Crustal contamination and diversity of magma sources in the northwestern Ethiopian volcanic province

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Geochemical and isotopic data are presented for Bure volcanic rocks from the northwestern Ethiopian plateau to investigate the processes involved in the genesis of the erupted magma and the nature of mantle source compositions during plume-induced continental rifting. The Bure area is mainly composed of flood basalts (30–25 Ma), ranging from transitional tholeiite to alkaline basalts, with a probable Quaternary alkaline basalt single lava flow, scoria cones and trachyte plugs. The transitional tholeiites have variable incompatible elements and isotopic ratios ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70329\text{--}0.70429$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51281\text{--}0.51304$ and $^{206}\text{Pb}/^{204}\text{Pb} = 18.36\text{--}19.08$). In contrast, the alkaline basalts display a homogeneous incompatible element and Sr–Nd isotopic ratios ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70311\text{--}0.70363$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.51279\text{--}0.51288$) with a wide range of Pb isotopes ($^{206}\text{Pb}/^{204}\text{Pb} = 18.91\text{--}19.83$). Isotope and trace element variations within the Bure lavas reflect the involvement of: 1) an intrinsic isotopically depleted plume component, 2) a plume component having radiogenic Pb isotope and 3) an enriched crustal component. The first and third components played a significant contribution in the initial stage of plume-induced continental flood basalt magmatism.

Keywords: East African rift, Sr–Nd–Pb isotopes, Afar plume, Crustal contamination, Continental flood basalts

INTRODUCTION

The magmatism along the NNE–SSW running Ethiopian–Kenyan rift, the encircling plateaus and the Afar Depression together represent one of the largest, currently active igneous provinces in the East Africa (Fig. 1a). The East African Rift System (EARS) forms the southwestern part of the Afro–Arabian triple junction that comprises the Red Sea and the Gulf of Aden oceanic rift, which were formed by the separation of the Arabian and African plates (Fig. 1a). EARS is several hundred kilometers long and characterized by widely distributed volcanic provinces that were initiated in the Eocene to Oligocene as a result of lithospheric extension due to the domal uplift of the surrounding regions. It is widely accepted that the distribution and timing of magmatism and uplift of the entire area resulted from the upwelling of a complex, heterogeneous African mantle plume (Kieffer et al., 2004 and references therein).

The extensive flood basalt plateaus in Ethiopia, Saudi Arabia and Yemen well represented part of this complexity. The continental flood basalt (CFB) magma-

tism in these regions is mainly divided into two groups: 1) an older group of predominantly transitional to subalkaline flood basalts (pre-rift volcanism) and 2) a younger group consisting of mainly alkaline volcanics (syn- to post-rift volcanism). Among these plateaus, the Ethiopian one is ideal for studying the nature of the mantle sources of CFBs as it represents a complete record of the flood basalt volcanism, from its initial phase to the onset of continental rifting.

Three mantle sources (old subcontinental lithosphere, the HIMU-type (high μ) Afar mantle plume and the depleted mantle) have been proposed as potential sources for the Ethiopian CFBs (e.g., Vidal et al., 1991; Deniel et al., 1994; Stewart and Rogers, 1996). Moreover, these basalts suffered variable degrees of crustal contamination (White and McKenzie, 1989; Baker et al., 1996; Pik et al., 1998, 1999). The geochemistry of Ethiopian CFB magmas, therefore, reflects a complex interplay of source heterogeneity, variable extents of melting, and evolution of the magmas prior to eruption.

In this paper, we present major and trace elements and Sr–Nd–Pb isotope data for volcanic rocks from the Bure area with new K–Ar dating results. The Bure area is located in the western part of the northwestern Ethiopian plateau of the East African CFB province (Fig. 1a), where

Figure 1. Location of the study sites: (a) shaded relief map of northeastern Africa and Arabia (NASA SRTM30) illustrating the position of the three rifts (Main Ethiopian Rift, MER, Gulf of Aden and Red Sea), as well as the Ethiopian and Yemeni plateaus, which surround the Afar Depression, with the Bure area indicated; (b) simplified geological map of the Bure area; topographic contour lines (interval = 500 m) are indicated; FB=flood basalts. Basement rocks include Precambrian gneisses, low-grade metamorphic rocks and granitoids.

both pre-rift and post-rift basalts are widely distributed. Although Pik et al. (1998, 1999) and Kieffer et al. (2004) reported detailed geochemical data for basalts in the northwestern Ethiopian plateau, there are no such data for the Bure volcanic rocks. Our dataset has been used to investigate the nature of asthenospheric and lithospheric

mantle sources involved in the genesis of these magmas and the compositional effects of interactions between plume melts and crustal materials. Geochemical variation is also discussed in the context of the geodynamic evolution of plume-induced continental rifting.

Table 1. Major and trace element contents by XRF and modal compositions of volcanic rocks from the Bure area

Type	Transitional tholeiite basalts										
Sample No	TD-1228A	TD-1202	TD-1239	ASW-503	TL-208	TL-229	TL-253	EH-235A	AN-201	MH-4510A	MH-4521
SiO ₂ (wt%)	50.56	51.62	46.93	51.39	52.85	50.11	48.90	48.52	47.01	49.18	49.50
TiO ₂	2.441	1.706	1.260	2.312	2.231	2.092	2.306	2.126	1.252	3.500	3.544
Al ₂ O ₃	13.88	14.47	14.29	14.24	14.20	15.63	14.44	15.92	15.53	13.11	13.99
Fe ₂ O ₃	13.91	11.94	11.62	13.39	12.21	12.90	13.74	11.98	11.98	16.51	13.27
MnO	0.21	0.17	0.18	0.18	0.19	0.19	0.19	0.18	0.18	0.24	0.22
MgO	5.00	6.05	11.14	5.29	3.77	5.16	5.79	6.56	8.65	3.89	4.73
CaO	9.67	10.44	9.64	8.98	6.76	10.83	11.04	10.69	10.48	8.59	8.77
Na ₂ O	2.94	2.71	2.89	2.86	3.36	2.56	2.62	2.62	2.14	2.94	3.07
K ₂ O	0.62	0.44	0.64	0.94	2.35	0.48	0.45	0.74	0.36	1.18	1.05
P ₂ O ₅	0.214	0.130	0.197	0.268	0.807	0.176	0.197	0.229	0.114	0.416	0.811
LOI	0.46	0.34	0.35	2.46	1.22	0.72	0.93	2.07	3.42	0.87	1.18
Total	99.90	100.02	99.14	102.31	99.94	100.85	100.60	101.64	101.12	100.43	100.13
XRF data											
Ba (ppm)	134	149	236	308	1665	132	86	194	754	232	797
Ce	30	32	18	55	120	18	21	30	8	62	69
Co	42	39	60	43	29	39	44	39	46	38	34
Cr	23	71	457	45	19	56	45	184	326	19	48
Nb	7.4	5.8	21.5	10.3	17.7	6.7	10.0	12.9	4.3	18.7	17.8
Ni	22	32	283	63	12	29	46	100	134	12	12
Pb	5	4	2	4	12	4	2	4	3	7	6
Rb	14	8	14	18	28	13	9	13	8	24	18
Sr	264	257	333	351	742	299	272	337	350	264	560
Th	1	3	3	2	3	2	2	4	—	5	4
V	392	263	191	310	227	368	372	345	251	397	338
Y	31	27	22	33	38	26	25	25	21	42	31
Zr	145	114	90	181	317	127	130	154	94	222	158
Phenocryst (%)											
Plagioclase		6.60		6.00		10.00	10.90	15.00			
Olivine			9.80		10.00						
Clinopyroxene				10.60	5.00		0.20	6.90			
Orthopyroxene				7.00							
Groundmass		93.40	90.20	76.40	85.00	90.00	88.90	78.10			

LOI, loss on ignition; Fe₂O₃, total Fe₂O₃.

