

High-Pressure Melting Experiments on Basalt-Peridotite Layered Source (KLB-1/N-MORB): Implications for Magma Genesis in Hawaii

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Abstract

In order to understand the melting processes that occur within recycled oceanic crust and mantle in a heterogeneous plume (e.g., that beneath the Hawaiian Islands), a series of high-pressure-high-temperature layered experiments were performed at 2.9 GPa, 5 GPa, and 8 GPa, from 1300°C to 1650°C, using a fertile peridotite KLB-1 and N-MORB. Our experiments at conditions below the dry peridotite solidus produced melt compositions that ranged from basaltic andesite to tholeiite. An Opx reaction band formed between eclogite and peridotite layers, likely via chemical reaction between a silica-rich eclogite-derived partial melt and olivine in the peridotite matrix. At temperatures at or above the dry peridotite solidus, substantial melting occurred in both basalt and peridotite layers, and fully molten basalt melt and melt pockets from the peridotite layer combined. In our layered experiments, major and minor element contents in reacted melts closely matched those of Hawaiian tholeiite and picrite, except for Fe. Partial melts of anhydrous run products had ~55 - 57 wt% SiO₂ at low temperature (*i.e.*, were andesitic) and had ~50 -53 wt% SiO₂ at high temperatures, slightly below the dry peridotite solidus (*i.e.*, were tholeiitic, and similar to those that occur during the Hawaii shield-building stage). Based on the Fe- and LREE-enriched signature in Hawaiian tholeiites, we propose that recycled components in the Hawaiian plume are not modern N-MORB, but are Fe-rich tholeiite; a lithology that was common in the Archaean and early Proterozoic. We have demonstrated that the entire compositional spectrum of Hawaiian tholeiites (basalt to picrite) can be formed by basalt-peridotite reactive melting near the dry solidus of peridotite. Based on these results, we propose that the potential temperature of the sub-Hawaiian plume may be much lower than previously estimated.

Keywords

Hawaiian Tholeiite, Recycled Oceanic Crust, High Pressure, Layered Experiments, N-MORB, Major Elements

1. Introduction

The mantle plume beneath the Hawaiian Islands is the largest known example in the Earth today [1]. Unlike other ocean islands that are dominated by alkali basalts, more than 90% of the volcanic products on Hawaii are tholeiitic in composition [2]. The Kilauea volcano is currently in its shield-building stage, whereas the Mauna Loa volcano will imminently end its shield-building stage. These Hawaiian tholeiites were once thought to be the products of melting of upper-mantle peridotite at extreme temperatures [3], although such peridotite-derived magmas are lower in SiO₂, FeO, TiO₂, and K₂O than Hawaiian tholeiite for any given MgO content [4] [5]. It is now generally accepted that the tholeiite lavas that contribute to the main shield-building stage are supplied by reactive melting of peridotite and mafic lithologies entrained in the plume axis [6]-[11]. Dynamic modelling of eclogite-peridotite hybrid plumes has accounted for the distribution of Kea-type and Loa-type volcanoes, as well as the sequential change of igneous rock types in shield volcanoes [12] [13]. Further, several melting experiments and numerical modelling simulations of heterogeneous mantle plumes have been performed recently in order to clarify the petrogenesis of tholeiite magma in Hawaiian plume [7] [14] [15] [16].

Sobolev et al. [10] proposed that Hawaiian tholeiite magma is formed from melting of a pyroxenite source rock. For this mechanism, they suggested that olivine in mantle peridotite is consumed by reaction with silicic melts derived from deep-seated partial melting of recycled oceanic crust, which thus forms a secondary pyroxenite source. Mallik and Dasgupta [17] showed experimentally that a wall-rock reaction between MORB-derived eclogite and peridotite could produce magmas with compositions from tholeiitic basalt to alkali basalt; however, the melting processes that may occur in such a hybrid source are disputed. In this study, we carried out a series of high-temperature-high-pressure melting experiments in order to elucidate the physical and geochemical characteristics of melting processes in layered basalt-peridotite source. Layered experiments were carried out at a pressure of 2.9 GPa using a piston-cylinder apparatus, and at 5 GPa and 8 GPa using a multi-anvil apparatus. A fertile spinel-lherzolite and N-type mid-ocean ridge basalt (MORB) were used as starting materials.

2. Experimental Approach

2.1. Starting Materials

N-type MORB sample NAM-7 [18] was used as the eclogite component in our experiments, whereas spinel lherzolite sample KLB-1 was used as the fertile



mantle peridotite component [4]. The chemical compositions and representative mineral constituents of each starting material are presented in Table 1. Both rock types were powdered and dried at 1 atmosphere under a $CO-H_2$ buffer, which is close to an NNO buffer, and were kept in a furnace at 200°C in order to prevent atmospheric hydration.

