Ferropicrite from the Lalibela area in the Ethiopian large igneous province

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Ferropicrite (FeO* = 14.0 wt% and MgO = 13.9 wt%) and picritic ferrobasalt (FeO* = 14.7 wt% and MgO = 10.8 wt%) lava flows are found near Lalibela in the Oligocene (~ 30 Ma) Ethiopian large igneous province (LIP) in association with ultratitaniferous transitional basalt and picrite of the second high-Ti (HT2) series. The dominant phenocryst in the studied samples is Mg-rich olivine (up to Fo_{88.9}) with high CaO contents (to 0.42 wt%) without any kink band structure, indicating that the olivines are crystallized from a magnesian melt. Spinel microphenocrysts and inclusions in olivine are characterized by extremely high Cr# (79–84), moderate Mg# (18–51), moderate Fe³⁺# (11–39) and high TiO₂ (3.6–14.8 wt%). The clinopyroxene phenocrysts are Mg# = 74–88, TiO₂ = 0.84–1.82 wt%, and Al₂O₃ = 1.2–3.2 wt% in the cores. The REE contents of clinopyroxenes display enrichment in LREE (La_N/Yb_N = 1.2–1.9) and MREE (Eu_N/Yb_N = 3.3–4.3) relative to HREE. Relative depletion of HFSE (e.g., Nb and Zr) is also observed. In general, these trace element characteristics of clinopyroxene are similar to those of the HT2 basalts. Some of the clinopyroxene crystals show strong reverse zoning with abrupt increase in Cr, Ni and Mg# from core to rim, which may be resulted from reaction of melt with mantle peridotite during magma ascent. Bulk rock chemistry of the studied samples exhibits very low Al₂O₃/TiO₂ (1.8–2.2) and high Zr/Y (8.2–10.2) ratios. These may indicate the important role for garnet during melting and that the lavas were formed by a small degree of partial melting which apparently contradicts to the high Cr# of spinel. In view of low Cr/Al ratio of the bulk rock, the high Cr# of spinel suggests very high temperature of the magma (and the mantle plume). The origin of these ferropicrite and picritic ferrobasalt could be attributed to high pressure partial melting of peridotite-eclogite (pyroxenite) mixture that possibly incorporated recycled oceanic crust components.

Keywords: Ferropicrite, Cr-spinel, Large igneous province, Oligocene, Lalibela, Eclogitic source

INTRODUCTION

Ferropicrites are subalkaline or mildly alkaline primitive rocks that were reported for the first time from the Paleoproterozoic Pechenga volcanic belt of the Kola Peninsula by Hanski and Smolkin (1989), who defined ferropicrite as an MgO rich volcanic rock with FeO* higher than 14 wt%. Ferropicrites may have similar MgO contents to komatiites (~ 19 wt%) but significantly higher TiO₂ contents (>1 wt%) like meimechite (Le Bas, 2000). The geochemical characteristics of ferropicrites and meimechites indicates their derivation by lower de-

gree of partial melting at higher pressure as compared to common continental flood basalt picrite that originate as more homogenized and voluminous melting at lower pressures (Gibson, 2002). For the last two decades, a number of ferropicritic whole-rock compositions have been reported from the Precambrian volcanic belts e.g., Slave and Superior Provinces (Goldstein and Francis, 2008; Francis et al., 1999) and from the Phanerozoic continental flood basalt provinces (CFB) (Siberian Traps, Karoo, Paraná-Etendeka, North Atlantic, Emeishan; Wooden et al., 1993; Gibson et al., 2000; Riley et al., 2005; Zhang et al., 2006). Ichiyama et al. (2006) reported ferropicritic, highly magnesian olivine cumulates from a Permian accreted oceanic plateau, southwestern Japan. Recently, several petrogenetic models are provided for

Figure 1. Sketch map of the Ethiopian large igneous province (LIP) including the Yemen conjugate margin, modified after Beccaluva et al. (2009) and Natali et al. (2011). Oligocene (~30 Ma) volcanic rocks: LT, Low-Ti tholeiitic basalts; HT1, High-Ti tholeiitic basalts; HT2, very High-Ti transitional basalts and picrites. Location of ferropicrite from the Dilb road section reported in this study is indicated by star. Miocene to Quaternary volcanic rocks in the Main Ethiopian Rift (MER), are not shown. CFB, Continental flood basalt.

the origin of ferropicrite. Gibson (2002) describes the significance of recycled oceanic crust as a 're-fertilizer' of peridotite in the starting mantle plume head. Ichiyama et al. (2006) and Tuff et al. (2005) also suggested analogous models with recycled eclogitic or pyroxenitic mantle source, respectively. On the basis of silicate liquid immiscibility study, Jakobsen et al. (2005) interpreted that ferropicrites could also form by mixing of evolved, immiscible Fe-rich liquid with picritic mantle melts. More recently, Sobolev et al. (2007) described that iron-rich source regions in the mantle can be produced by pyroxenite veining. Generally, ferropicrites are attributed to anomalously hot mantle sources and mantle plumes (Hanski and Smolkin, 1995; Goldstein and Francis, 2008).

Picritic lavas from Ethiopian LIP are representative of the second high-Ti (HT2) series, as described by Pik et al. (1998) and Beccaluva et al. (2009) and are overlain by rhyolitic ignimbrite of 30 Ma age (Hofmann et al., 1997). In previous literatures the occurrence of Fe-rich picrite in Ethiopian large igneous province (LIP) has been unrecognized.

In this study, we report the results of the mineral chemistry and whole rock geochemistry of ferropicrite

(Sample 1) and picritic ferrobasalt (Samples 2 and 3) rocks from the eastern part of Ethiopian large igneous province in order to obtain insight into the characteristics of their mantle source. Ferropicrite and picritic ferrobasalt samples were obtained from the Dilb road section of the Lalibela area, eastern portion of Ethiopian LIP (Fig. 1).

GEOLOGICAL SETTING

The Oligocene Ethiopian LIP represents one of the youngest, best exposed sequences of mafic and felsic volcanic rocks, associated with incipient lithospheric break-up (extensional tectonics) and plume impingement (Marty et al., 1996). It is dissected by the Main Ethiopian Rift (MER)-Red Sea-Gulf of Aden rift system (with the Afar R-R-R-triple junction), which indicates the close association of magmatism and lithospheric extension and hence satisfy the plume theory. In addition, the tectonomagmatic and geophysical studies shows that the existence of deep mantle plume (Ritsema et al., 1999; Courtillot et al., 2003). The present remnants of Ethiopian flood volcanism cover an area of at least $6 \times 10^6 \text{ km}^2$ and have a total volume of about $\sim 3.5 \times 10^5 \text{ km}^3$ (Mohr and Zanet-

