

Sub-lithospheric source for Quaternary alkaline Tepi shield, southwest Ethiopia

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Mineral chemistry, major and trace elements and Sr-Nd isotopes are presented for basalts and trachybasalts from the Quaternary alkaline Tepi shield from southwest Ethiopia. The lavas are variably porphyritic with phenocrysts of olivine (Fo₆₇₋₈₇), clinopyroxene (Wo₄₅₋₄₇En₃₈₋₄₀Fs₁₃₋₁₆), plagioclase (An₅₇₋₆₈) and Ti-magnetite set in a microcrystalline matrix. Although there are two high-MgO lavas (10.6–10.8 wt.% MgO), the majority of specimens are more evolved (MgO = 4.7–6.2 wt.%). The major element variations can be explained by olivine + clinopyroxene ± plagioclase fractionation, most likely consistent with low P fractionation. The geochemical variations observed in the Tepi lavas are interpreted in terms of variable open system fractional crystallization of a magma sourced from primitive mantle like source.

Keywords: alkaline lava, southwest Ethiopia, primitive mantle, Tepi shield

INTRODUCTION

Most continental flood basalt provinces (CFBs) are associated with low volume alkaline rocks (e.g., Paraná-Etendeka, Ewart *et al.*, 1998; Ethiopia, Keiffer *et al.*, 2004). These low volume alkaline rocks are either very early eruptives preserved at the base of the lava pile or post-date the main tholeiitic eruptive phase. The origin of such alkaline magmas is still debated; certain authors (e.g., le Roex and Lanyon, 1998; Rogers *et al.*, 1992) favour lithospheric source regions, while others (e.g., Latin *et al.*, 1993) propose a contribution from sub-lithospheric sources such as a mantle plume. Even though alkaline magmas in flood basalt provinces may be volumetrically minor, still they can provide keys to the nature of the mantle and important clues as to the Earth's works.

It might be worth mentioning the wider question of why small degree, alkalic melts are exposed from Tanzania in the south to as far as Israel. The alkaline rocks of east Africa are important corollaries to the main phase of Tertiary volcanism. This paper presents geochemical data for a suite of Quaternary alkaline lavas from southwest Ethiopia (near Tepi, Fig. 1), a remote and poorly studied region of the Ethiopian flood basalt province. The samples were collected in 1998 during the Franco-Ethiopian Geosciences Cooperation Project (Ethiopia 2000). These data are used to constrain the petrogenesis of the basalts in an attempt to understand the nature of the source region.

The small number of samples makes it difficult to establish with certainty the behaviour of the suite, the role of fractionation in controlling major and trace element abundances, and source phenomenon. But still, the wealth of data presented does this paper to have the potential to make a solid contribution to the understanding of young alkalic magmatism in Ethiopia and, perhaps, other portions of the east African rift system.

GEOLOGICAL SETTING

The earliest Tertiary volcanism (basalt and associated rhyolite) in east Africa is found in south and southwest Ethiopia. Magmatism in southwest Ethiopia started in middle Eocene ca. 49 Ma (Davidson and Rex, 1980) and has continued episodically to recent times (Ayalew *et al.*, 1999; Ebinger *et al.*, 1993; George *et al.*, 1998; WoldeGabriel *et al.*, 1991). Davidson (1983) and Davidson and Rex (1980) broadly divided the Tertiary volcanic rocks in southwest Ethiopia into two categories: pre-rift and post-rift volcanic rocks.

The pre-rift category comprises the oldest main sequence (49 to 35 Ma) and the younger flows (32 to 21 Ma). The main sequence (bimodal basalt and rhyolite) overlies crystalline basement with basal red sandstone, which deposited on a peneplain during early Tertiary. The younger flows either lie above oldest suite or rest directly on crystalline basement, and all lack basal red grit beneath them. The post-rift sequence (19 Ma to present) comprises the mid Miocene flood basalts, which lie unconformably on tilted pre-rift flows, and overlying silicic lavas and pyroclastic rocks, and the phonolite and