2.2. Experimental Conditions

Our melting experiments were performed at pressures of 2.9 GPa, 5 GPa, and 8 GPa, temperatures from 1300°C to 1650°C, and for durations of 1 - 24 hours (Figure 1 and Table 2). All run conditions and the resultant phases produced are listed in Table 2. Anhydrous solidi for KLB-1 and N-MORB NAM-7 are shown in Figure 1 (after [4] and [18], respectively), where it can be seen that the latter is situated at temperatures ~200°C below than that of the former. In order to investigate wall-rock reactions between molten eclogite and ambient mantle peridotite in an ascending plume, most of the experiments in this study were conducted at temperatures below the dry peridotite solidus.

2.3. Experimental Apparatus and Sample Assembly

All experiments were carried out at the Magma Factory in the Tokyo Institute of Technology, Japan [19]. Each individual rock powder was pressed into a separate pellet, and both were then placed into graphite/platinum double capsules to avoid Fe-loss. Figure 2 shows the capsule assembly with the N-MORB layer placed on the top of peridotite layer near to the thermocouple.

Table 1. Chemical compositions of starting materials.

			KLB-1			NAM-7
	Bulk (wt%)	Oliv (wt%)	Opx (wt%)	Cpx (wt%)	Sp (wt%)	(wt%)
SiO ₂	44.48	39.64	54.24	51.13	0.06	49.71
TiO ₂	0.16	0	0.11	0.58	0.11	1.71
Al_2O_3	3.59	0.03	4.97	7.4	58.48	15.68
FeO (t)	8.1	10.52	6.57	3.11	10.68	9.46
MnO	0.12	0.16	0.16	0.1		0.18
MgO	39.22	48.25	32.16	14.7	21.61	8.43
CaO	3.44	0.08	0.85	19.54	0	11.73
Na ₂ O	0.3	0.01	0.12	1.72	0	2.76
K ₂ O	0.02	0	0	0.01	0	0.23
P_2O_5	0.03	-	-	-	-	0.02
Cr_2O_3	0.31	0.01	0.34	0.78	7.82	-
NiO	0.25	0.39	0.11	0.11	0.43	-
Total	100.02	99.09	99.63	99.18	99.19	99.91
MgO#	0.896	0.891	0.897	0.894	0.783	0.614



Figure 1. Solidus of peridotite KLB-1, NMORB and run conditions.

Table 2. Run conditions and phase assemblages of each layer.

	DICD	THO		Mineral Modes (Weight Fraction)						
Kun No.	P/GPa	1/ C	Durations/h	MORB Layer	KLB-1 Layer					
P948	2.9	1300	3	Cpx + Pl + Grt + Rt	Ol + Opx + Cpx + Sp + Grt (tr)					
P951	2.9	1300	24	Cpx + Grt + Coe	Ol + Opx + Cpx + Grt (tr)					
P928	2.9	1460	1	Cpx + Grt + M	Ol + Opx + Cpx + Sp + Grt (tr)					
P937	2.9	1460	9	М	Ol + Opx + Cpx + M (tr)					
P931	2.9	1460	24	Cpx + Grt + M	Ol + Opx + Sp + Grt (tr)					
P929	2.9	1500	1	Cpx + Grt + M	Ol + Opx + Cpx + Sp + Grt (tr)					
P938	2.9	1500	9	М	Ol + Opx + M					
P935	2.9	1500	24	Cpx + Grt + M	Ol + Opx + Cpx					
P932	2.9	1540	1	Cpx + M	Ol + Opx + Cpx + Grt + M (tr)					
P939	2.9	1540	9	М	Ol + Opx + Cpx + M					
P936	2.9	1540	24	М	Ol					
S1813	5	1300	3	Cpx + Grt + Coe	Ol + Opx + Cpx + Grt(tr) + Sp (tr)					
S1797	5	1450	3	Cpx + Grt + M	Ol + Cpx + Opx + Grt + Sp (tr)					
S1802	5	1450	20	Cpx + Grt + M	Ol + Cpx + Opx + Grt + Sp (tr)					
S1799	5	1500	3	Cpx + Grt + M	Ol + Opx + Cpx + Grt + Sp (tr)					
S1788	5	1550	3	М	Ol + Cpx + Opx + Grt + Sp (tr)					
S1790	5	1650	3	М	Opx					
S1808	8	1300	3	Cpx + Grt + Coe	Ol + Opx + Cpx + Grt + Sp (tr)					
S1812	8	1500	3	Cpx + Grt + Coe	Ol + Opx + Cpx + Grt + Sp (tr)					

"tr" represents for trace amount of minerals or melts which cannot be analyzed by EPMA.