For normative calculation Fe₂O₃/FeO = 0.15 is assumed.

GEOLOGICAL SETTING

The Ethiopian volcanic province is composed of Tertiary (Trap series) and Quaternary (Aden series) basaltic successions (Mohr, 1963) with thicknesses varying from 700 to 2,000 m at the plateau-rift margins (Berhe et al., 1987) and about 300,000 km³ (Mohr, 1963; Hart et al., 1989; Tefera et al., 1996). The volcanic province is subdivided into three major geographical and geomorphological parts (Fig. 1a): the Ethiopian plateaus (northwestern, southwestern and southeastern), the Main Ethiopian Rift (MER) and the Afar Rift (Kazmin, 1979; Berhe et al., 1987; Hart

et al., 1989). Although the post-rift volcanism has been concentrated mainly along the axis of MER, it also occurred in the Tana graben in the NW plateau region (Kazmin, 1972, 1979) and along the Yere-Tulu Wellel volcano-tectonic lineaments between the northwestern and southwestern plateaus (Abebe et al., 1998).

The Ethiopian flood basalts occurred in three main episodes 30 Ma, 22–12 Ma and < 5 Ma (Stewart and Rogers, 1996; Kieffer et al., 2004). The occurrence of the latest stage volcanism outside the MER might be related to the development of new rift and fracture zones (Davidson and Rex, 1980).

Table 1. (Continued)

Type	Alkaline basalts										
Sample No	WH-3496	TN-28	TD-1034B	SM-172	SM-120	SOG-3136	SOG-3061B	SOG-3104	TN-85	SOG-3091	SOG-3005
SiO ₂ (wt%)	47.07	43.20	46.84	47.21	49.68	44.55	58.31	57.58	49.99	44.75	44.37
TiO ₂	3.723	3.894	3.142	2.505	2.260	2.978	1.009	0.428	2.167	3.735	2.430
Al ₂ O ₃	13.88	14.18	16.46	16.72	16.97	15.72	18.32	18.09	15.20	15.09	12.52
Fe ₂ O ₃	14.04	13.39	14.48	12.90	10.43	13.03	4.75	6.12	12.52	14.88	11.50
MnO	0.21	0.19	0.21	0.18	0.21	0.19	0.23	0.38	0.18	0.23	0.17
MgO	6.05	8.34	4.38	5.39	4.28	7.96	1.06	0.90	4.66	4.87	12.01
CaO	10.26	10.34	6.60	7.91	6.32	8.88	2.93	1.72	9.10	8.05	11.53
Na ₂ O	2.77	2.79	3.82	3.71	4.32	3.09	6.62	6.78	3.38	3.52	2.05
K ₂ O	0.49	0.67	1.39	1.00	2.40	0.98	3.96	4.87	0.93	1.86	0.82
P ₂ O ₅	0.808	0.568	0.532	0.585	1.027	0.599	0.240	0.241	0.278	0.907	0.379
LOI	0.87	2.89	1.88	1.24	2.02	2.06	1.34	1.63	1.77	2.28	2.60
Total	100.17	100.45	99.73	99.35	99.92	100.04	98.77	98.74	100.17	100.18	100.39
XRF data											
Ba (ppm)	799	476	569	426	945	354	1516	883	318	624	325
Ce	57	71	67	64	120	68	140	198	57	109	40
Co	39	46	41	44	21	52	6	8	41	37	54
Cr	61	241	10	21	16	27	5	7	20	18	767
Nb	13.6	56.5	36.4	29.7	76	36	128	195	22	81	30
Ni	30	83	3	20	8	79	8	6	20	5	255
Pb	5	3	5	6	5	4	8	11	5	4	3
Rb	13	15	23	17	46	18	89	119	18	59	19
Sr	677	740	520	556	1133	601	1077	268	425	927	432
Th	2	3	2	2	6	3	9	15	4	5	4
V	353	302	162	169	149	233	17	4	340	168	284
Y	25	24	33	31	26	28	29	30	28	29	22
Zr	133	230	226	182	231	188	312	427	198	304	163
Phenocryst (%)											
Plagioclase			20.90	9.20	13.10	1.50	1.30	0.60	7.60		0.30
Olivine		8.00			1.20	12.20				2.70	7.00
Clinopyroxene		2.00		1.30	0.70	0.10		2.80			10.20
Fe-Ti oxides					2.00		0.30	0.40		8.80	
Groundmass		90.00	79.10	89.50	83.00	86.20	98.40	96.20	92.40	88.50	82.50

LOI, loss on ignition; Fe₂O₃, total Fe₂O₃.For normative calculation Fe₂O₃/FeO = 0.15 is assumed.

Although the Ethiopian CFBs have been the subject of numerous publications (e.g., Mohr and Zanettin, 1988; Hart et al., 1989; Schilling et al., 1992; Deniel et al., 1994; Stewart and Rogers, 1996; Barrat et al., 1998; Pik et al., 1999; Barrat et al., 2003; Kieffer et al., 2004), there are still Ethiopian flood basalt regions poorly known. The Bure area is one of them. In this region, Cenozoic volcanic rocks lie unconformably on Precambrian basement (Fig. 1b).

New K-Ar ages, commercially obtained from four representative Bure volcanic rock samples (see Appendix for data; the locations of dated samples are shown in Fig.

1b) indicate 29.3–26.6 Ma for transitional tholeiite CFBs and 28.3–25.3 Ma for alkaline CFBs. Although previous studies have suggested that the East African flood basalts were erupted about 30 Ma over a period of 1–2 My (e.g., Baker et al., 1996; Hofmann et al., 1997), ages obtained in this study imply a much longer period (30–25 Ma) of flood basalts activity in the region. Such a longer age distribution appears compatible with the compilation of Kieffer et al. (2004). Although there are no available age data for recent basalt flow, scoria and trachyte plugs, the field occurrence of these rocks suggests that their formation took place in the Quaternary.