tin, 1988). Rochette et al. (1998) estimated as the original volume reached up to 10^6 km^3 . This voluminous basaltic magmatism was emplaced in a rather short time interval $\sim 30 \pm 1 \text{ Ma}$ (Hofmann et al., 1997) and successively followed by a number of huge shield volcanoes (Piccirillo et al., 1979). These shield volcanoes are a conspicuous feature of the Ethiopian LIP and distinguish it from other LIPs, such as Deccan and Karoo (Kieffer et al., 2004) and Siberia. The ferropicrite and picritic ferrobasalt of this study is considered as a part of the main flood basalt volcanism ($\sim 30 \text{ Ma}$). Ayalew et al. (2002) and Ayalew and Ishiwatari (2011) described the presence of significant volume of rhyolite (up to 20%) with a maximum thickness of $\sim 500 \text{ m}$ mostly on the upper part of the Ethiopian continental flood basalt sequence. The final phase of volcanism (i.e., Pliocene to present) mostly concentrated along the Main Ethiopian Rift and Afar region. However, volumetrically small volcanic rocks as old as 45–40 Ma are found in southern and south-western Ethiopia (George et al., 1998). All the Ethiopian plateau rocks rest either directly over the Neoproterozoic crystalline basement or over the Mesozoic sedimentary sequences. According to Pik et al. (1998) and Beccaluva et al. (2009), the Northern Ethiopian plateau basalts are classified into three magma types based on their TiO_2 content (Fig. 1): Low-Ti tholeiites (LT) distributed in the northwestern areas; the first high-Ti lavas (HT1) in the eastern areas and ultratitaniferous transitional basalt and picrites of the second high-Ti (HT2) series, which are concentrated in the Lalibela area close to the Afar depression. The lava piles in the Lalibela area reaches up to $\sim 1800 \text{ m}$ thick, consisting of basaltic and picritic units capped by rhyolitic ignimbrite. The HT2 picrites are geographically localized in the high-Ti sub-province and the ferropicrite and picritic ferrobasalt rocks occur associated with HT2 basalt and picrite series. Ferropicrites constitute volumetrically minor parts of Ethiopian LIP and they typically form thin flows at or near the base of thick lava piles in the Lalibela area.

ANALYTICAL METHODS

The major element analysis of the constituent minerals of these samples was determined by electron probe micro analyser (EPMA) using energy dispersive X-ray spectrometer Oxford Link ISIS equipped on the JEOL JSM-5410 Scanning electron microscope (SEM) at the Earth Science department laboratory of Tohoku University, Japan. The operating conditions were at 15 kV acceleration voltage and a beam current of 1 nA. A number of natural standards were applied for calibration, and the data were corrected with ZAF quantitative procedure.

Major and some trace elements for the whole-rock analyses, such as V, Cr, Ni, Rb, Sr, Ba, Y, Zr, Nb, were carried out by X-ray fluorescence spectrometer (XRF-RIX 2100) at the aforementioned department, Tohoku University. Three glass beads were prepared by using fusion procedure, which consists of heating a 1:5 mixture of sample and flux ($\text{Li}_2\text{B}_4\text{O}_7$) at $\sim 1050^\circ\text{C}$. The Loss on Ignition (LOI) is determined by weighing a 1 gram of rock powder before and after ignition at 750°C for 6 hours. Trace element concentrations of clinopyroxene in ferropicrite and picritic ferrobasalts were determined by a laser ablation (193 nm ArF excimer: MicroLas GeoLas Q-plus)-inductively coupled plasma spectrometer Agilent 7500S (LA-ICP-MS) at Kanazawa University (Ishida et al., 2004). The analysis was conducted by ablating spot of 50–60 μm in diameter at laser power of 8 J/cm^2 . NIST SRM 612 glass was used as a standard. The trace element concentration of NIST SRM 612 was selected from Pearce et al. (1997). ^{29}Si was used as internal standard for pyroxene, with concentration of SiO_2 determined by EPMA.

WHOLE ROCK CHEMISTRY

Major and trace elements

Table 1 shows whole-rock analyses of the ferropicrite and picritic ferrobasalt from the Lalibela area. The studied samples are characterized by high TiO_2 (3.8–5.1 wt%) and FeO^* (total Fe as FeO) (14.0–14.7 wt%) (Fig. 2). The FeO^* content is within the range of ferropicrites of other LIPs (Superior Province, Pechenga, Siberia, Paraná-Etendeka and Japan). The Fe/Mn ratios of the bulk rock range from 78 to 82, which is higher than those reported for the Ethiopian picritic lava (70–76; Rogers et al., 2010). The Ni/Cr ratio is also high (0.4 in ferropicrite). The MgO content ranges from 10.5 to 13.8 wt% and Sample 1 satisfies the definition of picrite ($>12 \text{ wt}\%$ MgO) (Le Bas, 2000). A general decrease of Ni (500 to 350 ppm) with decreasing Mg# (64 to 56) implies removal of olivine through evolution from ferropicritic to ferro-basaltic composition. They show enrichment of high field strength elements (HFSE), e.g., P_2O_5 (0.35–0.64 wt%), Nb (24–32 ppm), Y (34–39 ppm) and TiO_2 (3.8–5.1 wt%) and their increase with decreasing MgO (Figs. 2 and 3). They are further characterized by very high V (407–490 ppm) content. The content of Zr (283–378 ppm) in the Ethiopian ferropicrite is very high and is comparable to that of Siberian ferropicrite, but the latter is characterized by higher Nb/Y ratio. Figure 4 shows the variations of $\text{Al}_2\text{O}_3/\text{TiO}_2$ with respect to Zr/Y ratios for the ferropicrite and picritic ferrobasalt. In comparison

Table 1. Whole rock chemistry of the ferropicrite and picritic ferrobasalts from the Lalibela area, Ethiopian LIP

Rock	Ferropicrite	Picritic ferrobasalts	
Sample	1	2	3
Major elements (wt%)			
SiO ₂	45.82	43.04	44.03
TiO ₂	3.84	4.74	5.04
Al ₂ O ₃	8.58	8.65	9.23
FeO*	14.00	14.50	14.70
CaO	10.00	9.87	10.63
MgO	13.92	10.05	10.81
MnO	0.18	0.18	0.18
K ₂ O	0.76	0.90	0.76
Na ₂ O	1.82	1.89	2.02
P ₂ O ₅	0.35	0.62	0.58
Total	99.27	94.44	97.98
LOI	-0.01	1.58	0.10
Mg#	63.9	55.3	56.7
Trace elements (ppm)			
V	407	463	490
Cr	195	40.8	18.2
Ni	501	389	356
Rb	16.1	20.3	9.6
Sr	415	503	567
Ba	210	268	282
Y	34.4	38.9	37.2
Zr	283	359	378
Nb	23.6	31.0	31.9

*Total iron as FeO.

Mg# (= Mg/Mg + Fe_{Total}) × 100.

LOI, Loss on ignition.

with other ferropicrites (Superior Province, Pechenga, Paraná-Etendeka and Japan) the Ethiopian ferropicrite and picritic ferrobasalt exhibit low Al₂O₃/TiO₂ ratio close to Siberian ferropicrite (~ 2.2) and are similar to HT2 basalt and picrite (Beccaluva et al., 2009).

According to the Pik et al. (1998) classification of the Ethiopian LIP based on Ti/Y ratio, the studied samples falls in the HT1 compositional field (not shown). The high FeO* content of these samples are similar to the first high-Ti basalts (HT1) of Adigrat area (Beccaluva et al., 2009). However, the latter is characterized by lower MgO (<10 wt%), CaO/Al₂O₃ (~ 0.5) and Ni (≤110 ppm), supporting HT2 affiliation of our samples.