Figure 2. Capsule assemblage used for layered experiments.

Experiments performed at 2.9 GPa were conducted using a Boyd-England-type piston-cylinder apparatus, and were based on a half-inch calibration of talc/Pyrex-glass/graphite assembly [4] with W-5%Re, W-26%Re thermocouples (a cross section of this configuration is shown in **Figure 3(a)**). In those runs, the two-lithology starting material was kept at 1200°C and 2.9 GPa for 20 hours before the final experiment in order to convert low-pressure mineral assemblages to subsolidus high-pressure eclogite and garnet peridotite assemblages. Conversely, 5 GPa and 8 GPa experiments were performed using a 1000-ton end-loaded Kawai-type multi-anvil apparatus [19]. We used 18 mm edge-length MgO octahedra as the pressure medium, and FUJILLOY (TN-05) tungsten carbide anvils with truncation edge lengths of 11 mm. LaCrO₃ was employed as the heater, and W-5%Re and W-26%Re were used as thermocouples (**Figure 3(a)**). The pressure calibration of Aoki and Takahashi [20] was used.

2.4. Analytical Methods

Run products were collected, mounted in epoxy, polished, and carbon-coated for electron microprobe analysis (EPMA). Textures and chemical compositions were analysed with a JEOL-JXA8530F electron microprobe housed at the ELSI, Tokyo Institute of Technology. The acceleration voltage, beam current, and peak measurement time were 15.0 kV, 1×10^{-8} A and 20 s, respectively. Na was analysed for 10 s in order to avoid count loss. Mineral grains were analysed using a focused electron beam, while a defocused beam (~5 - 30 µm) was used for silicate melt.

3. Results and Discussions

3.1. Phase Assemblages and Textures

All run conditions and the phases produced in each lithology are listed in **Table 2**. The eclogite layer contained clinopyroxene (Cpx), plagioclase (Pl), garnet (Grt), and coesite (Coe) at subsolidus temperatures, and Cpx, Grt, and silicate melt at suprasolidus temperatures (only a low degree of partial melting was observed). Basaltic melts coexisted with Cpx and Grt in isolated subsolidus peridotite layers. The peridotite failed to melt in most of our experiments, where it consisted



(c) Work flow diagram



Figure 3. (a) Cross section for the 2.9 GPa piston cylinder experiments with talc/Pyrexglass/graphite assembly. (b) Cross section for 5 and 8 GPa multi-anvil experiments with MgO/LaCrO₃/MgO assembly. (c) Work flow diagram of the experimental procedures.

of olivine (Oliv), orthopyroxene (Opx), Cpx, and Grt. An additional Al-rich phase (Cr-rich spinel) was present in 2.9-GPa run products, though this transformed to garnet at higher pressures. Significant melting took place in runs conducted at temperatures above the peridotite solidus—particularly near the basalt melt layer—with Oliv and Opx present as restitic phases in the suprasolidus regime. Melt pockets spread along matrix Opx-Oliv grain boundaries, while Cpx, Grt, and spinel were consumed.

Cpx and Grt produced at subsolidus basalt temperatures were mostly subhedral to euhedral (Figure 4(a), Figure 4(b)), although traces of melt occurred along



their grain boundaries at temperatures slightly above the dry eclogite solidus (Figure 4(d), Figure 4(e)). In the peridotite layer, Opx was mostly euhedral (Figure 4(c), Figure 4(f)), olivine occurred along Opx-Cpx-garnet grain boundaries (*i.e.*, within the peridotite matrix), and garnet had a poikilitic texture.

3.2. Reaction Band of Opx

Since partial melt formed in eclogite at pressure-temperature conditions below the peridotite solidus would not have been in chemical equilibrium with Oliv, thin Opx reaction bands formed between both rock types via chemical reaction between silica-rich partial melt of eclogite and Oliv in the peridotite matrix. At subsolidus peridotite conditions, the thickness of the Opx reaction band positively correlated with the run temperature and durations. As partially melted eclogite layers were separated from peridotite by thin Opx bands, chemical reactions between each basalt and peridotite layer were thus hindered and could only proceed via solid-state diffusion. At higher temperatures, substantial melting occurred both in basalt and peridotite layers, and fully molten basalt melts merged with molten pockets in peridotite. Extensive chemical mass transport was able to take place through chemical diffusion and liquid percolation under these conditions, and so basalt melting consistently allowed chemical equilibrium to be established with ambient peridotite, even in short runs.

