Ol} + W^{Opx}$$

and x is the fraction of plagioclase relative to the sum of clinopyroxene and plagioclase fractions:

$$x = W^{Plag}/(W^{Cpx} + W^{Plag})$$

Replacing the mineral fractions using these two relationships, we can change equation (10) to become

$$(1-x)(1-y) + x(1-y) + y = 1,$$

where

$$(1-x)(1-y) = W^{Cpx} \tag{11}$$

$$x(1-y) = W^{Plag}. \tag{12}$$

Because the Sm and Hf concentrations are extremely low in both olivine and orthopyroxene due to very low partition coefficients, and because we are interested only in the relative proportions of clinopyroxene and plagioclase, the terms for olivine and orthopyroxene can be neglected. Equation (9) then becomes

$$C_{Hf}^{Cum} = C_{Hf}^{Cpx} W^{Cpx} + C_{Hf}^{Plag} W^{Plag}. \tag{13}$$

Replacing W^{Cpx} and W^{Plag} using (11) and (12) gives

$$C_{Hf}^{Cum} = C_{Hf}^{Cpx}(1-x)(1-y) + C_{Hf}^{Plag} x \,(1-y) \tag{14}$$

$$C_{Sm}^{Cum} = C_{Sm}^{Cpx}(1-x)(1-y) + C_{Sm}^{Plag} x \,(1-y). \tag{15}$$

These two equations simplify to give

$$C_{Hf}^{Cum} = [C_{Hf}^{Cpx}(1-x) + C_{Hf}^{Plag} x] \,(1-y) \tag{16}$$

$$C_{sin}^{Cum} = [C_{Sm}^{Cpx}(1-x) + C_{Sm}^{Plag} x] \,(1-y). \tag{17}$$

Combining (16) and (17) gives

$$C_{Sm}^{Cum}/C_{Hf}^{Cum} = [x(C_{Sm}^{Plag} - C_{Sm}^{Cpx}) + C_{Sm}^{Cpx}] / [x(C_{Hf}^{Plag} - C_{Hf}^{Cpx}) + C_{Hf}^{Cpx}] \quad (18)$$

(18) can be rearranged into

$$C_{Sm}^{Cum}/C_{Hf}^{Cum} \, x(C_{Hf}^{Plag} - C_{Hf}^{Cpx}) + C_{Sm}^{Cum}/C_{Hf}^{Cum} C_{Hf}^{Cpx} = x(C_{Sm}^{Plag} - C_{Sm}^{Cpx}) + C_{Sm}^{Cpx}. \quad (19)$$

and then into

$$x C_{Sm}^{Cum}/C_{Hf}^{Cum}(C_{Hf}^{Plag} - C_{Hf}^{Cpx}) - x(C_{Sm}^{Plag} - C_{Sm}^{Cpx}) = C_{Sm}^{Cpx} - C_{Sm}^{Cum}/C_{Hf}^{Cum} C_{Hf}^{Cpx} \quad (20)$$

x can be extracted from (20):

$$x = [C_{Sm}^{Cpx} - C_{Sm}^{Cum}/C_{Hf}^{Cum} C_{Hf}^{Cpx}] / \{C_{Sm}^{Cum}/C_{Hf}^{Cum} [C_{Hf}^{Plag} - C_{Hf}^{Cpx}] - [C_{Sm}^{Plag} - C_{Sm}^{Cpx}]\}. \quad (21)$$

C_{Hf}^{Plag} can then be replaced by $C_{Hf}^{Cpx}/D_{Hf}^{Cpx/Plag}$ using (4) and C_{Sm}^{Plag} can be replaced by $C_{Sm}^{Cpx}/D_{Sm}^{Cpx/Plag}$ using (3).

[53] Rearranging (21) gives

$$x = [C_{Sm}^{Cpx} - C_{Sm}^{Cum}/C_{Hf}^{Cum} C_{Hf}^{Cpx}] / \{C_{Sm}^{Cum}/C_{Hf}^{Cum} [C_{Hf}^{Cpx}/D_{Hf}^{Cpx/Plag} - C_{Hf}^{Cpx}] - [C_{Sm}^{Cpx}/D_{Sm}^{Cpx/Plag} - C_{Sm}^{Cpx}]\}. \quad (22)$$

C_{Hf}^{Cpx} can then be replaced using (8) to obtain

$$x = [C_{Sm}^{Cpx} - C_{Sm}^{Cum}/C_{Hf}^{Cum} C_{Sm}^{Cpx} D_{Hf}^{Cpx/liq}/D_{Sm}^{Cpx/liq} C_{Hf}^{liq}/C_{Sm}^{liq}] / \{C_{Sm}^{Cum}/C_{Hf}^{Cum} C_{Sm}^{Cpx} D_{Hf}^{Cpx/liq}/D_{Sm}^{Cpx/liq} C_{Hf}^{liq}/C_{Sm}^{liq} [1/D_{Hf}^{Cpx/Plag} - 1] - [C_{Sm}^{Cpx}/D_{Sm}^{Cpx/Plag} - C_{Sm}^{Cpx}]\}. \quad (23)$$

C_{Sm}^{Cpx} can be eliminated from the top and bottom of (23) to give

$$x = [1 - C_{Sm}^{Cum}/C_{Hf}^{Cum} D_{Hf}^{Cpx/liq}/D_{Sm}^{Cpx/liq} C_{Hf}^{liq}/C_{Sm}^{liq}] / \{C_{Sm}^{Cum}/C_{Hf}^{Cum} D_{Hf}^{Cpx/liq}/D_{Sm}^{Cpx/liq} C_{Hf}^{liq}/C_{Sm}^{liq} [1/D_{Hf}^{Cpx/Plag} - 1] - [1/D_{Sm}^{Cpx/Plag} - 1]\}.$$

Replacing variables by their numerical values given in Table 4 gives

$$x = \{1 - 1.75[0.55/0.67][1/1.4]\}/\{1.75[0.55/0.67][1/1.4] \cdot [((1/0.55)/0.01) - 1][((1/0.67)/0.053) - 1]\} = 0.30.$$

The same procedure can be applied to the relationship between Sr and Nd to give a x value of 0.38. From Ce/Pb, we obtain a x value of 0.51.

[54] The proportion of plagioclase to the sum of plagioclase and clinopyroxene in the cumulate phase (value x) is therefore evaluated at 38% using the Sr/Nd ratio, 30% using the Sm/Hf ratio, and 51% using Ce/Pb ratio. The amount of olivine and orthopyroxene in the source region (value y in (11) and (12)) is not constrained by the calculation.

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