Table 1. (Continued)

SOG-3043	Quat. basalts		Trachyte plugs		
	TD-1003	SOG-3157	TD-1136A2	TD-1135B	SM-113
45.72	46.56	48.54	64.01	63.91	63.98
1.931	1.743	1.755	0.171	0.174	0.407
14.72	14.91	16.77	17.09	17.01	15.85
11.00	10.91	11.72	4.11	4.00	4.44
0.18	0.17	0.16	0.14	0.09	0.19
9.63	10.05	6.14	0.08	0.05	0.16
10.14	10.27	10.42	0.40	0.59	0.34
3.97	3.01	3.28	6.78	6.8	7.31
1.47	1.17	1.00	5.36	5.49	5.05
0.495	0.293	0.279	0.038	0.068	0.046
0.36	0.14	0.67	0.77	0.99	0.75
99.61	99.22	100.74	98.95	99.17	98.53
593	366	347	162	123	32
72	43	50	320	354	338
45	51	34	4	4	4
315	321	158	6	5	8
75	32	26	176	182	356
187	184	51	16	13	11
4	2	4	12	13	20
43	24	18	123	145	193
733	518	518	14	14	19
6	2	3	15	15	29
199	227	219	4	3	6
20	17	22	90	83	50
169	135	133	1072	1144	944
	0.20	2.00			
7.20	15.60	8.00			
	0.10				
92.80	84.10	90.00			

Using a combination of stratigraphic information and geochronological and petrological data, the volcanic rocks of the Bure area can be deduced as: 1) transitional tholeiitic, 2) alkaline CFBs formed in the Oligocene and 3) Quaternary basalts, scoria cones and trachyte plugs.

PETROGRAPHY OF VOLCANIC ROCKS FROM THE BURE AREA

Both the transitional tholeiite and alkaline CFBs have porphyritic to aphyric textures (Table 1). Ophitic and subophitic textures are also observed in the transitional tholeiites. Most CFBs samples contain phenocrysts of olivine (altered to iddingsite along the rims and fractures), clino-

pyroxene and plagioclase set in a groundmass, which has the same phases plus opaque minerals and ranges from holocrystalline to intergranular and trachytic. In the transitional tholeiite CFBs phenocrysts of orthopyroxene may occur. The Quaternary basalt consists of a single lava flow with pahoehoe structure and occurs along small graben-like features. The basalt is vesicular and contains olivine phenocrysts with minor plagioclase and clinopyroxene set in a holocrystalline groundmass (Table 1). The scoria cones are characterized by poorly to moderately sorted and loose grains ranging from lapilli- to bomb-size and having different shapes (rod, spindle, etc.). The rock fragments in the scoria are mainly olivine to olivine-clinopyroxene phryic basalts and mantle xenoliths. The trachyte forms columnar-jointed upright plugs which intruded the older basalts. The plugs contain coarse- to medium-grained sanidine with trachytic texture.

GEOCHEMISTRY

Analytical methods

Representative samples from all rock types, except for scoria, were crushed into mm-sized chips using a hydraulic crusher; the freshest rock chips carefully handpicked under a stereomicroscope were pulverized with an alumina ceramic swing mill.

The whole-rock major elements and selected trace elements (Co, Cr, V, Ni, Nb, Pb, Rb, Th, Y, Zr, Ba and Ce) were determined on the fused glass beads by using X-ray fluorescence spectrometry (Shimadzu XRF-1800) at the Department of Physics and Earth Sciences, University of the Ryukyus (Table 1). The glass beads were prepared by fusing mixtures of 1 (± 0.0005) g of rock powder and 5 (± 0.0010) g of lithium tetraborate. Calibration curves were constructed using international standard rock samples from the Geological Survey of Japan (GSJ) and US Geological Survey (USGS).

The concentrations of most trace elements, including rare earth elements (REE), were measured by inductively coupled plasma mass spectroscopy (ICP-MS), Yokogawa Analytical Systems (now Agilent Technologies) HP4500, at the University of the Ryukyus (Table 2). Detailed analytical procedures are given in Shinjo et al. (2000). A USGS BCR-2 standard solution was used as calibration standard with ^{115}In internal standard. ICP-MS data are used in the figures herein.

Reproducibility and accuracy of the XRF analyses were checked using the international rock standards JB-1 (GSJ), BCR-2 (USGS) and BHVO-2 (USGS), whereas those of the ICP-MS analyses were checked using the international rock standard JA-1 (GSJ). Accuracy for

Table 2. Trace element contents obtained by ICP-MS of volcanic rocks from the Bure area

Type	Transitional tholeiite basalts									Alkaline basalts	
Sample no	TD-1228A	ASW-503	TL-253	EH-235A	AN-201	MH-4510A	MH-4521	TD-1202	TD-1239	TD-1034B	SM-120
Sc (ppm)	43.8	36.0	38.4	42.2	31.1	40.5	28.5	37.6	28.7	20.8	12.1
V	436	375	340	471	223	498	329	334	203	158	161
Cr	24	52	33	209	168	22	37	71	456	14	18
Co	55	63	51	70	47	64	34	52	64	45	26
Ni	34	97	51	171	105	35	19	43	298	13	12
Rb	18.0	15.7	8.3	8.9	4.5	41.3	19.9	9.8	13.7	34.3	53.6
Sr	392	322	335	296	295	439	616	373	351	744	1,223
Y	46.2	31.2	32.5	22.0	18.8	60.0	36.6	39.4	26.3	49.9	32.0
Zr	211	165	155	126	70	305	161	157	83	323	217
Nb	11.2	10.3	14.6	12.2	4.0	23.3	20.7	8.6	19.8	48.5	71.5
Cs	0.19	0.33	0.06	0.06	0.02	0.38	0.33	0.10	0.10	0.15	0.44
Ba	133	343	89	243	653	279	733	150	242	597	1,007
Hf	5.04	4.51	3.91	3.61	1.79	7.37	4.04	3.86	2.09	6.89	4.84
Ta	0.65	0.59	0.83	0.73	0.22	1.39	1.18	0.46	1.12	2.44	3.99
Pb	2.82	4.77	1.59	2.52	0.71	3.45	3.19	2.04	1.06	4.54	5.25
Th	1.32	1.94	1.08	1.72	0.31	2.65	2.09	1.03	1.42	2.81	5.58
U	0.51	0.71	0.31	0.44	0.10	0.72	0.67	0.47	0.37	0.70	1.43
La	11.16	20.09	10.31	17.50	4.70	28.33	25.59	8.91	14.39	30.33	60.68
Ce	28.21	48.53	25.49	43.14	11.94	68.14	62.39	21.66	24.66	66.74	121.20
Pr	4.31	6.70	3.60	5.93	1.83	9.41	8.99	3.17	3.15	8.76	14.21
Nd	20.11	30.14	16.55	26.63	8.58	42.09	41.54	14.78	13.35	36.07	54.26
Sm	6.21	8.05	4.86	7.01	2.60	11.56	9.71	4.67	3.01	8.78	10.13
Eu	2.17	2.56	1.69	2.36	1.03	3.63	3.72	1.75	1.20	2.99	3.15
Gd	7.38	8.04	5.62	6.76	3.06	13.23	9.50	6.04	3.87	9.35	8.97
Tb	1.27	1.29	0.92	1.07	0.54	2.12	1.32	1.05	0.64	1.43	1.21
Dy	7.70	6.99	5.69	5.66	3.32	12.58	7.14	6.44	4.10	8.25	6.58
Ho	1.58	1.39	1.13	1.07	0.71	2.48	1.36	1.31	0.87	1.66	1.29
Er	4.19	3.63	2.96	2.72	1.93	6.41	3.39	3.50	2.46	4.35	3.38
Tm	0.62	0.51	0.44	0.37	0.29	0.88	0.46	0.51	0.35	0.64	0.48
Yb	3.96	3.16	2.75	2.21	1.83	5.12	2.87	3.30	2.17	4.17	3.00
Lu	0.55	0.45	0.39	0.31	0.27	0.70	0.40	0.45	0.32	0.60	0.43

major and trace elements is mostly better than 3% and 10%, respectively.