3.3. Phase and Melt Compositions

Representative chemical compositions of individual solid and melt phases are listed in **Table 3**. Melts produced at all experimental conditions exhibited compositions that plotted in the basalt to basaltic andesite domains on a Harker diagram (**Figure 5**). Black crosses represent data from Mallik and Dasgupta [17]. Basaltic andesite melts dominated peridotite subsolidus runs, while relatively



Figure 4. Backscattered electron images of run products. a) P951, 2.9 GPa, 1300°C, 24 h; b) P951 basalt layer; c) P951 peridotite layer; d) P931, 2.9 GPa, 1460°C, 24 h; e) P931 basalt layer; f) P931 peridotite layer.

 Table 3. Representative chemical compositions of individual phase in weight percent.

Run No.	P (GPa)	T (°C)	Duration (h)	Layer	Phase	SiO_2	${\rm TiO}_2$	Al_2O_3	FeO	MnO	MgO	CaO	Na ₂ O	K_2O	P_2O_5	V_2O_3	Cr_2O_3	NiO	Total
P948	2.9	1300	3	MORB	Cpx1	52.46	0.80	5.64	10.44	0.19	15.99	10.91	2.12	0.00	0.09	0.00	0.00	0.03	98.68
					Орх	53.17	0.45	2.96	12.14	0.18	26.58	2.61	0.41	0.00	0.00	0.00	0.00	0.12	98.61
					Grt	38.00	0.88	20.50	22.20	0.41	7.39	8.92	0.13	0.01	0.16	0.00	0.00	0.01	98.60
					Pl	51.55	0.09	29.73	0.60	0.00	0.10	12.51	3.92	0.62	0.09	0.00	0.00	0.02	99.24
					Rt	5.75	79.85	3.46	5.24	0.06	1.54	1.63	0.05	0.01	0.00	7.91	0.00	0.01	105.51
				KLB-1	Ol	39.98	0.01	0.04	10.22	0.14	48.32	0.13	0.02	0.00	0.02	0.00	0.00	0.37	99.25
					Орх	53.70	0.12	4.95	6.52	0.14	32.36	0.86	0.12	0.00	0.01	0.00	0.00	0.10	98.88
					Срх	51.02	0.58	7.09	3.31	0.09	15.16	19.47	1.66	0.00	0.00	0.00	0.00	0.05	98.42
					Sp	0.12	0.14	56.69	10.22	0.12	20.53	0.06	0.00	0.00	0.00	0.00	4.52	0.32	92.72
P951	2.9	1300	24	MORB	Срх	50.56	1.64	13.97	6.99	0.09	7.65	13.93	3.83	0.01	0.07	0.00	0.00	0.04	98.76
					Grt	39.16	0.86	21.45	18.63	0.40	9.01	9.15	0.18	0.01	0.21	0.00	0.00	0.01	99.09
					Coe	93.75	0.07	1.49	0.89	0.01	0.45	0.53	0.02	0.00	0.00	0.00	0.00	0.00	97.20
P928	2.9	1460	1	MORB	Cpx1	50.60	0.95	13.18	8.00	0.16	8.96	13.47	3.34	0.02	0.01	0.00	0.00	0.03	98.73
					Cpx2	49.15	1.06	16.51	7.23	0.12	7.57	13.45	3.50	0.02	0.01	0.00	0.00	0.02	98.63
					Срх3	52.51	0.78	7.26	9.75	0.18	14.81	10.60	2.32	0.00	0.03	0.00	0.00	0.04	98.28
					Grt	38.75	0.92	21.17	18.44	0.42	9.75	8.32	0.18	0.01	0.09	0.00	0.00	0.02	98.07
				VID 1		54.39 40.31	3.03	0.11	9.30	0.11	2.21	7.39	5.25 0.02	1.12	0.44	0.00	0.00	0.01	90.55
				KLD-1	Onv	54 41	0.03	4.94	6 50	0.14	31.02	0.21	0.03	0.00	0.02	0.00	0.00	0.50	99.15
					Срх	51 78	0.13	7.08	3 14	0.15	15 21	19.06	1.49	0.01	0.04	0.00	0.00	0.11	99.20
					Sn	0.069	0.12	56 76	9.86	0.00	20.83	0.03	0.00	0.00	0.01	0.00	5.22	0.00	93.36
P931	2.9	1460	24	MORB	Cpx	49.83	0.87	13.95	7.24	0.15	9.84	14.14	3.13	0.01	0.03	0.00	0.00	0.01	99.20
					Grt	39.68	0.76	22.08	15.95	0.41	11.94	8.24	0.11	0.00	0.04	0.00	0.00	0.01	99.23
					М	52.66	2.83	15.12	10.40	0.14	4.19	8.66	3.22	0.68	0.27	0.00	0.00	0.00	98.18
				KLB-1	Ol	40.55	0.01	0.12	10.44	0.12	48.15	0.25	0.03	0.00	0.02	0.00	0.00	0.36	100.06
					Орх	54.72	0.15	4.99	6.55	0.13	32.03	1.06	0.16	0.01	0.05	0.00	0.00	0.12	99.98
					Sp	0.37	0.34	57.31	9.39	0.12	21.31	0.04	0.02	0.00	0.00	0.00	4.98	0.32	94.18
P929	2.9	1500	1	MORB	Срх	49.50	0.71	13.37	6.70	0.16	10.32	14.61	2.95	0.01	0.02	0.00	0.00	0.03	98.38
					Grt	39.22	0.79	21.39	16.17	0.39	11.92	7.98	0.16	0.01	0.07	0.00	0.00	0.04	98.15
					М	51.21	2.62	15.34	11.38	0.17	3.72	8.45	2.93	0.62	0.26	0.00	0.00	0.01	96.70
				KLB-1	Ol	39.88	0.01	0.15	10.73	0.14	47.56	0.29	0.03	0.00	0.06	0.00	0.00	0.39	99.22
					Opx	53.89	0.15	4.95	6.71	0.13	32.10	0.88	0.13	0.01	0.02	0.00	0.00	0.11	99.07
					Срх	50.95	0.61	7.13	3.28	0.08	15.21	19.12	1.63	0.01	0.04	0.00	0.00	0.06	98.12
					Sp	0.07	0.12	56.76	9.86	0.12	20.83	0.03	0.00	0.01	0.00	0.00	5.22	0.35	93.36
P935	2.9	1500	24	MORB	Срх	52.53	0.42	8.29	5.47	0.14	18.30	12.38	1.86	0.00	0.02	0.00	0.00	0.04	99.45
					Grt	41.16	0.56	22.39	10.21	0.31	17.85	6.57	0.04	0.01	0.03	0.00	0.00	0.01	99.14
					М	47.49	2.01	12.87	8.98	0.16	12.21	8.68	2.78	0.42	0.24	0.00	0.00	0.01	95.83