PETROGRAPHY AND MINERAL CHEMISTRY

Ferropicrite and picritic ferrobasalts examined in this study shows porphyritic texture with phenocryst phases of olivine (15–30 vol%) and augitic clinopyroxene (10–25 vol%) (Fig. 5). Minor plagioclase microphenocrysts occur in one of the studied samples. Chrome-spinels are included in olivine and rarely occur as microphenocrysts set in the groundmass, which comprises a mixture

Figure 2. Major element variations with respect to MgO of the ferropicrite and picritic ferrobasalt rocks. For comparison, Ethiopian LIP (LT, low-Ti basalt; HT1, high-Ti 1 basalt; HT2, high-Ti 2 basalt and picrite; Beccaluva et al., 2009), ferropicrites from Superior Province (Goldstein and Francis, 2008), Pechenga (Hanski and Smolkin, 1995), Siberia (Arndt et al., 1995), Paraná-Etendeka (Gibson et al., 2000), Japan (Ichiyama et al., 2006), the composition of a picritic melt produced from GA1₅₀MPY90₅₀ at 3.5 GPa (Yaxley and Green, 1998) and 97SB68 starting composition of Tuff et al. (2005) experiment.

of plagioclase, clinopyroxene, and ilmenite. Olivine phenocrysts typically show hexagonal euhedral shape (Figs. 5a and 5b) with irregular cracks and slight iddingsite alteration along the cracks. Some of the faces on olivine crystal are curved and embayed. Smaller olivines (~ 2 mm) are generally rounded and exhibit a rim of distinctive red tarnish of iddingsite formed by oxidation of olivine. Some olivine crystals are completely replaced by iddingsite. Deformed, kink-banded crystals are absent.

Figure 3. Trace element variation with respect to MgO of Ethiopian ferropicrite and picritic ferrobalt. Symbols and data sources are as in Figure 2.

Figure 4. Bulk-rock $\text{Al}_2\text{O}_3/\text{TiO}_2$ versus Zr/Y plot for the Ethiopian ferropicrite and picritic ferrobalt. Data sources are as in Figure 2. The arrow assumes a single peridotitic source.

Clinopyroxenes occur as euhedral, elongated pinkish phenocrysts (<4 mm) which are partially embayed and resorbed (Figs. 5c and 5d). In places, olivine and clinopyroxene occur together as glomerocrysts up to 7 mm in size in which olivines appear to be interstitial between clinopyroxenes. Ilmenites (up to 0.2 mm) are also included in some clinopyroxene phenocrysts. Representative compositions of the main mineral phases are shown in Tables 2–5.

Olivine phenocrysts in the studied samples are homogenous and show a narrow compositional range (Fo_{78-88}), which corresponds to the previously reported values from HT2 basalts and picrites (Fo_{77-90} , Beccaluva et al., 2009). The Fo content of olivines from the Ethiopian ferropicrite and picritic ferrobalt fall within the range of those in Archean and Phanerozoic ferropicrites (Fo_{83-84} in Pechenga complex, Hanski and Smolkin, 1995; Fo_{85-88} in Emeishan/Lijiang, Zhang et al., 2006). Generally, the largest olivines are the most magnesian, whereas smaller crystals are relatively Fe-rich. NiO in the Fe-rich olivine cores reaches 0.3 wt% (Fig. 6). The CaO contents range from 0.28 to 0.42 wt%, indicating that they are not mantle xenocrysts (Simkin and Smith, 1970; Gurenko et al., 1996; Thompson and Gibson, 2000; Kawabata et al., 2011) and MnO contents vary between 0.14 and 0.24 wt%.

The Cr-spinels are characterized by extremely high $\text{Cr}\#[100\text{Cr}/(\text{Cr} + \text{Al})]$ (up to 84), moderate $\text{Mg}\#[100\text{Mg}/(\text{Mg} + \text{Fe}^{2+})]$ (18–51) and moderate $\text{Fe}^{3+}\#[100\text{Fe}^{3+}/(\text{Cr} + \text{Al} + \text{Fe}^{3+})]$ (11–39) (Table 3). The Cr_2O_3 content varies from 14 to 49 wt%. The TiO_2 contents of Cr-spinels are very high (3.6–14.8 wt%) as compared to Cr-spinels in meimechite and depleted ferropicrites from Vestfjella (Heinonen and Luttinen, 2010). The Cr# of Cr-spinels from these ferropicrite and picritic ferrobalt is as high as those in boninite and is distinctly higher than Cr-spinels in abyssal peridotites (Dick and Bullen, 1984), MORB (Sigurdsson and Schilling, 1976), picritic basalts (e.g., West Greenland; Larsen and Pedersen, 2000, Emeishan; Kamenetsky et al., 2012, Iceland; Sigurdsson et al., 2000, Sorachi-Yezo; Ichiyama et al., 2012) and ferropicrites from Pechenga (Hanski, 1992) and accreted oceanic plateau in Japan (Mino-Tamba belt; Ichiyama et al., 2006), (Figs. 7a and 7b). Figure 8 shows the relationship between Cr-spinel and bulk rock in their Cr/Al ratios of the studied samples and other related rocks. The high Cr/Al of the Cr-spinels and very low Cr/Al of the host rock is unique feature of the studied Ethiopian ferropicritic rocks.

Clinopyroxene phenocrysts are $\text{Mg}\# = 74-88$, $\text{TiO}_2 = 0.84-1.82$ wt%, and $\text{Al}_2\text{O}_3 = 1.2-3.2$ wt% in the cores. Clinopyroxenes are Mg-rich augite ($\text{Wo}_{43-46}\text{En}_{41-48}\text{Fs}_{7-15}$) in composition. They commonly show normal zoning

Figure 5. Photomicrographs of Ethiopian ferropicrite and picritic ferrobasalt. (a) Crossed polarized light showing porphyritic texture with abundant magnesian olivine phenocrysts. (b) Back-scattered electron images of olivine phenocrysts and spinel inclusions. Subhedral to euhedral olivine phenocrysts are set in a microcrystalline groundmass. (c) Crossed polarized light images of clinopyroxene with reverse zoning, Cpx3 of Sample 1 and (d) that with resorbed texture, Cpx1 of Sample 2. Small circles in the clinopyroxene phenocrysts show ICP-MS analytical points (Table 5). Ol, olivine; Cpx, clinopyroxene; Sp, spinel.