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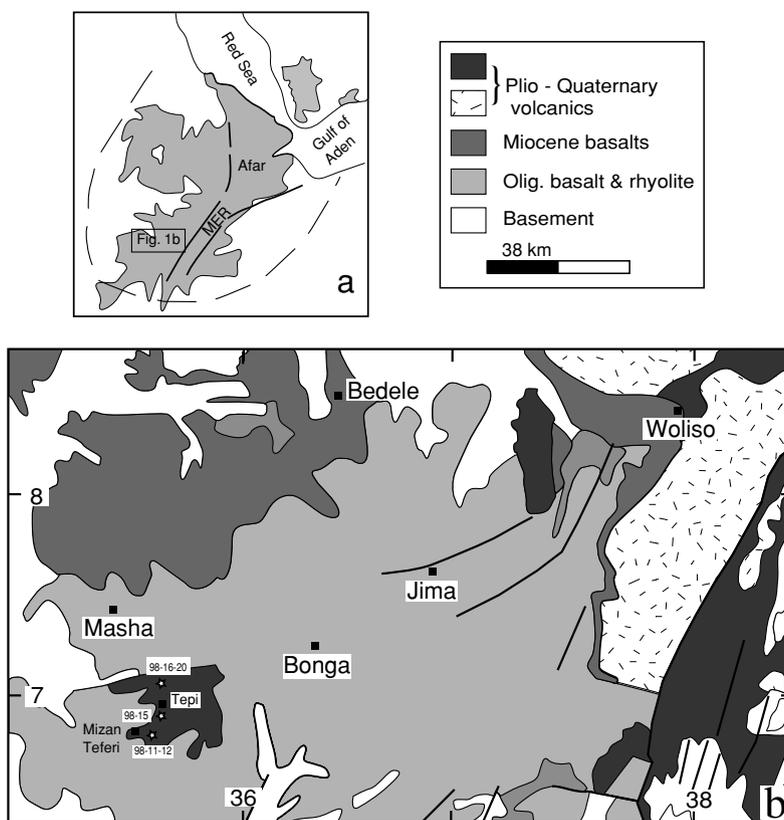


Fig. 1. (a) Location map of the Afro-Arabian large igneous province and the Afar triple rift junction. (b) Generalized geologic map of the southwest Ethiopia volcanic rocks and other lithologic units (modified after Merla *et al.*, 1979). Small numbers (with the prefix 98-) refer to sample numbers.

alkali trachyte flows and small intrusions, and the Quaternary volcanism.

Throughout the Oligocene, a broad arch developed concave to the northeast (Davidson and Rex, 1980). This uplift allowed erosion of the earlier volcanic cover, re-exposing basement rocks prior to extrusion of younger lavas. Major rift structures formed across this uplift in late Miocene ca. 13–12 Ma (Ebinger *et al.*, 1993), although shallow proto-rifts may have existed somewhat earlier (late Oligocene or early Miocene, Zanettin *et al.*, 1978). Rift topography was fully developed by the early Pliocene (5–4.5 Ma).

Quaternary volcanism in the Tepi area is related to new developing rifts and fracture zones (east-northeast faults, Davidson, 1983). The Quaternary volcanism can be divided at least into two phases based on morphological relationships: (1) the sub-horizontal, shield-forming columnar flows; (2) some scoria cones with their parasitic lava flows fed from vents around the base of the cones. There is no geochronological data available for this Quaternary volcanic field, but its relatively unmodified geomorphological expression (e.g., prominent cin-

der cones with explosion craters) confirms its recent age, most likely Holocene.

GEOCHEMISTRY

Petrography and mineral chemistry

The Tepi lavas have aphyric to mildly porphyritic textures with phenocrysts of olivine (Fo_{67-87}), clinopyroxene ($\text{Wo}_{45-47}\text{En}_{38-40}\text{Fs}_{13-16}$) and plagioclase (An_{57-68}) embedded in a microcrystalline matrix consisting of the same phase as the phenocryst assemblage. Phenocryst proportions range from 5–15 vol.% in the basalts to 10 vol.% in the trachybasalts. Ti-magnetites occurring as small euhedral grains are an important phase of the matrix. Table 1 reports the composition of representative phases. Olivine is the dominant phenocryst phase. Clinopyroxene does not always occur as phenocryst but is ubiquitous in the groundmass. Some samples are completely aphyric with very rare microphenocrysts of olivine, clinopyroxene, plagioclase and Ti-magnetites embedded in a cryptocrystalline groundmass.

Major elements

Major and trace element data for the Tepi Quaternary basalts and hawaiites are reported in Table 2. The lavas plot in the alkaline field on the TAS (total alkali-silica) diagram (Fig. 2), and they are nepheline normative. The lavas, with two exceptions, have MgO contents ranging from 4.7 to 6.2 wt.% and Mg values (Mg# = Mg/(Mg + Fe)) between 38 and 50. Magmas with such chemical characteristics could not be primary mantle partial melts and thus they underwent variable degrees of olivine fractionation. Two alkali basalts (samples 98-17 and 98-19) have relatively high MgO contents (10.6–10.8 wt.%) and Mg values (64–65), and are inferred to have undergone only limited fractionation.

Bivariate major element plots (Fig. 3) show that the lavas display an evolutionary trend; (i) Al₂O₃ contents of the mafic lavas increase with decreasing MgO content among samples with > 4.8 wt.% MgO, then decrease among the most evolved lavas, (ii) a continuous decrease in CaO/Al₂O₃, indicating removal of clinopyroxene which infers deeper level processes, (iii) an increase in TiO₂ indicating that Fe-Ti oxides were not involved in the fractionating assemblage and (iv) P₂O₅ behaves as an incompatible element within the suite. The overall data trends can be explained by olivine + clinopyroxene ± plagioclase fractionation, consistent with the observed phenocryst assemblage.