Contin	ued																		
				KLB-1	Ol	40.58	0.02	0.15	10.32	0.14	48.17	0.30	0.03	0.00	0.01	0.00	0.00	0.34	100.07
					Орх	54.64	0.15	4.99	6.38	0.14	31.97	1.08	0.17	0.00	0.03	0.00	0.00	0.13	99.69
P932	2.9	1540	1	MORB	Срх	50.35	0.70	11.99	6.27	0.16	13.43	14.64	2.10	0.01	0.02	0.00	0.00	0.01	99.67
					Sp	0.12	0.42	57.43	10.09	0.08	20.73	0.09	0.02	0.01	0.00	0.00	5.59	0.38	94.95
					М	48.76	1.60	13.93	9.79	0.18	9.45	10.95	2.59	0.24	0.11	0.00	0.00	0.01	97.62
				KLB-1	Ol	40.57	0.01	0.16	10.33	0.14	48.13	0.30	0.04	0.01	0.00	0.00	0.00	0.35	100.04
					Орх	54.73	0.14	4.94	6.57	0.15	32.30	0.92	0.11	0.01	0.02	0.00	0.00	0.09	99.96
					Срх	52.73	0.28	6.86	5.31	0.12	23.02	9.88	0.86	0.01	0.02	0.00	0.00	0.11	99.20
					Grt	42.34	0.66	21.75	6.84	0.20	21.25	5.46	0.08	0.04	0.12	0.00	0.00	0.03	98.76
P936	2.9	1540	24	MORB	М	48.14	1.09	11.00	6.44	0.17	19.90	8.64	1.81	0.18	0.06	0.00	0.00	0.01	97.43
				KLB-1	Ol	41.59	0.01	0.17	5.95	0.11	52.60	0.23	0.02	0.01	0.04	0.00	0.00	0.01	100.74
S1813	5	1300	3	MORB	Срх	51.61	1.25	15.46	5.93	0.08	6.87	12.69	4.53	0.16	0.09	0.00	0.00	0.03	98.70
					Grt	39.85	1.10	20.99	18.03	0.37	8.84	10.08	0.31	0.08	0.22	0.00	0.00	0.02	99.89
					Coe	97.54	0.11	0.52	0.48	0.02	0.11	0.24	0.01	0.01	0.00	0.00	0.00	0.00	99.05
				KLB-1	Ol	40.11	0.02	0.04	10.23	0.14	48.92	0.11	0.01	0.00	0.04	0.00	0.00	0.35	99.97
					Орх	54.04	0.13	4.88	6.52	0.15	32.58	0.88	0.11	0.01	0.05	0.00	0.00	0.11	99.45
					Срх	51.44	0.58	6.80	3.36	0.08	15.65	19.22	1.66	0.00	0.05	0.00	0.00	0.07	98.93
					Sp	0.14	0.15	57.44	10.50	0.11	20.92	0.05	0.01	0.00	0.04	0.00	4.64	0.40	94.37
S1797	5	1450	3	MORB	Срх	52.68	1.01	13.42	6.75	0.11	9.50	13.16	3.91	0.04	0.01	0.15	0.05	0.02	100.82
					Grt	41.34	0.80	22.39	15.04	0.36	12.53	8.55	0.11	0.00	0.07	0.10	0.09	0.01	101.39
					М	51.78	2.38	14.59	9.96	0.15	5.91	8.95	3.37	0.60	0.16	0.27	0.01	0.02	98.14
				KLB-1	Ol	41.35	0.02	0.08	11.72	0.12	48.64	0.20	0.05	0.01	0.01	0.01	0.07	0.38	102.66
					Орх	55.88	0.12	4.79	6.68	0.13	33.12	0.81	0.16	0.00	0.01	0.02	0.27	0.13	102.13
					Срх	53.35	0.56	7.66	4.31	0.09	16.27	15.65	2.26	0.01	0.00	0.07	0.38	0.07	100.67
					Grt	42.41	0.73	22.88	10.86	0.27	16.95	7.23	0.12	0.00	0.00	0.11	0.02	0.01	101.58
					Sp	0.15	0.53	58.35	9.54	0.09	22.06	0.07	0.00	0.00	0.00	0.11	7.88	0.41	99.18
S1802	5	1450	20	MORB	Срх	52.90	1.09	14.07	7.09	0.11	8.04	11.43	4.17	0.01	0.02	0.15	0.03	0.02	99.13
					Grt	40.58	0.98	22.05	17.68	0.39	9.77	8.12	0.19	0.01	0.02	0.13	0.01	0.03	99.94
					М	54.84	3.57	12.93	8.62	0.10	3.29	6.55	2.89	1.13	0.09	0.39	0.01	0.01	94.43
				KLB-1	Ol	41.12	0.03	0.08	10.55	0.10	48.90	0.17	0.02	0.01	0.00	0.00	0.05	0.41	101.45
					Орх	55.07	0.18	4.32	6.57	0.11	32.40	1.01	0.19	0.00	0.00	0.04	0.30	0.13	100.32
					Срх	52.48	0.52	6.56	3.58	0.08	16.19	16.87	1.56	0.01	0.01	0.09	0.61	0.08	98.64
					Grt	41.97	0.61	21.24	7.10	0.20	21.18	4.54	0.01	0.01	0.00	0.09	2.27	0.02	99.23
S1799	5	1500	3	MORB	Срх	51.05	0.88	15.09	6.57	0.13	8.18	13.53	3.97	0.01	0.00	0.00	0.00	0.04	99.44
					Grt	39.26	0.91	21.77	16.74	0.39	10.33	9.53	0.15	0.01	0.06	0.00	0.00	0.01	99.16
					М	56.00	4.52	13.05	9.44	0.10	2.22	7.23	2.70	1.40	0.41	0.42	0.01	0.01	97.49
				KLB-1	Ol	41.32	0.03	0.09	10.33	0.12	49.17	0.21	0.04	0.01	0.01	0.00	0.06	0.37	101.74
					Орх	55.84	0.20	4.10	6.86	0.13	32.23	1.34	0.23	0.01	0.01	0.04	0.25	0.13	101.36