Table 2. Representative analyses of olivine phenocrysts in ferropicrite and picritic ferrobasalt rocks from Lalibela area, Ethiopian LIP

Sample	1 Ferropicrite						2 Picritic ferrobasalt				3 Picritic ferrobasalt					
Mineral	Ol1	Ol2		Ol3		Ol3		Ol4		Ol2	Ol3		Ol5		Ol6	
	Core	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Core	Rim	Core	Core	Rim	
SiO ₂	39.03	41.68	40.00	40.94	39.08	42.12	40.73	41.01	40.44	40.04	40.51	40.96	39.92	39.29	40.97	
FeO*	19.48	12.39	16.33	11.41	18.59	10.63	11.91	10.52	12.75	14.40	14.69	14.52	13.23	16.48	17.26	
MnO	0.24	0.16	0.26	0.20	0.30	0.18	0.18	0.14	0.22	0.11	0.23	0.24	0.19	0.23	0.24	
MgO	39.35	46.96	42.32	46.55	40.28	48.00	46.19	47.18	44.90	43.74	43.82	44.32	43.59	40.87	42.70	
CaO	0.29	0.34	0.32	0.42	0.34	0.31	0.31	0.28	0.31	0.40	0.37	0.36	0.33	0.37	0.36	
NiO	0.27	0.22	0.25	0.25	0.39	0.30	0.44	0.30	0.30	0.31	0.29	0.45	0.29	0.28	0.21	
Total	98.66	101.75	99.48	99.77	98.98	101.54	99.76	99.43	98.92	99.00	99.91	100.85	97.55	97.52	101.74	
Cations (O=4)																
Si	1.016	1.015	1.016	1.014	1.012	1.018	1.011	1.014	1.016	1.014	1.018	1.017	1.020	1.020	1.019	
Fe ²⁺	0.424	0.252	0.347	0.236	0.403	0.215	0.247	0.218	0.268	0.305	0.309	0.301	0.283	0.358	0.359	
Mn	0.005	0.003	0.006	0.004	0.007	0.004	0.004	0.003	0.005	0.002	0.005	0.005	0.004	0.005	0.005	
Mg	1.526	1.704	1.602	1.718	1.554	1.730	1.709	1.738	1.682	1.651	1.641	1.640	1.659	1.582	1.583	
Ca	0.008	0.009	0.009	0.011	0.009	0.008	0.008	0.007	0.008	0.011	0.010	0.010	0.009	0.010	0.010	
Ni	0.006	0.004	0.005	0.005	0.008	0.006	0.009	0.006	0.006	0.006	0.006	0.009	0.006	0.006	0.004	
Total	2.990	2.990	2.985	2.988	2.993	2.981	2.988	2.986	2.985	2.989	2.989	2.982	2.981	2.981	2.980	
Fo	78.26	87.12	82.20	87.92	79.41	88.95	87.34	88.85	86.23	84.41	84.15	84.49	85.43	81.55	81.51	

* Total Fe as FeO.

Abbreviation: Ol, olivine.

and it gives a trend of increasing Fe, Al, and Ti concentrations and decreasing Mg#, Si and Cr from core to rim (Fig. 9). However, some of the studied clinopyroxene crystals are very rich in Cr (up to 6240 ppm) and display very strong reverse zoning with significant increase of compatible elements (such as Cr and Ni; Tables 4 and 5) and decreasing REEs from core to rim. This unusual, significant reverse zoning provides insight in to the origin of these lavas (see Section **Eclogite versus peridotite as**

the source for Ethiopian ferropicrite). The trace element composition of clinopyroxenes of ferropicrite and picritic ferrobasalt rocks resembles those of HT2 basalt (Beccaluva et al., 2009), but they are enriched in total REE contents than those of iron-poor picrites. The REE contents of clinopyroxenes display enrichment in LREE ($La_N/Yb_N = 1.2-1.9$) and MREE ($Eu_N/Yb_N = 3.3-4.3$) relative to HREE. The primitive mantle-normalized pattern (Fig. 10) of clinopyroxene is characterized by low

Table 3. Representative analyses of spinel inclusions in olivine phenocrysts

Sample	1 Ferropicrite		2 Picritic ferrobalt				3 Picritic ferrobalt	
Mineral	Spl1(Ol1)	Spl4(Ol3)	Spl1(Ol1)	Spl2(Ol3)	Spl3(Ol4)	Spl5 Gm	Spl2(Ol2)	Spl5(Ol5)
TiO ₂	14.81	9.60	6.22	3.81	3.60	3.75	7.08	5.99
Al ₂ O ₃	8.02	5.52	5.85	6.85	6.44	5.90	6.12	4.74
Cr ₂ O ₃	13.97	38.50	37.38	48.93	47.31	43.21	34.44	37.85
FeO*	51.77	32.61	39.39	30.74	30.62	39.50	39.07	43.86
MnO	0.34	0.24	0.16	0.19	0.17	0.32	0.16	0.26
MgO	5.80	9.47	9.18	7.79	11.08	3.74	8.27	4.86
Total	94.71	95.94	98.18	98.31	99.22	96.42	95.14	97.56
Cations (O=4)								
Ti	0.398	0.253	0.160	0.099	0.090	0.102	0.188	0.161
Al	0.338	0.228	0.235	0.278	0.253	0.252	0.255	0.199
Cr	0.395	1.065	1.009	1.332	1.247	1.238	0.962	1.067
Fe ³⁺	0.470	0.202	0.437	0.192	0.319	0.306	0.407	0.413
Fe ²⁺	1.079	0.752	0.688	0.693	0.535	0.890	0.748	0.894
Mn	0.010	0.007	0.005	0.006	0.005	0.010	0.005	0.008
Mg	0.309	0.494	0.467	0.400	0.551	0.202	0.436	0.258
Total	2.999	3.001	3.001	3.000	3.000	3.000	3.001	3.000
Cr#	53.89	82.39	81.08	82.73	83.13	83.09	79.06	84.27
Mg#	22.28	39.65	40.44	36.59	50.74	18.49	36.81	22.40
Fe ³⁺ #	39.06	13.54	25.97	10.66	17.54	17.05	25.05	24.60

* Total Fe as FeO.

Cr# = 100Cr/(Cr + Al).

Mg# = 100Mg/(Mg + Fe²⁺).Fe³⁺# = 100Fe³⁺/(Cr + Al + Fe³⁺).

Abbreviations: Spl, spinel; Ol, olivine; Gm, groundmass.

Number of host olivine is indicated in parentheses.

Table 4. Representative analyses of clinopyroxene phenocrysts and microphenocrysts of ferropicrite and picritic ferrobalt rocks from Ethiopian LIP