Trace elements

The two high-MgO lavas have relatively elevated Ni (262–270 ppm) and Cr (528 ppm) contents, but the other samples have low contents of Ni of 21–69 ppm and Cr of 18–73 ppm, suggesting that these rocks do not represent primary magmas but rather underwent olivine and clinopyroxene fractionation. Sample 98-12 shows very strong depletion in Ni (4.2 ppm), Cr (1.2 ppm) and Cu (19.3 ppm).

A couple of plots of e.g., Ba, La against MgO (Fig. 4a and b) shows that Ba and La behave as incompatible element which confirms that fractionation played a major role in the evolution of the rocks. However, the small number of samples makes it difficult to be quantitative about fractionation processes. Variations of incompatible trace element ratios (e.g., Rb/Sr-Ba/Rb, Fig. 4c) show that the two primitive samples are characterized by high Rb/Sr and low Ba/Rb, which is consistent with melting of phlogopite-bearing source (Furman and Graham, 1999).

Chondrite-normalized rare earth element (REE) patterns (Fig. 5a) are essentially similar showing light-REE (LREE) enrichment (Ce/Yb_N = 5.0–8.3) with a slight enrichment in the lighter heavy-REE (Dy/Yb_N = 1.3–1.7). The two MgO-rich samples display small positive Eu anomaly (Eu/Eu* = 1.00–1.14). Only one sample (98-16)

Table 1. Compositions of representative phenocrysts from Tepi lavas

Phase	Olivine		Clinopyroxene		Ti-magnetite		Plagioclase	
	98-17	98-19	98-17	98-16	98-19	98-16	98-19	98-16
SiO ₂	39.94	40.23	49.14	47.05	48.18	48.18	50.56	52.37
TiO ₂	0.00	0.00	1.57	1.67	2.46	2.46	31.14	28.90
FeO	12.76	12.03	3.62	6.93	3.90	3.90	0.50	0.78
MnO	0.36	0.22	7.72	8.83	9.46	9.46	13.79	11.39
MgO	46.41	47.11	0.04	0.17	0.29	0.29	3.51	4.49
CaO	0.29	0.29	13.78	12.80	12.71	12.71	0.20	0.55
NiO	0.22	0.16	22.28	20.66	21.43	21.43	99.70	98.48
Total	99.98	100.04	99.39	99.05	99.03	99.03	67.7	56.5
%Fo	86.6	87.5	66.6				31.1	40.3
				%Wo	45.4	45.9	1.2	0.8
				%En	39.1	37.8		
				%Fs	12.8	16.3		
				%An				
				%Ab				
				%Or				

Mineral analyses were performed on Cameca SX 50 electron microprobe at the University of Poitiers in Nancy, France. Typical working conditions were 15 kV accelerating potential, 10 nA current and a beam diameter of 1 mm. Total for Ti-magnetite is low and that is because of Fe⁺²/Fe⁺³ problem.

