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Geochemical and Sr-Nd isotope ratios in Cenozoic basalts from Eritrea: evidence for temporal evolution from low-Ti tholeiitic to high-Ti alkaline basalts in Afro-Arabian Continental Flood Basalt Province

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ABSTRACT. — Mid-Tertiary continental flood basalts covering large part of Eritrea, Ethiopia and Yemen comprise an igneous province linked to a mantle plume still active beneath Afar. In Eritrea, Oligocene-Miocene basalts on the Central and Southern Highlands unconformably overlie and partially cover a lateritised Palaeozoic-Mesozoic sedimentary strata or a basement of Neoproterozoic island-arc rocks. The Oligocene-Miocene basalts, respectively from Menguda and Ona/Durko sections, have been analysed for major and trace elements and Sr-Nd isotopic compositions; such data are the first for the Eritrean flood basalts.

The older products from Menguda section are fine to medium-grained, olivine-phyric low-Ti tholeiitic basalts. They are characterised by relatively high MgO, compatible element contents and high CaO/Al_2O_3 ratios, and by low Fe, P, K and incompatible element contents. REE profiles are flat at near ten times chondritic values. No intercalated silicic volcanics are found. The younger basalts from Ona and Durko sections contain interbedded pyroclastic rocks up to 60 m total thickness. In contrast to the Menguda basalts, these younger lavas are high-Ti transitional to alkaline basalts. The temporal sequence in Eritrea is therefore from low-Ti tholeiitic basalts to high-Ti alkaline basalts. Furthermore, the younger basalts have relatively high Fe, P, K and incompatible element contents and low CaO/Al_2O_3 ratios.

$^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios in Menguda and Ona/Durko basalts show similar and restricted ranges, respectively 0.70331-0.70423 and 0.51280-0.51288 (εNd = +3.2 to +4.7), and 0.70341-0.70434 and 0.51284-0.51288 (εNd = +3.9 to +4.8). Correlation of Sr isotope ratios with MgO used as index of fractionation indicates that the rocks underwent crustal contamination. Moreover, the earlier magmas (low-Ti tholeiitic basalts) were derived from a higher degree of partial melting of an incorporated depleted component in the Afar plume. Whereas, the later magmas (high-Ti alkaline basalts) were derived from a lower degree of melting of the plume itself.

RIASSUNTO. — I basalti continentali del Terziario medio che coprono parte dell'Eritrea, Etiopia e Yemen, configurano una provincia magmatica correlabile ad un *plume* di mantello ancora attivo in corrispondenza dell'Afar. In Eritrea i basalti oligo-miocenici che affiorano negli altopiani centrali e meridionali si sovrappongono in modo discordante e coprono parzialmente livelli sedimentari di materiale lateritizzato di età paleozoica-mesozoica, oppure, alternativamente, un basamento di età neo-proterozoica riferibile ad un'attività di arco insulare. In questo lavoro vengono riportati, per la prima