Sr, Nd and Pb isotope analyses were undertaken on handpicked rock chips (≤ 1 mm) using a Finnigan MAT262 mass spectrometer at the University of the Ryukyus (Table 3). Representative samples were chosen to cover the entire compositional range. Rock chips with visible phenocrysts were rejected. Sr, Nd and Pb were extracted from the same solution through a combination of ion-exchange columns. Further analytical procedures are described in Shinjo et al. (2000). The isotopic ratios were corrected for mass fractionation by normalizing to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. During this

study, the SRM987 Sr standard gave a mean $^{87}\text{Sr}/^{86}\text{Sr} = 0.710239 \pm 0.000026$ (2SD; $n = 5$) and the Nd standard La Jolla gave a mean $^{143}\text{Nd}/^{144}\text{Nd} = 0.511831 \pm 0.000019$ (2SD; $n = 5$). The ^{204}Pb - ^{207}Pb double spike method was applied to Pb isotopic analyses. Fractionation-corrected values for SRM981 Pb standard ($n = 5$) were $^{206}\text{Pb}/^{204}\text{Pb} = 16.9411 \pm 0.0021$ (2SD), $^{207}\text{Pb}/^{204}\text{Pb} = 15.4983 \pm 0.0016$ (2SD) and $^{208}\text{Pb}/^{204}\text{Pb} = 36.7208 \pm 0.0039$ (2SD), which agree well with the preferred values from Thirlwall (2000).

Table 2. (Continued)

Type	Alkaline basalts						Quat. basalts		Trachyte plugs	
Sample no	SOG-3061B	SOG-3104	SOG-3091	SOG-3005	SOG-3043	SM-172	TD-1003	SOG-3157	TD-1136A2	SM-113
Sc (ppm)	2.9	2.6	15.3	38.6	28.4	24.0	26.7	27.9	4.0	4.6
V	16	6	143	337	233	144	223	195	3	4
Cr	16	8	18	711	225	21	165	92	12	9
Co	—	—	38	73	54	40	50	40	—	—
Ni	—	—	14	318	210	22	141	49	—	—
Rb	138	108	66.2	21.8	49.9	16.1	20.9	17.9	219	205
Sr	1,548	216	948	503	792	550	452	519	10	12
Y	45.4	27.2	35.7	23.1	24.1	34.5	17.7	22.2	122	52
Zr	472	379	308	155	155	176	107	127	1,251	1,064
Nb	168.0	152.5	83.3	32.9	79.9	30.6	29.7	30.8	175.8	347
Cs	0.81	0.27	0.47	0.38	0.53	0.10	0.25	0.21	0.17	0.82
Ba	1,690	974	580	361	643	403	341	322	194	34
Hf	8.78	8.57	6.94	3.71	3.55	4.35	2.62	3.05	32.2	24.3
Ta	8.38	8.02	4.51	1.94	4.28	1.78	1.66	1.68	9.17	18.92
Pb	9.27	10.20	4.28	2.45	3.19	1.98	2.01	2.12	14.3	26.3
Th	9.14	13.16	6.06	2.24	5.99	1.44	2.27	1.89	11.0	30.0
U	2.39	3.34	1.50	0.60	1.37	0.37	0.52	0.48	2.61	6.32
La	75.51	106.50	46.67	21.97	43.98	20.84	19.53	17.83	135	144
Ce	139.10	190.10	98.38	46.17	81.32	48.38	39.68	36.91	301	244
Pr	15.45	19.01	11.90	5.80	9.08	6.33	4.70	4.48	34.86	23.86
Nd	53.64	59.13	46.62	24.35	33.70	27.39	18.48	18.18	127.20	71.04
Sm	9.24	8.88	10.11	5.88	6.59	6.80	4.12	4.18	27.04	11.51
Eu	3.21	2.03	3.31	1.96	2.12	2.22	1.38	1.47	2.73	1.50
Gd	8.58	6.92	9.29	6.06	6.17	7.06	4.00	4.34	25.14	9.65
Tb	1.21	0.98	1.31	0.91	0.87	1.06	0.59	0.68	4.16	1.43
Dy	6.89	5.33	7.06	5.09	4.91	6.17	3.35	4.02	25.41	8.62
Ho	1.42	1.13	1.34	0.98	0.96	1.26	0.66	0.81	5.19	1.83
Er	4.07	3.26	3.31	2.52	2.52	3.44	1.83	2.14	14.69	5.62
Tm	0.65	0.52	0.47	0.34	0.35	0.47	0.25	0.31	2.30	0.92
Yb	4.36	3.55	2.95	2.00	2.19	3.17	1.66	2.03	14.59	7.03
Lu	0.66	0.56	0.41	0.27	0.32	0.45	0.23	0.28	2.10	1.05

Major element data

In total-alkali vs. silica and CIPW normative diagrams, the Bure volcanic rocks define two chemically distinct suites (Fig. 2). One suite includes ne-ol alkaline CFBs, the Quaternary basalts and the trachyte plugs, whereas the hy-qt transitional tholeiitic CFBs define the other suite. The alkaline CFBs vary from basanite, basalt, trachy-basalt to basaltic trachyandesite. A few alkaline CFBs exhibit the evolved trachytic composition observed in samples from the trachyte plugs. The transitional tholeiitic CFBs are generally basalts; only one sample has a basaltic trachyandesitic composition. Both the alkaline

and tholeiitic rocks exhibit a wide range of Mg# (70–25 and 68–35, respectively).