Table 2. Major (wt.%) and trace (ppm) element data for the Tepi lavas

Rock type	Basalt					Hawaiiite		
	98-19	98-17	98-11	98-15	98-12	98-16	98-20	98-18
SiO ₂	46.7	46.7	47.8	47.3	46.0	48.9	47.4	48.7
TiO ₂	1.87	1.90	2.40	3.55	3.61	2.08	2.21	2.38
Al ₂ O ₃	15.4	15.5	17.3	15.2	14.9	17.2	16.5	17.9
Fe ₂ O ₃	11.9	11.9	13.3	15.5	15.3	10.8	13.1	12.3
MnO	0.16	0.16	0.25	0.15	0.25	0.17	0.20	0.18
MgO	10.8	10.6	5.5	4.8	4.7	5.3	6.2	4.7
CaO	8.7	8.7	8.3	8.0	9.5	7.7	8.4	6.7
Na ₂ O	2.93	3.01	3.62	3.56	3.85	4.68	4.09	4.62
K ₂ O	0.99	1.04	0.97	1.24	0.93	2.24	1.14	1.64
P ₂ O ₅	0.52	0.52	0.58	0.73	1.08	0.85	0.69	0.86
Mg#	64.5	64.0	45.1	38.1	37.8	49.6	48.8	43.4
CIPW norm								
Pl	49.5	49	58.17	51.8	49.6	46.3	51.84	58.2
Or	5.79	6.03	5.67	7.33	5.5	13.1	6.68	9.57
Ne	0.39	0.94	0.00	0	1.83	6.43	3.07	1.97
Di	11.1	11.3	7.74	10.8	16.1	10.8	11.25	3.3
Hy	0	0	4.03	6.72	0	0	0.00	0
Ol	23	22.5	12.99	9.44	12.1	12.1	15.88	14.9
Il	3.51	3.57	4.52	6.72	6.86	3.89	4.16	4.48
Mt	5.6	5.51	5.52	5.55	5.55	5.5	5.52	5.61
Ap	1.18	1.18	1.34	1.69	2.48	1.95	1.60	1.97
Ba	213.7	213.2	355.5	550.5	485.8	949.6	265.4	624.4
Cr	528.7	528.2	26.3	19.6	1.2	73.1	121.0	18.3
Cs	0.20	0.25	0.27	0.83	0.30	0.57	0.27	0.18
Cu	54.0	54.5	20.7	39.4	19.3	33.8	42.2	38.6
Ga	17.0	17.8	19.8	26.1	19.4	18.4	19.5	18.1
Hf	3.68	3.94	3.62	6.15	3.67	3.36	4.31	5.69
Nb	23.2	24.9	28.0	27.5	30.4	78.9	29.0	47.1
Ni	262.0	270.4	28.0	45.0	4.2	38.1	69.3	21.3
Pb	2.20	2.66	3.42	4.76	3.88	4.68	3.09	3.61
Rb	18.2	19.6	17.7	22.0	17.8	61.4	23.2	24.6
Sr	451.9	476.0	575.7	496.2	701.2	1248.9	597.0	849.2
Ta	1.53	1.67	2.00	1.88	2.33	5.35	1.99	3.00
Th	1.88	2.20	2.53	2.99	2.83	7.41	2.62	3.61
U	0.48	0.55	0.39	0.69	0.66	1.26	0.70	0.97
V	173.0	171.1	255.2	274.9	221.6	183.3	182.3	110.0
Y	23.4	25.2	27.9	38.8	30.0	26.9	28.8	33.1
Zn	87.6	87.9	115.9	172.4	132.6	96.5	106.3	89.5
Zr	182.8	193.4	149.8	286.6	150.5	152.5	215.8	298.1
La	18.3	19.7	24.3	35.8	33.7	54.8	26.2	34.3
Ce	41.2	43.4	49.9	78.9	72.0	99.4	57.6	73.2
Pr	5.04	5.35	6.46	10.06	9.12	11.09	7.09	9.08
Nd	21.9	22.5	26.5	43.2	40.5	42.4	30.2	37.6
Sm	4.51	4.87	5.84	8.79	8.36	7.39	6.42	7.51
Eu	1.61	1.79	1.83	2.81	2.72	2.43	2.04	2.62
Gd	4.29	4.72	5.44	8.33	7.48	6.14	5.56	6.81
Tb	0.65	0.69	0.86	1.25	1.13	0.84	0.83	0.93
Dy	4.24	4.24	5.00	7.10	5.96	4.81	4.95	6.12
Ho	0.79	0.82	0.89	1.36	1.07	0.89	0.97	1.14
Er	1.92	2.06	2.51	3.43	2.76	2.49	2.31	2.88
Tm	0.32	0.32	0.39	0.50	0.38	0.30	0.36	0.48
Yb	1.83	2.14	2.54	3.01	2.20	2.26	2.21	2.72
Lu	0.30	0.33	0.40	0.51	0.41	0.36	0.35	0.50

Major elements were determined by ICP-AES and trace elements by ICP-MS at CRPG, Nancy, France. Total Fe as Fe₂O₃. Mg# = Mg/(Mg + Fe) with FeO/Fe₂O₃ = 0.8998.

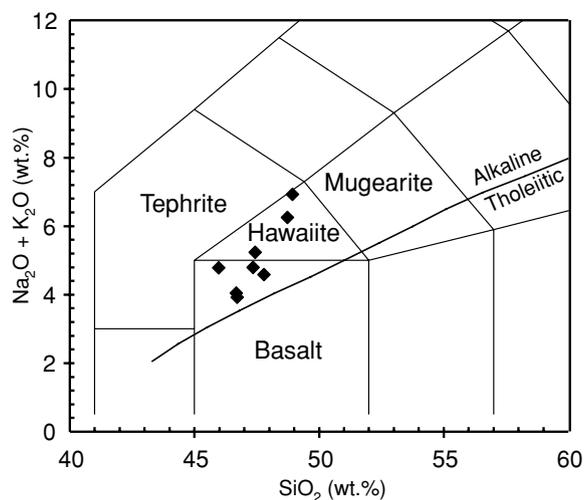


Fig. 2. Total alkalis v. silica (TAS, Le Bas et al., 1986) diagram for Tepi lavas, showing an alkaline composition. Alkaline/tholeiitic boundary is after Irvine and Baragar (1971).

is compositionally anomalous being slightly more LREE-enriched ($Ce/Yb_N = 11.2$), resulting in crossing REE patterns. This sample is also richer in incompatible elements (Ba, Nb, Rb, Sr, Ta, Th and U) than any other lava.

Primitive mantle-normalized incompatible trace element (ITE) variation diagrams (Fig. 5b) show typical intraplate volcanic patterns with enrichment in incompatible elements. The two primitive rocks do not have positive Ba anomaly, but the more evolved samples show positive Ba anomalies which call for the effects of fractionation.