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TABLE 1A – *Major and*

	Menguda Basalts													
Spl. No.	98MG01	98MG02	98MG03	98MG05	98MG06	98MG07	98MG08	98MG10	98MG11	98MG12	98MG14	98MG15	98MG16	98MG17
Major Elements (wt.%)														
SiO_2	47.05	46.40	45.19	46.27	46.29	45.93	45.82	46.13	45.70	46.79	47.00	46.68	46.52	47.01
TiO_2	0.78	0.81	0.77	1.05	0.88	0.85	1.12	0.76	0.71	0.78	0.95	1.04	0.97	0.89
Al_2O_3	16.25	16.22	14.92	15.76	15.95	15.72	14.61	15.14	14.27	14.75	15.73	15.81	15.99	16.41
Fe_2O_3	9.97	10.11	10.61	10.53	10.16	10.21	11.01	9.93	10.22	10.30	10.43	10.26	10.25	10.03
MnO	0.14	0.18	0.17	0.17	0.16	0.16	0.16	0.15	0.17	0.16	0.16	0.16	0.16	0.15
MgO	9.00	8.92	12.72	9.10	9.89	10.56	11.11	11.51	14.04	12.03	8.93	9.14	8.82	9.28
CaO	10.57	10.47	10.14	11.01	10.73	10.74	9.38	10.19	9.39	9.87	10.80	11.07	11.16	11.00
Na_2O	2.18	2.24	1.82	2.29	2.43	2.13	2.49	2.07	1.87	2.19	2.10	2.07	2.27	2.14
K_2O	0.18	0.14	0.25	0.20	0.20	0.17	0.55	0.34	0.25	0.33	0.27	0.22	0.22	0.20
P_2O_5	0.08	0.08	0.10	0.16	0.10	0.10	0.14	0.09	0.09	0.08	0.11	0.16	0.13	0.12
LOI	3.66	4.38	3.06	3.06	2.68	3.22	3.30	3.17	3.17	2.57	3.25	3.09	3.03	1.99
Total	99.94	100.03	99.90	99.67	99.56	99.89	99.80	99.62	100.05	100.00	99.80	99.79	99.60	99.31
Mg#	0.67	0.66	0.73	0.66	0.68	0.69	0.69	0.72	0.75	0.72	0.65	0.66	0.65	0.67
CaO/Al_2O_3	0.65	0.65	0.68	0.70	0.67	0.68	0.64	0.67	0.66	0.67	0.69	0.70	0.70	0.67
Trace Elements (ppm)														
Sc	28	27	31	33	31	29	26	33	28	29	30	32	33	31
V	186	173	189	208	192	180	187	184	162	182	195	193	191	192
Cr	394	356	718	437	404	491	538	541	710	699	409	400	377	393
Co	52	50	59	45	51	50	54	51	59	57	44	45	45	46
Ni	175	189	376	125	188	266	314	307	394	310	143	134	117	132
Cu	33	64	42	56	35	77	70	61	68	53	58	52	39	29
Zn	71	70	71	73	64	67	78	66	65	71	74	67	68	68
Ga	16	16	15	18	17	15	16	15	15	15	16	15	19	1
Rb	3	2	4	2	3	2	11	7	4	7	5	3	3	[illegible]
Sr	174	174	252	226	280	239	244	206	186	200	224	302	225	22
Y	19	20	18	22	17	17	20	18	18	20	22	20	22	2
Zr	58	60	53	72	52	49	92	63	62	68	76	66	68	6
Nb	4	3	2	4	3	3	4	3	2	3	4	3	3	[illegible]
Ba	62	61	101	122	111	93	131	133	98	136	92	99	105	8
Isotope Ratios														
$^{87}Sr/^{86}Sr$			0.70342			0.70331			0.70423		0.70376			0.7035
$^{143}Nd/^{144}Nd$						0.51284			0.51280		0.51288			0.5128
ε_{Nd}						3.95			3.16		4.68			4.2

trace element data (XRF)

	Ona Basalts								Durko basalts						
98MG18	ONA01/98	ONA02/98	ONA03/98	ONA04/98	ONA05/98	ONA06/98	ONA07/98	ONA08/98	DK03/99	DK04A/99	DK04B/99	DK06B/99	DK06C/99	DK08A/99	DK09/99
45.14	46.04	45.63	46.91	46.02	46.10	44.05	46.85	45.74	47.78	45.21	45.66	45.99	45.96	46.93	48.74
1.38	1.61	0.89	1.12	2.29	1.73	1.38	1.02	1.56	3.57	2.66	2.58	2.03	2.02	1.73	3.56
15.61	15.49	15.06	15.61	16.02	15.96	14.15	14.64	14.97	13.77	16.48	16.42	16.76	16.65	14.48	14.07
11.66	11.62	10.59	10.39	13.45	12.13	11.94	10.63	11.96	13.72	13.89	15.03	13.02	12.92	10.27	13.60
0.18	0.16	0.17	0.17	0.19	0.16	0.17	0.16	0.18	0.21	0.18	0.20	0.18	0.18	0.20	0.20
9.54	10.24	12.46	9.59	6.67	6.50	11.61	10.75	9.33	5.10	5.71	5.97	7.40	7.35	7.92	5.21
10.28	9.47	9.25	10.36	9.13	10.24	9.01	9.27	8.73	8.98	7.80	8.34	9.21	9.31	10.29	8.96
2.46	2.54	1.83	2.28	2.98	2.44	2.03	1.99	2.70	2.97	3.35	3.47	2.94	2.89	2.07	2.88
0.27	0.41	0.18	0.27	0.58	0.41	0.36	0.35	0.40	0.99	0.48	0.57	0.42	0.55	1.11	1.03
0.16	0.25	0.10	0.13	0.35	0.27	0.15	0.13	0.19	0.69	0.36	0.35	0.26	0.26	0.32	0.70
2.83	2.10	4.54	3.27	1.67	4.51	4.30	4.30	4.54	1.04	2.96	0.64	1.32	1.22	4.86	0.24
99.61	99.93	100.70	100.10	99.34	100.44	99.15	100.08	100.29	98.81	99.08	99.22	99.52	99.31	100.17	99.19
0.64	0.66	0.72	0.67	0.52	0.54	0.68	0.69	0.63	0.45	0.48	0.47	0.56	0.56	0.63	0.46
0.66	0.61	0.61	0.66	0.57	0.64	0.64	0.63	0.58	0.65	0.47	0.51	0.55	0.56	0.71	0.64
32															
187															
382	425	572	368	80	256	506	453	349	77	52	47	98	96	133	78
48	64	94	89	59	65	89	67	77	47	61	43	53	55	79	54
174	257	330	195	59	171	334	264	160	28	47	45	78	78	63	27
64	55	35	41	35	61	38	37	30	18	32	26	29	29	25	18
75	65	71	66	75	76	80	78	76	115	53	90	76	77	72	122
19															
5	28	25	26	28	27	28	27	28	35	28	28	27	30	34	34
293	218	134	153	195	175	314	156	202	331	297	565	494	291	397	334
22	17	16	18	23	20	16	17	17	21	19	21	19	19	17	21
90	92	41	51	102	83	90	59	79	126	139	142	132	108	125	126
4	17	10	11	19	15	11	11	10	26	24	18	18	17	29	26
89	208	211	243	264	308	190	345	266	682	256	262	249	248	2235	664
		0.70341					0.70364		0.70433						0.70434
		0.51287					0.51284		0.51287						0.51288
		4.51					3.90		4.44						4.80