Major element variations relative to MgO (wt%) are shown in Figure 3. MgO contents vary from 0.05 wt% in the trachyte to 12 wt% in the alkaline basalts, but most of the analyzed rocks contain < 6 wt% MgO. Negative trends are observed for SiO₂, K₂O and Na₂O (Fig. 3). TiO₂ is very variable and only a few Bure basalts fall into the field of low-Ti type basalts defined by Pik et al. (1998, 1999). CaO and Fe₂O₃ are almost constant in the Bure volcanic rocks with MgO > 6 wt%, whereas both define positive trends for rocks with lower MgO values, although the trend was not so well defined for Fe₂O₃ (Fig. 3). Al₂O₃

Table 3. Isotopic data for the Bure volcanic rocks

Samples	$^{87}\text{Sr}/^{86}\text{Sr}$	2SE	$^{143}\text{Nd}/^{144}\text{Nd}$	2SE	ϵ_{Nd}	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
Trachyte plugs								
TD-1136A2	0.737730	21	0.512838	10	3.90	18.3657	15.5420	37.9524
SM-113	0.721525	25	0.512763	13	2.44	19.4506	15.6413	39.2440
Quat. basalts (Alkaline)								
TD-1003	0.703569	20	0.512850	8	4.14	18.9140	15.5823	38.6000
SOG-3157	0.703627	16	0.512850	12	4.14	18.9286	15.5905	38.6360
Alkaline basalts								
TD-1034B	0.703407	17	0.512828	10	3.54	18.6354	15.6224	38.5295
SM-120	0.703379	17	0.512794	9	3.09	19.5763	15.6484	39.2853
SOG-3091	0.703548	16	0.512815	8	3.45	19.4503	15.6774	39.4226
SOG-3005	0.703279	13	0.512870	10	3.95	19.8325	15.6632	39.6138
SOG-3043	0.703145	15	0.512880	12	4.37	19.6072	15.6415	39.2357
SM-172	0.703232	17	0.512873	9	4.52	18.4220	15.5451	38.0134
Transitional tholeiite basalts								
TD-1228A	0.703774	18	0.512990	11	6.48	18.5630	15.5320	37.9504
TD-1239	0.703285	15	0.512886	14	4.74	19.0791	15.5948	38.8454
ASW-503	0.704293	15	0.512829	9	3.48	18.8396	15.5707	38.1825
TL-253	0.703447	19	0.513041	9	7.52	18.3556	15.4959	38.1313
EH-235A	0.703949	15	0.513034	10	7.50	18.4713	15.5220	38.1647
AN-201	0.703314	16	0.512807	11	2.93	18.6321	15.5648	38.1002
MH-4510A	0.703843	19	0.512979	9	6.39	18.4310	15.5196	38.2754
MH-4521	0.704279	16	0.512862	10	4.24	18.8497	15.5874	38.4454
TD-1202	0.704105	16	0.512905	9	4.80	18.7528	15.5556	38.1209

2SE (standard error) corresponds to last two digits. For ϵ_{Nd} calculations, t is assumed as 27 Ma for transitional tholeiite basalts and alkaline basalts, 0 Ma for Quaternary basalts and trachyte plugs. CHUR value for Nd is 0.512638.

is negatively correlated with MgO within the alkaline rocks, whereas it is scattered and displays lower values in the transitional tholeiite basalts. $\text{CaO}/\text{Al}_2\text{O}_3$ ratios are relatively constant in transitional tholeiite basalt (0.6–0.8), which implies that olivine fractionation was predominant and plagioclase was not an important phase during fractionation.

Trace element data

The variations of the two suites are also well expressed in MgO against some trace element diagrams (Fig. 4). The decreases in Cr and Ni reflect early fractionation of olivine in both alkaline and transitional tholeiite rocks, whereas a positive trend for V was observed among the alkaline rocks only, which suggests that clinopyroxene fractionation affected these rocks. The incompatible elements (Nb, Zr, Rb and Y) define negative trends, although with some dispersion, from basaltic to felsic compositions. Ba and Sr are very variable among the Bure volcanic rocks with MgO > 4 wt% and reach low values in the most evolved trachytic samples, which indicate that an

alkali feldspar fractionation affected these rocks.

The chondrite-normalized rare-earth element (REE) patterns are given in Figure 5. Light REE (LREE) enrichment relative to heavy REE (HREE) is stronger in alkaline rocks than in tholeiites. A negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.3\text{--}0.7$) is present in the evolved trachytes, which indicates that plagioclase fractionation played a significant role in their genesis.

Primitive mantle-normalized incompatible element diagrams of the representative samples are shown in Figure 6. The transitional tholeiite basalts have flat patterns with slightly negative Th and Nb–Ta anomalies and positive Ba and Pb spikes. The alkaline basalts show ocean island basalt (OIB)-like patterns enriched in both large ion lithophile (LILE) and high field strength (HFSE) elements with Nb–Ta peak. The alkaline basalts show weak Ba and Pb positive spikes and a Th–U trough. Trachyte plugs have irregular patterns enriched in LILE with pronounced negative anomalies in Ba, Sr, P and Ti, which is indicative of extensive fractionation of feldspar, apatite and Fe–Ti oxides.

Figure 2. (a) Total-alkali vs. silica diagram for the Bure volcanic rocks (Le Maitre et al., 1989). The Tholeiitic (T)-Alkaline (A) divide is shown (Irving and Baragar, 1971). (b) CIPW-normative composition diagram for the Bure volcanic rocks (Thompson et al., 1983). FB, flood basalts.

Sr-Nd-Pb isotope data

The Sr, Nd and Pb isotope compositions of representative samples of tholeiitic and alkaline rock types are shown in Table 4 and plotted in Figures 7 and 8. Also plotted are the isotopic compositions of Arabian lithospheric mantle and basalts from the Afar, Gulf of Aden, Djibouti, southern Ethiopia and northwestern Ethiopia. Most of the transitional tholeiite basalts from the Bure area are displaced to higher $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70329–0.70429) and $^{143}\text{Nd}/^{144}\text{Nd}$ (0.51281–0.51304), and plot in a region generally separate from the alkaline samples ($^{87}\text{Sr}/^{86}\text{Sr}$ = 0.70315–0.70363 and $^{143}\text{Nd}/^{144}\text{Nd}$ = 0.51279–0.51288). Moreover, the trends defined by these two types of rock are different (Fig. 7a). Indeed, tholeiitic rocks extend between the depleted (DM) and enriched (EMI) mantle end-members, whereas the alkaline rocks extend from the HIMU end-member towards enriched (EMI) mantle. The transitional tholeiite basalts mostly overlap the HT1 basalts of Pik et al. (1999) and fall in the intermediate position between

Djibouti and Afar and Gulf of Aden basalts. The alkaline basalts fall within the field of LT basalts with lower $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ and partially overlap the field of northern transect basalts from southern Ethiopia (Fig. 7b).

The Pb isotopic compositions of the Bure volcanic rocks cover the relatively wide range already observed for the northern transect basalts of southern Ethiopia and define a trend subparallel to the Northern Hemisphere Reference Line (NHRL) of Hart (1984) in Pb–Pb diagrams (Fig. 8a, b). In detail, most of the alkaline CFBs have more radiogenic Pb isotopic composition than the tholeiites and Quaternary basalts, which plot toward the HIMU field ($^{206}\text{Pb}/^{204}\text{Pb}$ = 19.45–19.83, $^{207}\text{Pb}/^{204}\text{Pb}$ = 15.65–15.68 and $^{208}\text{Pb}/^{204}\text{Pb}$ = 39.24–39.61). The Quaternary basalts are closer to the HT2-type basalts ($^{206}\text{Pb}/^{204}\text{Pb}$ = 18.91–18.93, $^{207}\text{Pb}/^{204}\text{Pb}$ = 15.58–15.59 and $^{208}\text{Pb}/^{204}\text{Pb}$ = 38.60–38.64), whereas the transitional tholeiite CFBs and the two Oligocene alkaline CFB samples have lower Pb isotopic ratios spread towards the DM field ($^{206}\text{Pb}/^{204}\text{Pb}$ = 18.36–19.08, $^{207}\text{Pb}/^{204}\text{Pb}$ = 15.50–15.59 and $^{208}\text{Pb}/^{204}\text{Pb}$ = 38.60–38.64).