Sr-Nd isotopes

Given the young age (Quaternary) of the rocks, the measured Sr and Nd isotopic ratios (Table 3) were not corrected for in situ decay of ^{87}Rb and ^{147}Sm and they considered as initial ratios. The Tepi lavas have $^{87}Sr/^{86}Sr$ ratios varying from 0.70313 to 0.70397 and $^{143}Nd/^{144}Nd$ ratios from 0.51280 to 0.51284. Although the Sr-Nd isotope datasets are limited, still they can provide some evi-

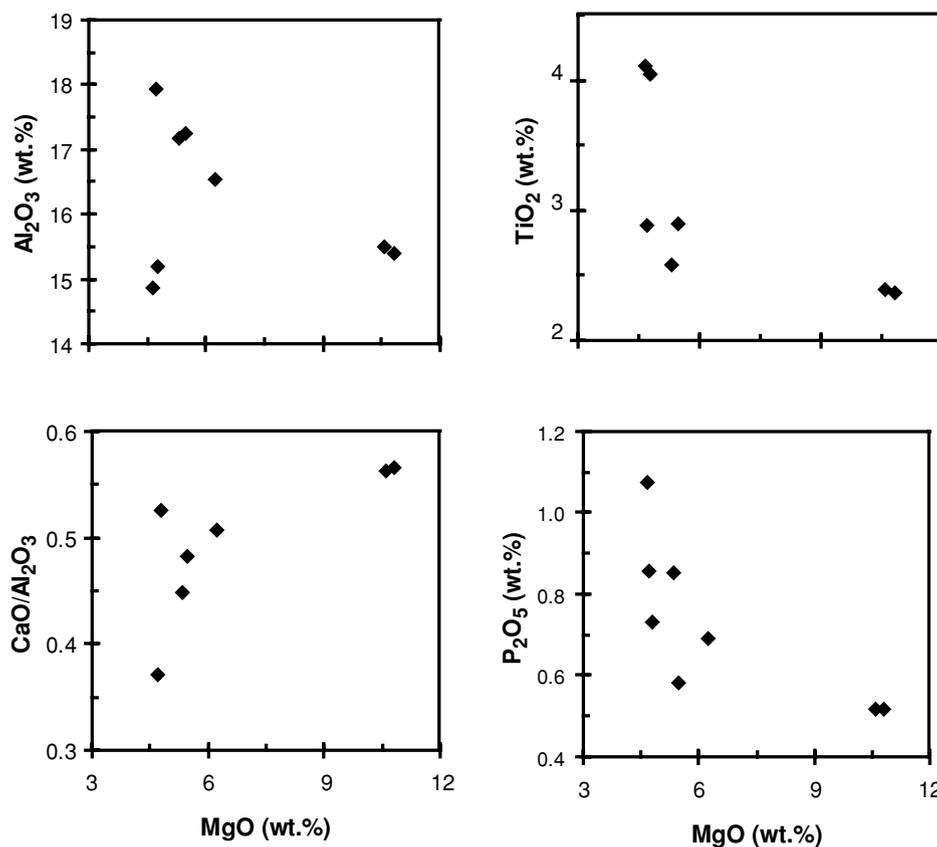


Fig. 3. Bivariate major element plots for Tepi basalts (recalculated to 100%, volatile-free). Note Al_2O_3 show inflected trends, indicating the change in the fractionating phases.