TABLE 1B

Trace element data (ICPMS)

	Menguda							Ona	Durko
Spl. No.	98MG01	98MG03	98MG07	98MG11	98MG14	98MG16	98MG17	ONA02/98	DK09/99
La	2.41	2.22	2.00	3.21	3.75	3.23	3.13	2.62	24.24
Ce	6.56	6.16	5.54	7.89	9.83	8.64	8.47	7.93	55.14
Pr	1.11	1.08	0.95	1.22	1.59	1.40	1.41	1.29	7.92
Nd	5.93	5.90	5.23	6.13	8.40	7.44	7.53	6.82	35.21
Sm	1.93	1.93	1.69	1.81	2.62	2.33	2.38	2.12	8.41
Eu	0.78	0.80	0.75	0.69	0.99	0.93	0.98	0.88	3.00
Gd	2.02	2.06	1.85	1.86	2.79	2.42	2.51	2.76	8.17
Tb	0.42	0.43	0.39	0.38	0.56	0.50	0.51	0.99	1.20
Dy	2.84	3.00	2.65	2.52	3.74	3.28	3.41	3.25	6.64
Ho	0.64	0.66	0.59	0.57	0.82	0.71	0.75	0.69	1.24
Er	1.71	1.83	1.56	1.51	2.12	1.88	1.96	2.07	3.46
Tm	0.24	0.25	0.22	0.22	0.30	0.25	0.27	0.28	0.41
Yb	1.70	1.83	1.59	1.55	2.05	1.82	1.90	1.98	2.67
Lu	0.25	0.27	0.23	0.23	0.30	0.26	0.27	0.32	0.40
Hf	1.39	1.29	1.13	1.38	1.95	1.61	1.54		
Pb	0.29	0.18	0.23	1.08	0.59	0.37	0.39		
Th	0.19	0.13	0.17	0.53	0.34	0.20	0.18		
U	0.02		0.02	0.15	0.05	0.03	0.02		

Dating of basal flows in Eritrea using the Ar-Ar method has yielded apparent ages close to 30 Ma (Drury *et al.* 1994). These ages are consistent with values obtained from basal flows in Northern Ethiopia and Yemen (Baker *et al.* 1996a; Hofmann *et al.* 1997; Ukstins *et al.* 2002; Coulié *et al.* 2003). Low-Ti tholeiitic basalts from Tekera section (~10 km west of Menguda basalts) yielded whole-rock plateau Ar-Ar ages of ca 32 Ma (Teklay *et al.*, 2003). Furthermore, recently Kieffer *et al.* (2004) reported that the low-Ti tholeiitic basalts in Ethiopia have relatively wider distribution than proposed by Pik *et al.* (1998, 1999) and wherever they outcrop they give ages very close to 30 Ma.