Sample	1 Ferropicrite				2 Picritic ferrobalt					3 Picritic ferrobalt					
Mineral	Cpx1		Cpx3		Cpx1		Cpx1Gm		Cpx3	Cpx1		Cpx2		Cpx3	
	Core	Rim	Core	Rim	Core	Rim	Core	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SiO ₂	53.87	50.45	50.74	52.46	51.78	50.62	49.55	53.50	51.78	51.25	48.90	50.59	50.47	50.81	48.08
TiO ₂	0.84	1.68	1.64	1.67	1.70	1.77	1.83	1.08	1.80	1.34	2.21	1.82	1.77	1.68	2.39
Al ₂ O ₃	1.25	2.50	2.71	2.74	2.55	2.62	2.82	1.22	2.76	1.75	3.49	3.21	3.18	2.98	4.14
Cr ₂ O ₃	0.73	0.38	0.22	0.62	0.12	0.25	0.15	0.67	0.20	0.73	0.62	0.89	0.24	0.08	0.06
FeO*	4.37	7.13	7.65	6.02	7.97	7.08	9.24	4.83	8.05	5.03	6.80	6.23	7.16	6.96	8.39
MnO	0.16	0.20	0.07	0.14	0.16	0.13	n.d.	n.d.	n.d.	0.15	0.17	0.09	0.13	0.21	0.14
MgO	17.36	15.33	15.02	16.15	15.26	15.12	14.21	16.96	15.33	15.97	14.54	15.57	14.91	15.35	13.53
CaO	22.48	20.96	20.61	21.67	21.43	21.26	20.93	22.6	20.73	21.79	21.46	21.42	21.38	21.26	21.06
Total	101.06	98.63	98.66	101.47	100.97	98.85	98.73	100.86	100.65	98.01	98.19	99.82	99.24	99.33	97.79
Cations (O=6)															
Si	1.949	1.895	1.904	1.902	1.903	1.896	1.878	1.944	1.904	1.922	1.851	1.873	1.884	1.893	1.837
Ti	0.023	0.047	0.046	0.046	0.047	0.050	0.052	0.030	0.050	0.038	0.063	0.051	0.050	0.047	0.069
Al	0.053	0.111	0.120	0.117	0.111	0.116	0.126	0.052	0.120	0.077	0.156	0.140	0.140	0.131	0.187
Cr	0.021	0.011	0.007	0.018	0.003	0.007	0.004	0.019	0.006	0.022	0.018	0.026	0.007	0.002	0.002
Fe ²⁺	0.132	0.224	0.240	0.182	0.245	0.222	0.293	0.147	0.248	0.158	0.215	0.193	0.224	0.217	0.268
Mn	0.005	0.006	0.002	0.004	0.005	0.004	n.d.	n.d.	n.d.	0.005	0.005	0.003	0.004	0.007	0.004
Mg	0.936	0.859	0.840	0.873	0.836	0.844	0.803	0.919	0.840	0.893	0.821	0.859	0.830	0.852	0.771
Ca	0.871	0.844	0.828	0.842	0.844	0.853	0.850	0.880	0.817	0.876	0.870	0.850	0.855	0.848	0.862
Total	3.990	3.997	3.985	3.984	3.994	3.992	4.006	3.991	3.985	3.991	3.999	3.992	3.994	3.997	4.000
Wo	44.9	43.8	43.4	44.4	43.8	44.5	43.7	45.2	42.9	45.5	45.7	44.7	44.8	44.2	45.4
En	48.3	44.6	44.0	46.0	43.4	44.0	41.3	47.2	44.1	46.4	43.0	45.2	43.5	44.4	40.5
Fs	6.8	11.6	12.6	9.6	12.7	11.6	15.1	7.5	13.0	8.2	11.3	10.1	11.7	11.3	14.1
Mg#	87.63	79.31	77.78	82.71	77.34	79.2	74.33	86.22	77.25	84.98	79.22	81.67	78.78	79.72	74.19

*Total Fe as FeO.

Mg# = 100Mg/(Mg + Fe²⁺).

Abbreviations: Cpx, clinopyroxene; Wo, wollastonite; En, enstatite; Fs, ferrosilite; Gm, groundmass; n.d., not detected.

Table 5. Representative trace element analyses (LA-ICP-MS; values in ppm) of clinopyroxenes from ferropicrite and picritic ferrobalt rocks from Lalibela area, Ethiopian LIP

Sample	1 Ferropicrite		2 Picritic ferrobalt				3 Picritic ferrobalt			
Mineral	Cpx3		Cpx1		Cpx2		Cpx1		Cpx2	
	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim
Sc	64.3	62.2	64.2	66.1	81.1	73.1	68.4	68.4	58.9	61.1
Ti	7480	7840	10050	10010	11140	10600	8580	8690	7110	9750
V	449	313	471	419	391	402	247	252	202	314
Cr	886	4240	809	2040	2550	2440	6240	5850	2120	2320
Co	52.6	44.9	49.0	49.3	47.4	48.4	39.2	39.1	41.7	42.0
Ni	262	358	255	305	300	295	374	347	375	364
Rb	0.004	0.043	0.02	0.10	0.01	0.01	0.01	0.001	0.004	0.01
Sr	49.9	46.9	73.5	70.0	68.3	65.7	58.6	62.1	56.1	77.7
Y	14.6	11.2	18.0	15.5	14.2	16.8	11.0	11.3	10.6	14.1
Zr	35.0	25.7	62.4	54.4	53.5	60.7	30.2	31.8	24.0	45.9
Nb	0.1	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.1	0.2
Cs	n.d.	0.002	n.d.	0.010	n.d.	0.0003	n.d.	0.002	n.d.	n.d.
Ba	0.02	0.64	0.23	0.33	0.03	0.05	0.02	0.03	0.01	0.02
La	2.2	1.4	3.3	2.8	2.7	2.8	2.1	2.3	1.6	2.6
Ce	10.7	7.2	15.9	13.7	12.6	13.5	9.3	10.4	7.6	12.8
Pr	2.1	1.4	2.9	2.6	2.4	2.5	1.7	1.9	1.5	2.4
Nd	12.2	8.3	17.5	15.0	13.9	15.0	10.0	11.0	8.8	13.9
Sm	4.0	2.8	5.5	4.8	4.6	5.1	3.3	3.6	3.0	4.5
Eu	1.3	0.9	1.8	1.6	1.5	1.6	1.1	1.2	1.0	1.5
Gd	4.3	3.1	5.7	4.9	4.6	5.2	3.5	3.8	3.3	4.5
Tb	0.6	0.5	0.8	0.7	0.6	0.7	0.5	0.6	0.5	0.7
Dy	3.6	2.7	4.5	3.9	3.6	4.0	2.9	3.1	2.7	3.7
Ho	0.6	0.5	0.8	0.7	0.6	0.7	0.5	0.5	0.4	0.6
Er	1.5	1.1	1.8	1.5	1.4	1.6	1.2	1.2	1.1	1.5
Tm	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0.2
Yb	1.1	0.8	1.3	1.0	0.9	1.1	0.8	0.9	0.8	1.0
Lu	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Hf	1.7	1.2	2.8	2.4	2.6	2.8	1.7	1.7	1.2	2.2
Ta	0.02	0.02	0.05	0.04	0.04	0.04	0.03	0.03	0.01	0.04
Pb	0.05	0.05	0.10	0.06	0.04	0.03	0.05	0.05	0.05	0.04
Th	0.01	0.01	0.03	0.02	0.03	0.02	0.02	0.02	0.01	0.02
U	0.003	0.003	0.007	0.004	0.004	0.003	0.002	0.006	0.002	0.005

Abbreviations: Cpx, clinopyroxene; n.d. not detected.

Figure 6. Fo content versus NiO (wt%) for olivines in ferropicrite and picritic ferrobalt rocks from Ethiopian LIP. Those of the komatiites from Superior Province (Arndt et al., 1977); meimechite from Siberian traps (Elkins-Tanton et al., 2007), ferropicrites from Karoo and Ferrar provinces (Heinonen and Luttinen, 2008), Paraná-Etendeka provinces (Gibson et al., 2000) and picrites from Sorachi-Yezo (Ichiyama et al., 2012). The composition of olivines from the LT (low-Ti) and HT2 (high-Ti 2 basalt and picrites) of Ethiopian LIP (Beccaluva et al., 2009) are also shown for comparison.

contents of Pb, Zr and LILE (e.g., Ba, Rb, Sr) relative to the neighboring elements, which is consistent with the low $D_{Cpx/liq}^{LILE}$ (Tuff and Gibson, 2007). Slight depletion

of HFSE (e.g., Nb and Ta) is also observed relative to LREE (La and Ce). There is no significant negative Eu anomaly ($Eu/Eu^* = 0.95-1$).