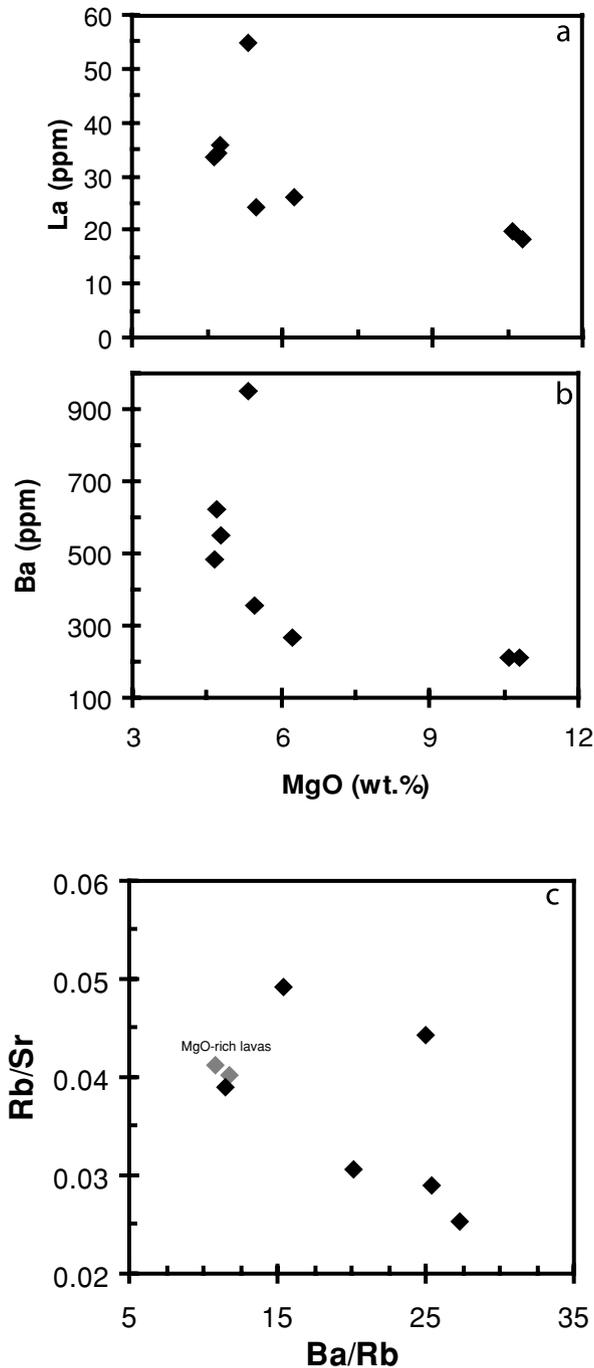


Fig. 4. Bivariate trace element plots for Tepi lavas, showing variations of some incompatible trace elements.

dence for the state of the mantle source. Variations of Sr isotopes against other chemical indices (e.g., MgO and SiO₂, Fig. 6) are less strongly indicative of contamination (there are no clear co-variations), but still suggest involvement of crust.

DISCUSSION

As discussed in the previous section the major and trace element variations observed in the Tepi lavas confirm the importance of fractionation in the evolution of the rocks. This section focuses on the role of contamination in crustal chambers and then address the issues of source phenomenon or process.

Lithospheric source region v. Crustal contamination

Before discussing the source of the Tepi lavas, it is important to find evidence for or against crustal interaction. In this regard the use of Ce/Pb ratios are particularly useful because the range of mantle values is well known (Hofmann *et al.*, 1986). Figure 7 shows Ce/Pb plotted against MgO. It is clear that only two of the samples fall within the “mantle array” of Hofmann *et al.* (25 ± 5), but the rest of the samples plots in the field of crustal/lithospheric values, which give a strong indication of lithospheric source material for mafic magmatism or alternatively crustal contamination of mantle-derived liquids. Then some strong case must be made for being able to distinguish lithosphere from crust. The evidence below is suggestive of crustal contamination.

The two most MgO-rich lavas plot at lower Ce/Pb values, so while they are indeed quite primitive it is not immediately apparent that they represent liquids derived directly from the lithosphere or sublithospheric sources. Crust indeed will have low Ce/Pb values but lithosphere may be higher. In the plot of ⁸⁷Sr/⁸⁶Sr against Ce/Pb (Fig. 7 inset), there is a clear linear trend that indicates samples with high ⁸⁷Sr/⁸⁶Sr values have low Ce/Pb values. This indicator points towards crustal involvement, albeit at a minor level (i.e., the high Sr values are still much lower than those observed among modern lavas erupted along the Main Ethiopian Rift). Variations of Sr isotopes against other chemical indices (MgO, SiO₂, Fig. 6) are less strongly indicative of contamination, but still suggest involvement of crust rather than lithosphere.

Mantle source composition

Given the degree of crystallization that must have occurred to get to ~5 wt.% MgO, the two MgO-rich samples are the only ones that are appropriate for evaluating a source composition. Although the two high-MgO samples were not analysed for their isotopic composition, issues of source composition are addressed more thoroughly using the trace element data.

The two mafic samples do not show positive Ba anomaly. The presence of positive Ba anomalies in the evolved lavas calls for the effects of fractionation. The primitive samples have elevated Ti/Eu values (6373–6985), suggesting that the MgO-rich rocks do not require carbonatite metasomatism. Melts derived from carbonatite metasomatised lithospheric mantle are inferred to have