In the Southern Eritrean highlands, sections at Ona and Durko expose fine-grained basalts that pertain to the Adi Ugri basalts (Zanettin *et al.* 1999). The Ona and Durko flows are thicker than those at Menguda, and form a trap geomorphology. A further contrast comes from the presence of interbedded pyroclastic rocks that can attain some 60 m thickness, including a thin lignite layer. At Ona the basalts rest upon lateritised Precambrian rocks, whereas at Durko lateritised Mesozoic sandstones locally intervene. At both Ona and Durko the basalts are composed of fine-grained plagioclase, clinopyroxene and opaques, with porphyritic texture sometimes developed with phenocrysts of plagioclase (±olivine). Sub-ophitic, intergranular, and pilotaxitic textures are developed. Zanettin *et al.* (1999) consider the Adi Ugri basalts to be younger than the Asmara basalts. Clay deposits that include thin layers of lignite interbedded with the Adi Ugri basalts contain a Deinotherium tooth (Vialli, 1966) that suggests a Lower Miocene age (< 24 Ma) for the Adi Ugri basalts (Zanettin *et al.*, 1999) Although the stratigraphic relationship between the Menguda and Ona/Durko basalts is not yet proven by the present authors, recent mapping of a >400-m lava section in the Central Highlands finds pyroclastic rocks interbedded with the upper flows (Teklay *et al.* 2002), which may be correlated with the pyroclastic rocks in the Ona/Durko successions. Accordingly, the alkaline Upper Basalt flows of Tekera section are correlatable with the Ona and

Durko basalts. Whole-rock Ar-Ar age of ca. 20 Ma (Teklay *et al.*, 2003) for the Upper Basalt flows of Tekera gave a Lower Miocene age for the Ona and Durko basalts that is in agreement with the age range for the Deinotherium tooth.

ANALYTICAL PROCEDURES

Major and trace elements on flood basalts from the Menguda section (15 samples) and Ona/Durko sections (15 samples) were analyzed by standard X-Ray fluorescence spectrometry using routine techniques of the analytical facility of the Department of Geosciences, University of Mainz and Earth and Planetary Sciences Department, University of New Mexico, respectively. Rare earth elements of representative Menguda basalts were analyzed at the Centre de Geochemie de la Surface (CNRS) and Ona/Durko basalts at the University of Minnesota using an inductively coupled plasma mass spectrometer (ICP-MS; Fison VG Isoplasma). Replicate analyses from samples and standards such as BEN-1 indicate that the accuracy of the rare earth and trace element determinations are ≤ the 5% level. The analytical data are presented in Table 1.

The isotopic compositions of Nd and Sr were determined on a Micromass Sector 54 at the Department of Earth and Planetary Sciences, University of New Mexico, USA. Nd and Sr measurements were normalized to $^{146}Nd/^{144}Nd = 0.7219$ and $^{88}Sr/^{86}Sr = 0.1194$, respectively. La Jolla Nd and NBS-987 Sr standards were measured during the course of this study, obtaining $^{143}Nd/^{144}Nd$ ratio of 0.511853±8 (2-σ, N = 8) and $^{87}Sr/^{86}Sr$ ratio of 0.710292±6 (2-σ, N = 3), respectively. Nd and Sr procedural blanks are in the range of 20 pg resulting in negligible blank corrections.

MAJOR AND TRACE ELEMENTS COMPOSITIONS

Fifteen flood basalt samples from the Menguda and fifteen from the Ona/Durko regions were analysed (Table 1). On a total alkali-silica (TAS) diagram, all thirty samples plot in the basalt field, between 44 and 49% SiO_2 (Fig. 2). As with

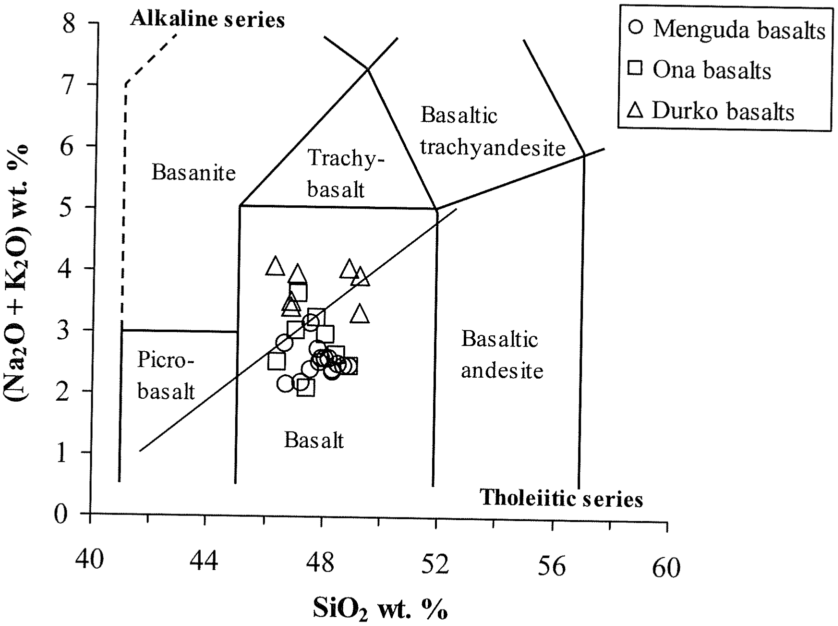

Fig. 2 – TAS classification of the flood basalts. Line between subalkaline and alkaline after MacDonald and Katsura (1964).