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					Срх	53.20	0.46	5.95	3.73	0.11	17.76	17.16	1.43	0.01	0.02	0.08	0.58	0.07	100.54
					Grt	44.76	0.39	21.19	7.15	0.25	21.51	5.70	0.06	0.01	0.00	0.05	1.23	0.03	102.31
					Sp	4.78	0.48	50.17	10.35	0.12	22.07	0.48	0.00	0.01	0.02	0.16	11.09	0.40	100.13
S1788	5	1550	3	MORB	М	49.79	1.73	14.00	9.64	0.18	9.64	9.85	2.85	0.32	0.17	0.19	0.04	0.01	98.41
				KLB-1	Ol	40.44	0.03	0.14	11.00	0.12	49.74	0.28	0.06	0.01	0.05	0.00	0.07	0.31	102.24
					Opx	55.21	0.11	4.86	6.54	0.15	33.31	0.87	0.16	0.01	0.00	0.05	0.27	0.10	101.62
					Срх	54.33	0.31	4.68	5.61	0.15	25.00	9.49	0.84	0.01	0.01	0.07	0.46	0.06	101.02
S1790	5	1650	3	MORB	М	48.83	0.88	9.54	7.22	0.14	23.03	7.04	1.70	0.15	0.05	0.10	0.18	0.02	98.88
				KLB-1	Opx	57.43	0.09	3.86	4.03	0.07	34.45	1.38	0.24	0.00	0.01	0.01	0.28	0.02	101.87
S1808	8	1300	3	MORB	Срх	54.28	0.75	11.10	5.14	0.06	8.73	12.77	5.31	0.27	0.01	0.00	0.00	0.01	98.42
					Grt	40.92	1.09	20.05	16.30	0.31	9.90	9.78	0.74	0.07	0.20	0.00	0.00	0.01	99.38
					Coe	96.14	0.06	0.65	0.52	0.01	0.28	0.44	0.22	0.02	0.00	0.00	0.00	0.01	98.33
				KLB-1	Ol	40.46	0.03	0.16	9.98	0.10	48.38	0.12	0.02	0.01	0.01	0.00	0.00	0.39	99.65
					Opx	53.79	0.12	4.65	6.53	0.16	32.60	0.88	0.16	0.00	0.00	0.00	0.00	0.11	98.99
					Срх	51.46	0.49	6.54	3.36	0.07	15.86	19.17	1.59	0.01	0.01	0.00	0.00	0.10	98.66
					Grt	43.74	0.60	18.70	8.46	0.29	21.07	6.40	0.24	0.01	0.00	0.00	0.00	0.00	99.50
S1812	8	1500	3	MORB	Срх	53.89	1.16	11.53	5.21	0.07	8.40	13.02	4.97	0.22	0.03	0.00	0.00	0.02	98.52
					Grt	38.98	1.52	20.66	14.91	0.29	7.73	13.76	0.47	0.03	0.10	0.00	0.00	0.00	98.45
					Coe	98.78	0.05	0.12	0.37	0.01	0.05	0.11	0.04	0.00	0.00	0.00	0.00	0.03	99.57
				KLB-1	Ol	39.95	0.02	0.04	10.22	0.10	48.66	0.11	0.03	0.00	0.02	0.00	0.00	0.38	99.54
					Opx	54.11	0.18	4.64	6.43	0.14	32.33	0.96	0.21	0.01	0.03	0.00	0.00	0.09	99.12
					Срх	51.03	0.52	7.04	3.31	0.10	15.46	19.53	1.65	0.00	0.00	0.00	0.00	0.10	98.75
					Grt	41.10	1.11	20.18	7.52	0.26	21.64	4.48	0.08	0.01	0.19	0.00	0.00	0.04	96.60
					Sp	0.09	0.55	56.01	10.52	0.11	21.06	0.09	0.00	0.00	0.00	0.00	5.46	0.34	94.22