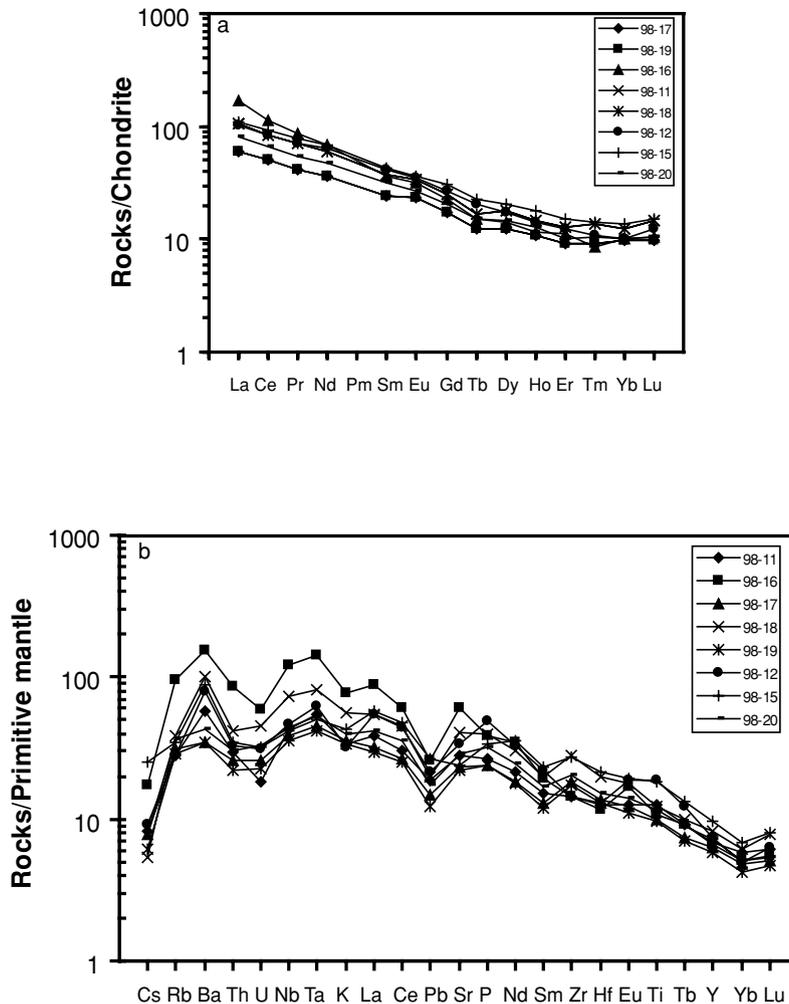


Fig. 5. Multi-element plots for Tepi lavas: (a) rare earth elements normalized to chondritic meteorites (Nakamura, 1974). The MREE-HREE contents do not look compelling for garnet. (b) Incompatible trace elements normalized to primitive mantle (McDonough and Sun, 1995).

Table 3. Sr and Nd isotopic compositions of Tepi lavas

Sample	98-15	98-12	98-16	98-18
$^{87}\text{Sr}/^{86}\text{Sr}$	0.703966 ± 77	0.703510 ± 12	0.703127 ± 48	0.703242 ± 48
$^{143}\text{Nd}/^{144}\text{Nd}$		0.512802 ± 28	0.512838 ± 13	

Details of Sr-Nd analytical procedures have been described by Ayalew *et al.* (2002).

high Zr/Hf, Nb/La and La/Yb ratios and low Ti/Eu (e.g., Nelson *et al.*, 1988). Plot of La/Nb-Ba/Nb (Fig. 8a) for the Tepi data, compared with those of southern Ethiopia (George and Rogers, 1999) and Turkana (Furman *et al.*, 2004) shows that the Tepi samples are indeed close to primitive mantle values, but some of the evolved rocks trend towards enriched mantle compositions (similar to the southern Ethiopia lavas).

REE profiles (e.g., La/Sm v. Sm/Yb) are particularly useful to distinguish melting between spinel and garnet peridotite (Lassiter and DePaolo, 1997). The two primitive samples plot close to the garnet-facies mantle melting curve (Fig. 8b). They have high La/Sm (4.03–4.05) and Sm/Yb (2.3–3.8) ratios, reflecting that they were generated through smaller degrees of partial melting of PM (primitive mantle).

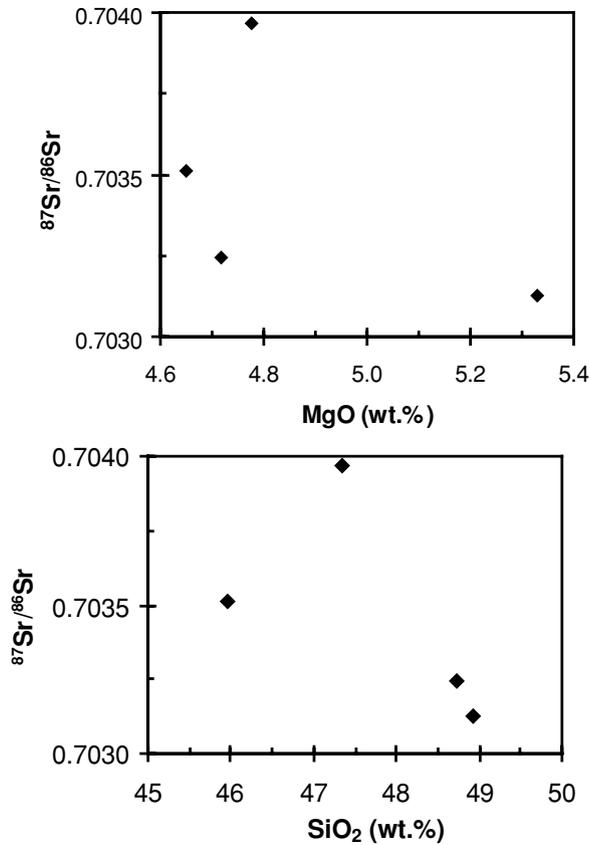


Fig. 6. Variations of Sr isotopes against other chemical indices (e.g., MgO and SiO_2) for the Tepi lavas. Note $^{87}\text{Sr}/^{86}\text{Sr}$ shows a broad negative correlation with MgO, respectively.