Figure 7. Cr-spinel composition of the Ethiopian ferropicrite and low-Ti basalt and HT2 picrites (Beccaluva et al., 2009). Those of the picrites from Sorachi-Yezo (Ichiyama et al., 2012), Iceland (Sigurdsson et al., 2000), Tamba belt (Ichiyama et al., 2006), Emeishan (Kamenetsky et al., 2012), West Greenland (Larsen and Pedersen, 2000), Vestfjella meimechites and ferropicrite (Heinonen and Luttinen, 2010) and the ferropicrites from Pechenga (Hanski, 1992). The composition of MORB (Sigurdsson and Schilling, 1976), abyssal peridotites (Dick and Bullen, 1984) and boninite are also taken for comparison.

Plagioclase microphenocrysts have labradorite composition ($An_{62}Ab_{36}Or_2$) while plagioclase in groundmass is andesine ($An_{41}Ab_{54}Or_4$), consistent with its late crystallization. The opaque minerals in the groundmass are mainly ilmenite.

DISCUSSION

Olivine Fo and NiO showing primitive mantle-derived melt

Primitive rocks that are associated with continental flood basalt LIPs are scarce, but their presence provides important information on the parental sources of these voluminous mantle derived magma. The most MgO-rich olivine that we analyzed is Fo_{88.9} (Table 2), which is higher than those of Paraná-Etendeka ferropicrite Fo₈₅ (Gibson et al., 2000) and slightly lower than those of anhydrous fertile lherzolite (Fo₉₀) (e.g., Ishiwatari, 1985). They are only slightly less forsteritic than the most magnesian olivine from HT2 picrites (Fo₉₀) of Ethiopia (Beccaluva et al., 2009) and picrites from Karoo (Fo₉₀, Cox and Jamieson,

1974). More magnesian olivines from Hokkaido, Japan (Fo₉₄, Ichiyama et al., 2012) and West Greenland (Fo₉₂, Pedersen, 1985) may represent higher potential temperature in the mantle. The magnesian and high NiO (up to 0.3 wt%) characteristics of olivine (Fig. 6) support the primitive, mantle-derived nature of the Ethiopian ferropicrite.

Primary bulk-rock nature of the melt

To assess the hypothetical primary melt compositions for the Ethiopian ferropicrite, we have tested a modeling program (PRIMELT2) (Herzberg and Asimow, 2008); however the outcome is unreliable due to the possible pyroxenite source component suggested by PRIMELT2 model. We thus focused on the modeling of primary melts on the basis of olivine-liquid equilibrium (Putirka, 2008). The analyzed samples are characterized by primitive olivine (>Fo₇₈; Table 2). The most Mg-rich olivine compositions (Fo₈₈ in ferropicrite and Fo₈₈₋₈₅ in picritic ferrobasalts) correspond to olivine that would crystallize from mantle derived melts. Assuming a $K_D(Fe-Mg)^{ol-liq}$ of 0.32 (Pu-

Figure 8. Bulk rock Cr/Al versus Spinel Cr/Al ratios for the Ethiopian ferropicrite and picritic ferrobasalts. Dashed arrows indicate the possible eclogitic and peridotitic sources. Data sources: Ethiopian LIP low-Ti and HT2 suits (Beccaluva et al., 2009); Abitibi komatiite (Barnes, 1985); Pioneer komatiite (Stiegler et al., 2012); Gorgona komatiite (Dietrich et al., 1981); Emeishan picrites (Kamenetsky et al., 2012); Siberian ferropicrite (Arndt et al., 1995); Karoo meimechite and ferropicrite (Heinonen and Luttinen, 2008, 2010); West Greenland picrite (Larsen and Pedersen, 2000); Hawaii picrite (Wilkinson and Hensel 1988); Tonga boninite (Sobolev and Danyushevsky, 1994); Sorachi-Yezo picrite (Ichiyama et al., 2012); Tango picrite (Ishiwatari and Imasaka, 2002); depleted (D-type) and enriched (E-type) picrites from Mikabu belt (Ichiyama et al., 2014); high magnesian andesite (HMA) and tholeiite lava Noto Peninsula (López and Ishiwatari, 2002); Mongolian high magnesian andesite and picrite (Erdenesaihan et al., 2013).

tirka, 2005), Fo_{85-88} would have been in equilibrium with a liquid with Mg# 64–71 and 15–19 wt% MgO. These observations indicate that the Ethiopian ferropicrite (Mg# 64), 14 wt% MgO and 14 wt% FeO^* ; Table 1 is likely to represent true Fe-rich mantle melt. Therefore, the high FeO^* content of Ethiopian ferropicrite is not an accumulation effect.

Temperature estimates

Gibson (2002) suggested that the ferropicritic liquid is generated by the partial melting of basalt plus peridotite mixture at $>1450^\circ\text{C}$ and >4.5 GPa. The experimental result of Tuff et al. (2005) confirmed that a ferropicrite melts 100% at 5 GPa and 1650°C , which is similar to the solidus (5 GPa and 1625°C) of silica-undersaturated garnet pyroxenite studied by Kogiso et al. (2003). These temperature are higher than the ambient upper mantle ($T_p \sim 1280\text{--}1475^\circ\text{C}$; McKenzie and Bickle, 1988) and

supports the derivation of ferropicrites from high temperature magma (and the plume). However, the available thermodynamic models are only compatible with peridotite sources (e.g., Herzberg and Asimow, 2008) and may not be applicable to estimate the physical conditions (pressure, mantle potential temperature) for pyroxene-rich sources. Considering the compositional similarity between the Ethiopian ferropicrite and 97SB68 in terms of MgO, FeO^* and Al_2O_3 (Fig. 2), the melting condition of our ferropicrite may be close to that of the melting experiment conducted by Tuff et al. (2005) as noted above.

Application of olivine-spinel geothermometer (Fabiès, 1979) to the ferropicrite and picritic ferrobasalt rocks results in temperatures as high as 1090°C for the most chromian spinel. This may represent closure temperature of Fe–Mg exchange between spinel inclusion and host olivine during cooling of the magma, and hence gives the lower limit of the magmatic temperature estimate.

Figure 9. Plots of Mg# versus TiO₂ (a) and Cr₂O₃ (b) for the ferropicrite and picritic ferrobasalt of Ethiopian LIP. For comparison, clinopyroxenes from the high-Ti 2 picrite (Beccaluva et al., 2009) are also plotted. Dashed arrow represents the core to rim reverse zoning trend within a single crystal.

In addition, the Cr content of spinel may provide a clue for the temperature of the magma from which it crystallized. The Cr content of the melt in equilibrium with spinel (Cr solubility) increases with increasing temperature (Barnes, 1986). Effect of oxygen fugacity also matters, but co-existing ilmenite and absence of magnetite suggest low oxygen fugacity. The high Cr/Al spinel would have been expected to crystallize from the magma having high Cr/Al ratio, or the magmatic temperature was very high, and these in turn may indicate high degrees of melting, however, the bulk rock data of our samples shows very low content of Cr. Thus, it is likely that the observed high Cr/Al ratio of spinel is due to high magmatic temperature.

High degree melting of the source mantle?