Figure 5. Total Alkali-SiO₂ compositions of reacted melts.



Si-rich tholeiitic melts dominated at temperatures near the dry peridotite solidus, the compositions of which were buffered by the aforementioned Opx reaction band along the interface of each rock type.

The relative K_2O and TiO_2 contents of melts formed within each starting material (yellow star in **Figure 6**) can be used as a proxy for the degree of melting of N-MORB. Lower K_2O and TiO_2 contents mean that the volume of melt increased by melting of peridotite, which essentially lacks K_2O and is very TiO_2 poor (**Figure 6(c)**, **Figure 6(d)**, **Figure 6(f)**). The presence of an Opx band caused chemical exchanges between both rock types to proceed solely by solidstate diffusion for as long as the peridotite lacked melt.

Because of the different starting materials used for layered experiments, our melt compositions (e.g., Ti, Na, Ca, and Fe) were systematically different from those reported by Mallik and Dasgupta [17]. In our study, all major elements except for Fe showed a close fit with a Hawaiian tholeiite composition. Partial melts of anhydrous run products contained ~55 - 57 wt% SiO₂ (*i.e.*, andesite) at low temperature and ~50 - 53 wt% SiO₂ (*i.e.*, tholeiite) at high temperature; the latter melt compositions being similar to those observed in Hawaii during its shield-building stage (Figure 6(b)). Composition of melts obtained at temperatures close to the dry peridotite solidus closely matched the composition of Hawaiian tholeiite (Figure 6(a)). Notably, N-MORB had almost entirely melted at these conditions. These results and their comparison with Hawaiian tholeiite (Figure (6)) show that the chemical composition of recycled eclogite in the sub-Hawaiian plume is more enriched in FeO than N-MORB is.