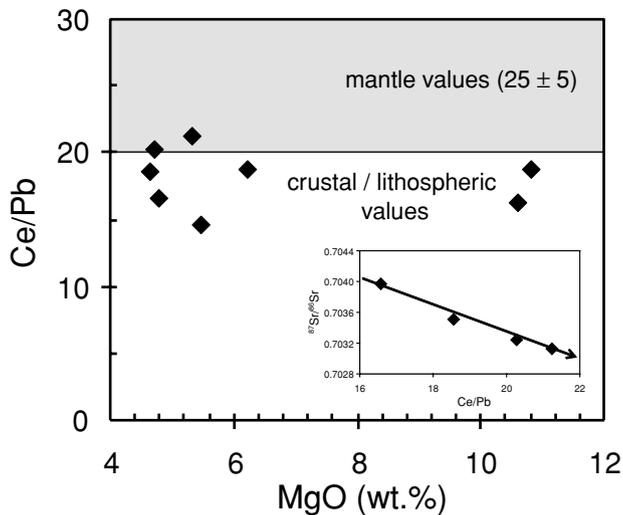


Fig. 7. Plot of Ce/Pb against MgO for the Tepi lavas, giving lithospheric/crustal values. Mantle compositional fields are after Hofmann et al. (1986).

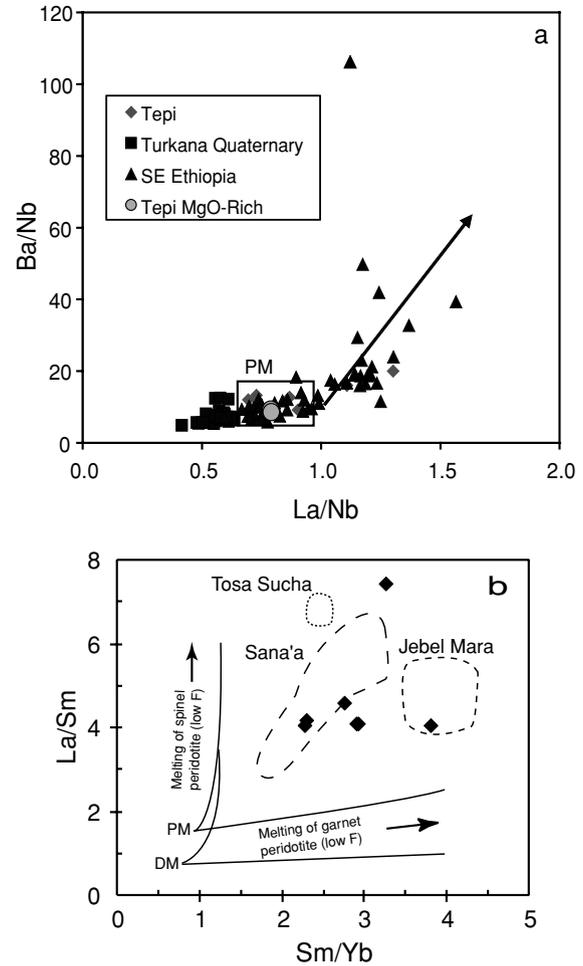


Fig. 8. Variations of Ba/Nb v. La/Nb (a) and La/Sm v. Sm/Yb (b) for the Tepi samples, compared with those of the southern Ethiopia (George and Rogers, 1999), Turkana (Furman et al., 2004), western Sudan (Davidson and Wilson, 1989) and western Yemen (Baker et al., 1997) lavas. Also shown fractional melting curves for a garnet and spinel lherzolite with primitive mantle (PM) and depleted mantle (DM) compositions (calculated after Baker et al., 1997; Lassiter and DePaola, 1997).

SUMMARY AND CONCLUSIONS

The largest issue is whether the Tepi melts are representative of an enriched mantle source or not. With possibly one or two exceptions, all the Tepi samples lie within the field expected of melts from primitive mantle sources in the presence of variable amounts of residual garnet. The Tosa Sucha volcanics lie at the extreme periphery of the field of primitive mantle melts (on Fig. 8b), because they have La/Sm ratios of 9–10 at Sm/Yb ratios of 2–3. This is consistent with their derivation from a more trace element-enriched source than primitive mantle. The fact that there is little evidence for source enrichment in the

Tepi rocks compared with the Tosa Sucha volcanics may imply that (i) the lithospheric mantle is clearly laterally heterogeneous (i.e., the lithosphere is indeed different between Tepi and Tosa Sucha), (ii) remobilisation of portions of the lithosphere enriched during Pan-African events which requires large-scale processes like those of the main Ethiopian rift and (iii) enriched, carbonatite metasomatism in east Africa may be restricted to the peripheries of the mantle plume where solidus temperatures may be lower.

The geochemical variations observed within the Tepi lavas are interpreted in terms of variable open system fractional crystallization of a magma sourced from primitive mantle like source.

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