Cr-spinel is one of the liquidus phases in basaltic magma and its chemical variation may have significant inferences about the degree of melting and source regions of magma (Dick and Bullen, 1984; Arai, 1994). The Cr-spinel of Ethiopian ferropicrite is significantly higher in Cr# (average 78.7) than those of MORB, Emeishan high-Ti picrite (Kamenetsky et al., 2012), Pechenga ferropicrite (Hanski, 1992) and comparable to those of boninite (Fig. 7). The TiO₂ content of Cr-spinel is also very high (Fig. 7b),

which is consistent with the high Ti characteristics of bulk rock chemistry of the studied samples. Moreover, the TiO₂ content of spinel is equal to or higher than those of LIP lavas (Kamenetsky et al., 2001). The high Cr/Al ratio of spinels from the Ethiopian ferropicrite and picritic ferrobasalts (Fig. 8) might indicate high degree of melting, but the bulk rock Cr/Al ratio is very low and is not proportional to that of spinel. Thus we propose very low Cr/Al of the source material (see Section **Cr/Al relationship between spinel and bulk rock: indicator of source lithology**). Removal of spinel in the early stage of magma evolution is another possibility (Fig. 8), but is unlikely in view of the very primitive nature of the magma. However, this interpretation apparently contradicts to the suggested small degree of partial melting (of peridotite source) on the basis of low Al₂O₃/TiO₂ and high Zr/Y ratios of bulk rock compositions (Fig. 4).

Cr/Al relationship between spinel and bulk rock: indicator of source lithology

Figure 8 shows the relationship between the bulk-rock Cr/Al and spinel Cr/Al ratios of the Ethiopian ferropicrite in comparison with mafic-ultramafic rocks of other igneous provinces. Based on this, the Cr/Al ratio of spinels of Ethiopian ferropicrite is similar to those of Archean komatiite (Stiegler et al., 2012), Siberian ferropicrite (Arndt et al., 1995), and boninite (Sobolev and Danyushevsky, 1994), although the bulk-rock Cr/Al ratio (<0.005) is significantly lower than those mentioned above.

The observed very low bulk-rock Cr/Al ratios in the Ethiopian ferropicrite and picritic ferrobasalts might be attributed to the removal of Cr-spinel in the early stage of magma evolution. However, primitive nature of the studied samples does not support extensive early stage crystal fractionation. On the other hand, Sorachi-Yezo picrites (Ichiyama et al., 2012), Mikabu D-type picrites (Ichiyama et al., 2014) and Abitibi komatiite (Barnes, 1985) shows high bulk rock Cr/Al but low spinel Cr/Al ratios, which might indicate the accumulation of spinel in the magma (Fig. 8). However, occurrence of high Fo olivines in these rocks is compatible with high degree melting of peridotitic mantle rather than olivine accumulation process in shallow magma chamber. Thus, bulk rock Cr/Al ratio of the primitive magmas may be mainly controlled by lithology of the source material in the mantle. For example, if the source is eclogite (or pyroxenite), bulk rock Cr/Al ratios of magma may not exceed 0.01, but if the source is peridotite, Cr/Al of the magma may be as high as 0.1 (Fig. 8). The very low Cr/Al ratio of the Ethiopian ferropicrite together with the others of low bulk-rock Cr/Al (such as those of Noto tholeiite and high

Figure 10. Primitive-mantle-normalized REE and trace element patterns for clinopyroxenes of ferropicrite and picritic ferrobalt rocks from Lalibela area, Ethiopian LIP. Normalizing values are from McDonough and Sun (1995). For comparison, clinopyroxene compositions from low-Ti (a)–(b) and High-Ti 2 basalt and picrites (c)–(d) of Ethiopian LIP are also plotted after Beccaluva et al. (2009).

magnesian andesite (HMA), López and Ishiwatari, 2002; Mongolia picrite and HMA, Erdenesaihan et al., 2013; Hawaii picrite, Wilkinson and Hensel, 1988) (Fig. 8) may suggest eclogitic source, which is supported by the lines of evidence as discussed later (see Section **Eclogite versus peridotite as the source for Ethiopian ferropicrite**).

High-pressure melting of the source mantle

The increasing Zr/Y and decreasing $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios (Fig. 4) are generally attributed to increase of melting pressure or melt segregation depth and increasing stability of garnet in the residue (Walter, 1998). The Ethiopian ferropicrite and picritic ferrobalt rocks are characterized by higher Zr/Y and lower $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios than other ferropicritic rocks (e.g., Superior Province, Pechenga, Paraná-Etendeka and Mino-Tamba), indicating that their source region contained residual garnet and thus the partial melting took place in the garnet stability field. The low Al content in magmas such as ferropicrite (Tuff et al.,

2005) and Al-depleted komatiites (Arndt et al., 2008; Robin-Popieul et al., 2012) is interpreted to indicate the presence of residual garnet in the mantle source. Compared to the Ethiopian ferropicrite, the ferropicrites of Siberia exhibit higher Zr/Y and lower $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios, suggesting higher melting pressure.

The high Ni content (501 ppm) along with the low Al_2O_3 (~9 wt%) of Ethiopian ferropicrite may also indicate that garnet was a residual phase in its mantle source. This interpretation is consistent with the high pressure experimental result on the Paraná-Etendeka ferropicrite produced by Tuff et al. (2005).

In addition, REE patterns of clinopyroxene phenocrysts from the studied samples show distinct convex upward patterns in chondrite-normalized diagrams (Fig. 10) with La_N/Yb_N (1.2–1.9) and Eu_N/Yb_N (3.3–4.3), resembling those reported HT2 basalt and picrites of Ethiopia (Beccaluva et al., 2009). Therefore, the strong HREE fractionation supports the presence of garnet in the mantle source region.

Bulk-rock high Fe/Mn and Ni/Cr ratios: a core-mantle issue?

High Fe/Mn ratios of basalts could be resulted from core-mantle interaction. However, on the basis of high Fe/Mn and unradiogenic $^{187}\text{Os}/^{188}\text{Os}$ content of the Ethiopian picrite, Rogers et al. (2010) speculated that the entrapment of core material in the source of the Afar mantle plume is unlikely. Basaltic melts with high Fe/Mn (>60) ratio can be formed by partial melting of pyroxenite at the degree of melting less than 70% (Kogiso and Hirschmann, 2001, Pertermann and Hirschmann, 2003, Kogiso et al., 2004) or of hydrous peridotite at the degree of melting greater than 50% (Parman and Grove, 2004).

High fraction of clinopyroxene crystallization (>30%) could also produce a melt with high Fe/Mn ratio (Liu et al., 2008). In view of high MgO (>10 wt%) of the studied samples, such a high degree of crystallization is unrealistic. High Fe/Mn could be also resulted from the presence of residual garnet in the source (Herzberg, 2011), because $D_{\text{Mn}}^{\text{Garnet/liquid}}$ is ~ 7 at low melt fraction (Pertermann and Hirschmann, 2003). High Ni content (500 ppm) and high Ni/Cr ratio of the Ethiopian ferropicrite (Table 1) may also suggest contribution of Fe-Ni metal in its magma genesis, but to attribute this to the core-mantle reaction must be too speculative.