Figure 3. Major element vs. MgO (wt%) diagram for Bure volcanic rocks. The dashed line in the TiO_2 -MgO plot (b) indicates the field of the NW Ethiopian Low-Ti (LT) magma type flood basalts (Pik et al., 1998, 1999).

$^{204}\text{Pb}=37.95\text{--}38.85$). The two analyzed trachyte samples display very different Pb isotopic compositions and plot at the ends of the field of the Bure samples.

DISCUSSION

Crustal contamination process

The variation of major, incompatible trace elements and Sr-Nd-Pb isotopic ratios within the Bure volcanic rocks might reflect either the contribution of different mantle sources or a crustal component in their petrogenesis (Figs. 2–8).

The transitional tholeiite CFBs have wide variability of incompatible trace element ratios, strong enrichment of Ba and Pb with depleted HFSE (Th, Nb and Ta) (Fig. 6)

and variable $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$ (Fig. 7) and unradiogenic $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 8). These variations cannot be explained by simple fractional crystallization and partial melting of common sources but require variations in both source compositions and melting conditions.

Moreover, the fact that the Bure volcanic rocks passed through the continental crust raises the possibility that crustal contamination produced some of their isotopic and geochemical signatures. Indeed, the negative MgO vs $^{87}\text{Sr}/^{86}\text{Sr}$ correlation and the large range of $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig. 9a) suggest that the transitional tholeiite basalts were subject to crustal contamination and might have experienced an assimilation-fractional crystallization (AFC) process (DePaolo, 1981). Other evidence in favor of crustal contamination is shown in Figure 9 (b, c), where the transitional tholeiite basalts tend to show a positive correlation

Figure 4. Trace element content vs. MgO (wt%) diagram for the Bure volcanic rocks.

of Rb/Nb with Rb and a negative correlation of Ba/Nb with $^{143}\text{Nd}/^{144}\text{Nd}$. The alkalis are strongly enriched in felsic crustal rocks with comparable or lower Nb compared with the basalts, and so even small degrees of contamination would cause strong enrichment in alkali element concentrations and lead to high alkali/Nb ratios in crustally contaminated basalts.

To test such a contamination process, we carried out simple mixing model using sample TL-253 as the basaltic end-member, because this sample has low Rb/Nb, Ba/Nb and $^{87}\text{Sr}/^{86}\text{Sr}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ without K, Rb and Ba spikes in the trace element spectra (Fig. 6). The compositions of samples X139 and X37 (Davidson and Wilson, 1989) were chosen as representative of the Pan-African upper crust (UC) and lower crust (LC), respectively. Bulk mixing curves between basalts TL-253 and UC/LC in Figure 9d indicate that, except for one sample, 10%–20%

of dominantly upper crust is required to explain the crustal contamination signature of transitional tholeiite basalts. A similar proportion of the upper crust in the mixture can also account for the $^{143}\text{Nd}/^{144}\text{Nd}$ (Fig. 9c) of the contaminated basalts. However, such a mixing calculation failed to explain the variation in $^{87}\text{Sr}/^{86}\text{Sr}$ and Ba/Nb (Fig. 9e). Bulk mixing calculations in the Sr isotopic system require a very low amount of UC (up to 5%), which suggests that the mixing process was not one of bulk contamination. Such a discrepancy could also be due to highly variable Pan-African crustal composition.

In summary, geochemical variation observed in the transitional tholeiite basalts can be accounted for by crustal contamination. In contrast, the uniform incompatible trace element ratios for the alkaline basalt suite, with a limited range of $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ but a wide range of $^{206}\text{Pb}/^{204}\text{Pb}$ (Figs. 7–9), indicate that fractional crystalli-

Figure 5. Chondrite-normalized REE patterns for representative Bure volcanic rocks. Chondrite values are taken from Sun and McDonough, 1989. (a) for Quaternary basalts, (b) for alkaline flood basalts and (c) for transitional tholeiite flood basalts. The shaded field shows the range of Quaternary and alkaline flood basalts.

zation of the primary magma from the OIB-like Afar plume was the dominant process for within-group variations in the alkaline basalts (Meshesha and Shinjo, 2004). The alkaline basalts resemble uncontaminated OIB-like Afar plume compositions of the northern transect syn- to post-rift basalts of southern Ethiopia (Stewart and Rogers, 1996), the younger basalts of Djibouti (Deniel et al., 1994) and HT2-type basalts (Pik et al., 1999). It is most important to note that the “presumed” least-contaminated transitional basalt (TL-253) cannot have been formed by the mixing of the alkaline magma with crustal components (Fig. 9c).

Partial melting and magma segregation depth

The compositional differences between alkaline basalts and least contaminated transitional tholeiite basalts are probably related to different depths and degrees of melting of the deeper asthenospheric mantle. For example, the differences in alkaline contents and degrees of silica satu-

Figure 6. Primitive mantle-normalized multielement patterns for representative Bure volcanic rocks. Primitive mantle values are from Sun and McDonough, 1989. (a) for Quaternary basalts and trachyte plugs, (b) for alkaline flood basalts and (c) for transitional tholeiite flood basalts.

ration between the two suites (Fig. 2) could reflect such different depths of melting (e.g., Kushiro, 1994). It is well known that small degrees of partial melting at high pressure produce magma with normative nepheline, whereas a large degree of melting at lower pressure produces magma with normative hypersthene and quartz (DePaolo and Daley, 2000).

Compositions of the most primitive basalts amongst Bure basalts were plotted onto the olivine-plagioclase-quartz plane from the diopside apex (Fig. 9f; Walker et al., 1979) with partial melt compositions obtained in peridotite melting experiments at various pressures (Hirose and Kushiro, 1993). These basalts plot close to the melt compositions found at pressures between ~2.5 and 3 GPa (i.e., depths greater than 70 km). This suggests that the melt was produced in the presence of garnet. In addition, chondrite-normalized Tb/Yb (or Dy/Yb) ratios are almost similar for both the alkaline ((Tb/Yb)_N = 1.3–2.1 and (Dy/Yb)_N = 1–1.7) and the tholeiitic magmas ((Tb/Yb)_N =

Figure 7. Sr-Nd isotope diagram for the Bure volcanic rocks: (a) data for the Bure volcanic rocks and the Arabian lithospheric mantle (Bluztajn et al., 1995) and (b) comparisons with other EARS regional data from Djibouti basalts (Deniel et al., 1994), Afar and Gulf of Aden basalts (Schilling et al., 1992), Low-Ti (LT), Intermediate (HT1) and High-Ti (HT2) basalts in the NW Ethiopian plateau (Pik et al., 1999) and Northern transect basalts of southern (NTS) Ethiopia (Stewart and Rogers, 1996). Depleted (DM), HIMU and Enriched (EMI and EMII) mantle are taken from Zindler and Hart (1986). Trachyte samples plot outside the diagram because of high Sr isotopic ratios.