3.4. Implications for Hawaiian Magma Genesis

A schematic model for melting processes in a heterogeneous Hawaiian plume is shown in **Figure 7** (after Takahashi and Nakajima [7]). We have demonstrated that the entire compositional spectrum of Hawaiian tholeiites (basalt to picrite) can be formed by basalt-peridotite hybrid melting near to the dry peridotite solidus. In other words, our results indicate that the temperature at the centre of the plume head may be close to that of the dry solidus of peridotite KLB-1 (1480°C at 3 GPa, Takahashi *et al.* [19]), or else slightly lower. This implies that the PMT (Potential mantle Temperature) of the Hawaiian plume may be much lower than has been previously estimated (e.g., 1558°C, Watson and McKenzie, [3]).

The size of the entrained eclogite component plays an essential role in the melting processes that occur within a heterogeneous plume. If the eclogite components were small (such as mafic dyke or mafic bands, which are common in peridotite massifs), partially molten eclogite layers could achieve equilibrium with the surrounding peridotite over geological timescales relevant to plume melting (*i.e.*, $10^4 - 10^6$ yr). Conversely, if eclogite blocks were large (e.g., km-scale or larger), melt formed in the eclogite blocks would be isolated from surrounding peridotite due to the formation of Opx bands at their interfaces. The time-scale of melt segregation from the partially molten eclogite may be faster



Figure 6. Major elements composition of reacted melts from layered experiments. Yellow star indicates the original composition of starting material NAM-7 [18]; red diamonds are compositions of run products conducted at 2.9 GPa, blue triangles are compositions of run products carried out at 5 GPa. Crosses represent the layered experiments data from Mallik & Dasgupta [17]. Tholeiitic basalt components of Kilauea, Manua Loa, Koolau and Loihi are also plotted in these diagrams as black, grey dots.

than that for reaction rate across the Opx band; thus, melts derived from eclogite domains would have geochemical signatures that record entrainment and would contaminate the surrounding peridotite less extensively.



Figure 7. Schematic model of the melting process in Hawaiian plume (modified after Takahashi & Nakajima [7]).

Takahashi and Nakajima [7] proposed that magma produced near the axis of the plume head may be a mixture of two types of melts: 1) basaltic andesite melt formed by eclogite melting, and 2) picritic melts formed by the reactive melting of eclogite and peridotite. According to their study of the Koolau volcano, an eclogite block larger than 1000 km³ supplied silica-rich magma at the last stage the volcano's formation, and remained in disequilibrium with peridotite during its lifetime. Hence layered eclogite-peridotite experiments are necessary in order to study the dynamics of the recycled oceanic crust in the ascending plume.

Tholeiite to basaltic andesite magmas could be generated in an upwelling mantle plume containing a recycled oceanic component (Figure 7) by hybridised melting of basalt and peridotite. High-silica tholeiitic OIB, such as occurs in Hawaii, may be formed under nearly dry conditions in a heterogeneous plume. The relative stability of Opx caused it to form in our experiments via chemical reaction between silicate melt and SiO2-undersaturated olivine from ambient peridotite. This Opx separated basaltic domains and peridotite domains during melting. Major-element compositions of melt derived from layered N-MORB and spinel lherzolite closely matched those of Hawaiian tholeiite. Very depleted heavy rare earth element (HREE) patterns in Hawaiian tholeiite might be attributed to percolation of partial melt in vertically elongated eclogite blobs in the centre of the plume. Enrichments in Fe, K, Ti, and light rare earth elements (LREE) in the Hawaiian tholeiite compared with modern MORB may indicate that the source of the recycled components in the Hawaiian plume is more enriched in Fe and incompatible elements than modern N-MORB is. A likely source material here is Fe-rich tholeiite, which was common in the Archaean and early Proterozoic [21]. This conclusion is consistent with model ages of Hawaiian magma sources determined by Pb isotopes [21].

4. Conclusions

We have carried out high-pressure melting experiments using an N-MORB/ peridotite (KLB-1) layered starting material in order to study magma genesis processes in the heterogeneous Hawaiian plume, which has entrained ancient oceanic crust. Major conclusions from this study are as follows:

- 1) In an upwelling mantle plume with a recycled oceanic component, N-MORB eclogite begins to melt at depth (5 GPa), but peridotite remains entirely solid almost up to the top of plume (~3 GPa).
- 2) Extensive partial melting occurs in eclogite domains, which produces tholeiite to basaltic andesite melts. Some chemical reaction occurs at the basaltperidotite interface.
- 3) Excluding FeO contents, the major-element composition of melts formed by reactive melting of N-MORB/KLB-1 at temperatures near the dry peridotite solidus are similar to Hawaiian tholeiite and picrite.
- 4) Relatively Fe- and LREE-enriched geochemical signatures in Hawaiian tholeiite compared with MORB suggest that the source of recycled components in the Hawaiian plume is more enriched in Fe and in incompatible elements than modern MORB.
- 5) The potential temperature of the Hawaiian plume could be 1450°C or lower.

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