Eclogite versus peridotite as the source for Ethiopian ferropicrite

The genesis of ferropicritic rocks have been considered to be associated with mantle plume (Gibson, 2002). Sobolev et al. (2007) suggested that ~ 2 –30% of recycled crust is involved in the mantle melting to form MORBs, OIBs, continental basalts and komatiites. On the basis of phase relation and bulk rock composition of the Paraná-Etendeka ferropicrite, Tuff et al. (2005) speculated that ferropicrite primary melt is unlikely to have been derived from partial melt of normal peridotite and melting of garnet pyroxenite source may have been significant. The occurrence of garnet liquidus phase with clinopyroxene at pressure ≥ 6 GPa, leading Tuff et al. (2005) to propose garnet pyroxenite as mantle source for the Paraná-Etendeka ferropicrite. Ichiyama et al. (2006) have suggested that suitable ferropicrite sources include recycled ferrobasalts and Fe-Ti gabbros (that should have been eclogitized in the source mantle). It is evident that ferropicrite liquid cannot originate in direct partial melting of ambient depleted peridotite (Stone et al., 1995).

Jakobsen et al. (2005) suggested a mixing between the peridotite-derived picritic melts with evolved Fe-rich basalts or immiscible liquids could result in a ferropicritic

composition. However, liquid immiscibility and subsequent mixing process is unlikely cause for the generation of Ethiopian ferropicritic melt because of two reasons: (1) immiscibility tends to fade away with increasing pressure (Charlier and Grove, 2012); (2) such mixing process would be expected to produce significant disequilibrium textures, which are not observed among studied rocks.

The bulk rock Cr/Al ratio (Fig. 8) may provide important clue about the source material. The extremely low bulk rock Cr/Al ratio of Ethiopian ferropicrite and picritic ferrobasalt rocks evidence that they cannot be formed from the partial melting of only peridotite mantle source as the other mafic-ultramafic rocks (e.g., Sorachi-Yezo picrites, Japan; D-type Mikabu picrite, Japan; Pioneer komatiite, South Africa). Thus, we suggest that the significant contribution of recycled eclogitic material for the origin of Ethiopian ferropicrite and picritic ferrobasalts.

Reversely zoned clinopyroxene; reaction with peridotitic mantle

The origin of reversely zoned clinopyroxenes with resorbed texture has been attributed to magma mixing in many literatures (e.g., Wass, 1979; Simonetti et al., 1996). Kay (1978) suggested that the reversely zoned clinopyroxene may indicate reaction between a silicic melt and peridotite in the upper mantle. Reversely zoned clinopyroxenes have been also reported from Cenozoic basalts (Wang et al., 2007) and late Jurassic high-Mg adakites of China (Gao et al., 2004), and suggested the presence of pyroxenite in the mantle source. Some of the analyzed clinopyroxene crystals of Ethiopian ferropicrite and picritic ferrobasalts exhibit unusually strong reverse zoning, which have a rim with distinctly high Mg#, Cr and Ni (Tables 4 and 5; Fig. 9). These zoning may indicate a significant increase of Mg#, Cr and Ni in the melt by assimilation of mantle peridotite (i.e., an olivine consuming reaction) or mixing with the peridotite-origin magma during magma ascent. Thus, the presence of these unusual reversely zoned clinopyroxene crystals may further proves the origin of Ethiopian ferropicrite and picritic ferrobasalt rocks from eclogitic source, and their reaction with the peridotitic mantle.

Experimental constraints for the source lithology

According to Yaxley and Green (1998), partial melting of relatively fusible eclogite inclusions produces SiO_2 -rich melts that react with olivine in the host garnet peridotite and generate a secondary garnet pyroxenite source in upwelling mantle. Progressive melting of this 're-fertilized' source may yields silica-undersaturated, more mafic par-

tial melt. Gibson (2002) suggested this 're-fertilized' source model to ferropicrite petrogenesis. Herzberg (2011) also discussed about the reaction between eclogite (pyroxenite)-origin melt and the host peridotite for the generation OIB.

Partial melting experiment of equal proportion of mixed basalt (GA1, in the form of coesite eclogite) and peridotite (MPY90) at 1500 °C and 3.5 GPa by Yaxley and Green (1998) and Yaxley (2000) yields a picritic melt that is close to Ethiopian ferropicrite composition. However, GA1₅₀MPY90₅₀ has slightly higher MgO (16.5 wt%) and Al₂O₃ (11.7 wt%), lower FeO* (12.50 wt%) as compared with Ethiopian ferropicrite (13.92 wt%, 8.58 wt% and 14.00 wt%, respectively) (Figs. 2a–2c). Tuff et al. (2005) proposed a source composition similar to a 75% basalt and 25% peridotite mixture at ≥5 GPa for the Paraná–Etendeka ferropicrite, but it is not supported by experimental data at this pressure. Likewise, we suggest that a higher pressure mixture of eclogite–peridotite (GA1₇₅MPY90₂₅) might be a plausible explanation to achieve the FeO* content similar with Ethiopian ferropicrite.

The high TiO₂ (>3 wt%) content of the Ethiopian ferropicrite and picritic ferrobasalts may further support the important role of Ti-rich recycled oceanic crust (eclogite).

Hydrous mantle melting?

The significance of water for the origin of ferropicrite is poorly known. However, different suggestions are given in literatures, such as the parental melt have been hydrous (Hanski and Smolkin, 1995; Fiorentini et al., 2008; their interpretation is based on the presence of kaersutite and phlogopite) and anhydrous (Gibson, 2002).

Partial melting experiment at high pressures (5–11 GPa) have been conducted on H₂O-saturated mantle peridotite (KLB-1) by Kawamoto and Holloway (1997). At about 7.5 GPa the partial melt have lower SiO₂, TiO₂, Al₂O₃, Na₂O and significantly higher MgO (32 wt%) than the Ethiopian ferropicrite, but similar FeO*. Thus, partial melt of H₂O saturated peridotite unlikely to be the source of Ethiopian ferropicrite. Moreover, the absence of primary magmatic hydrous mineral phases as phenocrysts, in the groundmass or as inclusions from the studied Ethiopian ferropicrite precludes its derivation from hydrous magma source.

In summary, the presence of ferropicrite in Ethiopian LIP may provide additional evidence for the high temperature and high pressure mafic magmatism of Afar plume during Oligocene (~30 Ma) and thus it may further proves for the high eruption temperature in Phanero-

zoic time. The origin of these ferropicrite and picritic ferrobasalt rocks could be attributed to high pressure partial melting of mantle peridotite that possibly incorporated recycled components (eclogite or garnet pyroxenite).

CONCLUSIONS

The ferropicrite and picritic ferrobasalt from Lalibela area show high Zr/Y and low Al₂O₃/TiO₂ ratios indicating higher pressure melting or smaller degree of partial melting, which apparently contradicts to the high Cr# of spinel in these rocks. The major and trace element data of the Ethiopian ferropicrite is compatible with the eclogitic source that possibly represents the recycled oceanic crust components in the upwelling Afar plume head. The occurrence of ferropicrite further supports the involvement of deep plume sources during Ethiopian LIP magmatism. In view of low Cr/Al ratio of the bulk rock, the high Cr# of spinel may be due to the very high temperature of the magma that originated in the eclogitic source. The occurrence of clinopyroxene crystals with extreme reverse zoning characteristics may further support the origin of Ethiopian ferropicrite and picritic ferrobasalts from eclogitic source at depths and their later interaction with the mantle peridotite.

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