1.3–2.2 and $(\text{Dy}/\text{Yb})_N = 1.2\text{--}1.7$). Both suites have higher MREE/HREE compared with normal mid-ocean ridge basalt (N-MORB) values (Sun and McDonough, 1989). As garnet is the only phase that is likely to fractionate Tb/Yb and Dy/Yb ratios significantly, and this can happen during partial melting of garnet peridotite within the mantle, the fractionated MREE/HREE signatures of the Bure volcanic rocks suggest that both suites were derived from a source deeper than MORB.

Moreover, chondrite-normalized La/Yb and Ce/Yb ratios are higher in the alkaline magmas ($(\text{La}/\text{Yb})_N = 4.7\text{--}21.5$ and $(\text{Ce}/\text{Yb})_N = 4.2\text{--}14.9$) than in the transitional tholeiitic magmas ($(\text{La}/\text{Yb})_N = 2\text{--}6.4$ and $(\text{Ce}/\text{Yb})_N = 1.8\text{--}6$). This suggests that the alkaline basalts were derived with a lower extent of melting compared with the tholeiitic basalts, if we assume similar incompatible element concentrations for their sources.

Figure 8. Pb isotope composition diagrams for the Bure volcanic rocks: (a) $^{206}\text{Pb}/^{204}\text{Pb}$ vs $^{208}\text{Pb}/^{204}\text{Pb}$ and (b) $^{206}\text{Pb}/^{204}\text{Pb}$ vs $^{207}\text{Pb}/^{204}\text{Pb}$, in comparison with other EARS regional data from Djibouti basalts (Deniel et al., 1994), Afar and Gulf of Aden basalts (Schilling et al., 1992), Low-Ti (LT), Intermediate (HT1) and High-Ti (HT2) basalts (Pik et al., 1999) and Northern transect basalts of southern (NTS) Ethiopia (Stewart and Rogers, 1996). Depleted (DM), HIMU and Enriched (EMI and EMII) mantle are taken from Zindler and Hart (1986).

Mantle source characteristics and geodynamic implications

The geochemical variations of the Bure volcanic rocks provide key factors for discussing the interaction process between the Afar plume and the continental crust (Baker et al., 1996; Pik et al., 1999) and/or lithospheric mantle (e.g., Vidal et al., 1991; Schilling et al., 1992; Deniel et al., 1994; Stewart and Rogers, 1996; George and Rogers, 2002). In the previous sections, the combined study of petrology, geochemistry and isotope ratios (Sr-Nd-Pb) have shown that different degrees of melting, fractionation, crustal contamination and heterogeneous mantle sources were responsible for the formation of variable geochemical compositions in the Bure volcanic rocks. Our dating results indicate coeval eruption of tholeiitic and alkalic magmas during 30–25 Ma.

As shown in Figure 10 in terms of Sr-Nd-Pb systematics, at least three components can be identified: an “intrinsic” isotopically depleted plume (component I), a plume having a higher Pb isotope (component II) and a crustal component (component III). The average proposed

Figure 9. (a) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. MgO, (b) Rb/Nb vs. Rb, (c) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. Ba/Nb, (d) $^{206}\text{Pb}/^{204}\text{Pb}$ vs. Nb/La and (e) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Ba/Nb diagrams showing requirement of crustal component and the arrow indicates the inferred trend for lower (LC) and upper crust (UC). The compositions for contaminant UC (X139) ($^{87}\text{Sr}/^{86}\text{Sr} = 0.727068$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512052$, $^{206}\text{Pb}/^{204}\text{Pb} = 19.035$, Sr = 220, Nd = 21.38, Pb = 67, La = 43.38, Nb = 8 and Ba = 88), LC (X37) ($^{87}\text{Sr}/^{86}\text{Sr} = 0.708630$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.511368$, $^{206}\text{Pb}/^{204}\text{Pb} = 17.625$, Sr = 678, Nd = 34.19, Pb = 14, La = 61.83, Nb = 7 and Ba = 2043) and UC (X36) are from Davidson and Wilson (1989). (f) Normative compositions of the most primitive basalts projected onto the Oliv (olivine)-Plag (plagioclase)-Qtz (silica) plane from the diopside apex for the Bure volcanic rocks. Partial melt compositions obtained in peridotite melting experiments at various pressures are from Hirose and Kushiro (1993).

Afar mantle plume (Schilling et al., 1992; Pik et al., 1999; Baker et al., 2000; Rogers et al., 2000) falls within the field defined by these components.

The two components (I and II) can be explained as compositional variation within the plume source. Although one might argue that component I could represent

a plume-unrelated ambient (depleted) asthenospheric mantle, its isotopic composition precludes a model involving partial melting of a typical N-MORB mantle source. Moreover, sample TL-253 transitional tholeiitic basalt, which has Sr-Nd-Pb isotopic compositions closer to component I (Fig. 10), does not have incompatible ele-

Figure 10. Diagrams of $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ (a), $^{143}\text{Nd}/^{144}\text{Nd}$ (b), Ba/Nb (c) and $^{143}\text{Nd}/^{144}\text{Nd}$ vs. Nb/La (d). Average Afar plume compositions are taken from Schilling et al., 1992; Pik et al., 1999; Baker et al., 2000; Rogers et al., 2000. Depleted (DM), HIMU and Enriched (EMI and EMII) mantle are taken from Zindler and Hart (1986). I, II and III indicate the possible end-members inferred for geochemical variations of the Bure volcanic rocks. HT2-type basalts and C component fields are from Pik et al. (1999) and Orihashi et al. (2001), respectively.

ment characteristics similar to N-MORB (Fig. 6), and its incompatible element ratios (e.g., La/Nb, Ba/La and Zr/Nb) are more typical to OIB than N-MORB. Thus, it is reasonable to suggest that the isotopically depleted but trace element-enriched “component I” was derived from a heterogeneous plume mantle source (Fig. 11, model 1).

An alternative interpretation of the component I signature could be a derivation from the lithospheric mantle (Fig. 11, model 2). Indeed, the Arabian lithospheric mantle also displays depleted Sr–Nd isotopic ratios (Bluztajn et al., 1995) that overlap with those of the depleted end-member of the transitional tholeiite basalts (Fig. 7). The occurrence of metasomatized mantle xenoliths in the area is also evidence of an interaction between the mantle lithosphere and the fluids and/or magmas released by a deeper upwelling plume (Conticelli et al., 1999). Examples of mafic lavas, which were supposed to have formed within the subcontinental lithosphere rather than within the underlying ambient asthenosphere or a rising mantle plume, have been reported from the Southern Kenya Rift

lavas (le Roex et al., 2001; Späth et al., 2001). A distinctive striking feature of these lavas is a strong but variable depletion in K on mantle-normalized incompatible element patterns, which has been ascribed to the partial melting of a source that contained residual amphibole. The presence of amphibole implies a shallow mantle source and suggests an origin from the subcontinental lithosphere rather than from the deeper asthenosphere. In the Bure lavas, negative K anomalies in mantle-normalized patterns of the least contaminated tholeiitic basalts are absent (Fig. 6). Therefore, a plume source origin for component I seems more likely.

Component II in Figure 10 is mostly represented by alkaline basalts and characterized by higher $^{206}\text{Pb}/^{204}\text{Pb}$ with OIB-like incompatible element ratios. Despite of similar ages of Bure alkaline basalts to the HT2 basalts, plume component II inferred from Bure basalts is isotopically dissimilar to those of HT2-type basalts (Fig. 10a, c). It has been widely accepted that the Oligocene Afar plume composition is best exemplified by the HT2-type

Figure 11. Simplified geodynamic model for the generation of the Bure volcanic rocks, not to scale. TB, Transitional basalts; AB, Alkaline basalts; QB, Quaternary basalts, scoria and trachyte plugs; CMC, Crustal Magma Chamber, MER, Main Ethiopian Rift.

basalts (Pik et al., 1999, 2006). On the other hand, Orihashi et al. (2001) have argued that “younger” (late Miocene to Recent) basalts from Yemen, Afar and Gulf of Aden region require three components: upper mantle (DM), enriched Pan-African lithospheric mantle (ELM) and an intermediate component between DM and HIMU. The intermediate component as the Afar mantle plume has the Sr, Nd and Pb isotope variation of the common component (C or focal zone (FOZO)) ($^{143}\text{Nd}/^{144}\text{Nd} = 0.51284\text{--}0.51295$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7030\text{--}0.7040$ and $^{206}\text{Pb}/^{204}\text{Pb} = 19.2\text{--}19.8$) rather than the HIMU component (Orihashi et al., 2001); this composition is also shown in Figures 10a and c. The Bure plume component II clearly overlaps the C component for the “younger” Afar plume. Because the Bure alkaline basalts are dated as Oligocene, the temporal change in isotope composition from HT2-type basalt-like to C component for the Afar plume cannot be validated. Instead, all these observations imply a highly heterogeneous nature for the Oligocene Afar plume at the initial stage of plume impingement.

Component III represents the enriched end-member

of the transitional tholeiite basalts, which trend towards crustal rock compositions. In addition, the rocks display incompatible trace element and isotope ratios (e.g., high Ba/Nb, low Nb/La, unradiogenic Pb and radiogenic Sr) consistent with crustal additions similar to LT-type basalts (Pik et al., 1998, 1999) and Yemen basalts (Baker et al., 1996). Plume upwelling initiated crustal extension in the middle to late Oligocene (e.g., White et al., 1989; Vidal et al., 1991; Schilling et al., 1992; Ebinger and Sleep, 1998; Pik et al., 1999) and the injection of isotopically depleted melt into the crustal chamber (Fig. 11, model 1), where AFC processes might have played an important role.

Subsequent plume upwelling induced rifting. Miocene–Quaternary magmas that originated from the plume source have been mostly confined to the MER and Afar regions (Fig. 11b). The Bure Quaternary volcanic rocks (basaltic lava, scoria and trachyte plugs) are also related to the last stage of rift development. Quaternary alkaline basalts have isotopic compositions that are different from those of Oligocene alkaline basalts but intermediate among component I, II and HT2-type basalts; Quaternary magmas might have been derived from a more homogenized plume source.

CONCLUSIONS

1. The Bure volcanic rocks are composed of two distinct volcanic suites: transitional tholeiite and alkaline CFBs. The eruptive sequence is voluminous transitional tholeiite and alkaline CFBs in the plateau-forming stage (30–25 Ma) followed by a minor amount of Quaternary alkaline single lava flow, scoria cones and highly fractionated trachyte plugs. The general successions of the erupted basalts are from hypersthene-quartz normative transitional tholeiites to nepheline-olivine normative alkaline basalts, although our new age data suggest coeval eruption of tholeiitic and alkaline lavas.
2. The isotopic ratio and trace element characteristics of the transitional tholeiite basalts are variable and more heterogeneous than the alkaline basalts. The transitional tholeiite basalts are characterized by higher incompatible element ratios (e.g., Ba/Nb and Rb/Nb), $^{87}\text{Sr}/^{86}\text{Sr}$ and unradiogenic Pb isotopes. These signatures can be explained by crustal contamination of the magmas. On the other hand, the alkaline basalt suite has a composition of homogeneous incompatible trace element ratios, low $^{87}\text{Sr}/^{86}\text{Sr}$ and more radiogenic Pb isotopes, which indicates that the alkaline basalts originated from a more enriched OIB-like Afar plume source with a low degree of partial melting. The crustal

effect was hardly observed in this suite. It is not clear why only the tholeiitic magmas suffered considerable crustal contamination.

3. We identify at least two mantle components that have distinctive Sr-Nd-Pb isotopic ratios (an intrinsic isotopically depleted plume component and a plume component having radiogenic Pb isotope); these two components clearly differ from the component observed in HT2-type basalts. We infer that both components originated in the upwelling plume source, due to heterogeneous nature of Afar mantle plume.

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APPENDIX

K-Ar age dating analytical method

Groundmass separates, concentrated by means of magnetic separation, were analyzed for K and Ar at the Hiruzen Institute for Geology and Chronology Co. Ltd. (Japan) and calculations of ages and errors were determined using the methods described by Nagao et al. (1984) and Itaya et al. (1991). The accuracy and reproducibility of these methods were within 2%. Decay constants $\lambda_e = 0.581 \times 10^{-10}/\text{yr}$, $\lambda_\beta = 4.962 \times 10^{-10}/\text{yr}$ and $^{40}\text{K}/\text{K} = 1.167 \times 10^{-4}$ are from Steiger and Jäger (1977). The results are presented in the table below.

Appendix. K-Ar age dating results for representative Bure volcanic rocks

Sample No.	Rock type	Location		K_2O (wt. %)	Rad. ^{40}Ar (10^{-8}cc STP/g)		Non-rad. ^{40}Ar (%)	K-Ar age (Ma)	
		Latitude (N)	Longitude (E)						
TD-1228A	TB	10°56'54"	37°25'06"	0.527	60.30	± 0.62	6.30	29.26	± 0.65
TD-1202	TB	10°33'12"	37°11'45"	0.393	40.87	± 0.58	29.0	26.60	± 1.40
SOG-3005	AB	10°50'43"	36°36'55"	0.758	84.00	± 1.10	24.4	28.34	± 0.67
TD-1034B	AB	10°38'57"	37°28'49"	1.023	101.5	± 1.00	7.10	25.27	± 0.56

STP, standard temperature and pressure; Rad. ^{40}Ar , radiogenic ^{40}Ar ; Non-rad ^{40}Ar , percent of nonradiogenic ^{40}Ar ; TB, Tholeiite flood basalts; AB, Alkaline flood basalts.