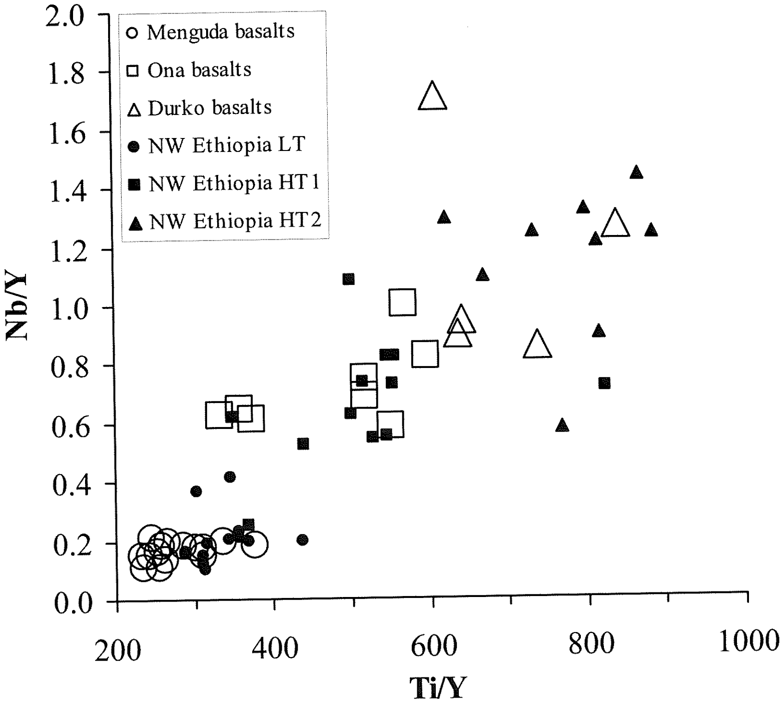

Fig. 3 – Ti/Y vs. Nb/Y diagram. LT (low-Ti), HT1 (high-Ti 1) and HT2 (high-Ti 2) of Northwestern Ethiopia CFB from Pik *et al.* (1998).

Oligocene basalts from neighboring Ethiopia and Yemen (Pik *et al.* 1998; Baker *et al.* 1996b), the Eritrean samples straddle the subalkaline-alkaline divide, confirming a transitional character. All are olivine-hypersthene normative, excepting two samples. The Menguda basalts show tholeiitic tendencies relative to a more alkaline character for the Ona/Durko basalts (Fig. 2). Pik *et al.* (1998) have classified the northwestern Ethiopian plateau basalts have been classified into low-Ti (LT), high-Ti 1 (HT1) and high-Ti (HT2) based on the HFS elements (TI, Y, Nb). On Ti/Y vs. Nb/Y diagram (Fig. 3) the Menguda, Ona and Durko basalts show similarity to the LT, HT1 and HT2 respectively.

Olivine-phyric Menguda basalts have high MgO (8.82-14.04%), Cr (356-718 ppm) and Ni (117-394 ppm). Although, some samples (e.g. 98MG011) are highly porphyritic and may contain cumulus olivine to explain their high MgO content, the magnesium number values are generally high (64 - 75), indicating that most of the analyzed samples are in equilibrium with mantle olivine (Fo$_{92}$). A clear decrease in Cr and Ni abundances with MgO (Table 1) is considered to express the importance of fractional crystallization of olivine, in agreement with the petrographic observation. This is further confirmed by progressive increases in CaO and Al$_2$O$_3$, whilst relatively constant SiO$_2$ indicates that pyroxene and plagioclase fractionation was not significant (Fig. 4 and Table 1). Likewise, the increase in TiO$_2$ with constant FeO* and V constrain titanomagnetite to a minor role as a fractionating phase (Fig. 4 and Table 1).

Furthermore, Menguda basalts have low TiO$_2$ (0.71-1.38%), P$_2$O$_5$ (0.08-0.16 %), K$_2$O (0.14-0.55%) and incompatible elements (e.g. Nb 2-4 ppm, Zr 49-92 ppm, Rb 2-11 ppm) (Figs. 4 and 5). Rare-earth element (REE) profiles are flat at 10x chondrite values, with normalised Ce/Yb ranging from 0.87 to 1.32 (Fig. 6a). The multi-element patterns, when compared with those of primitive mantle, show enrichment of large-ion

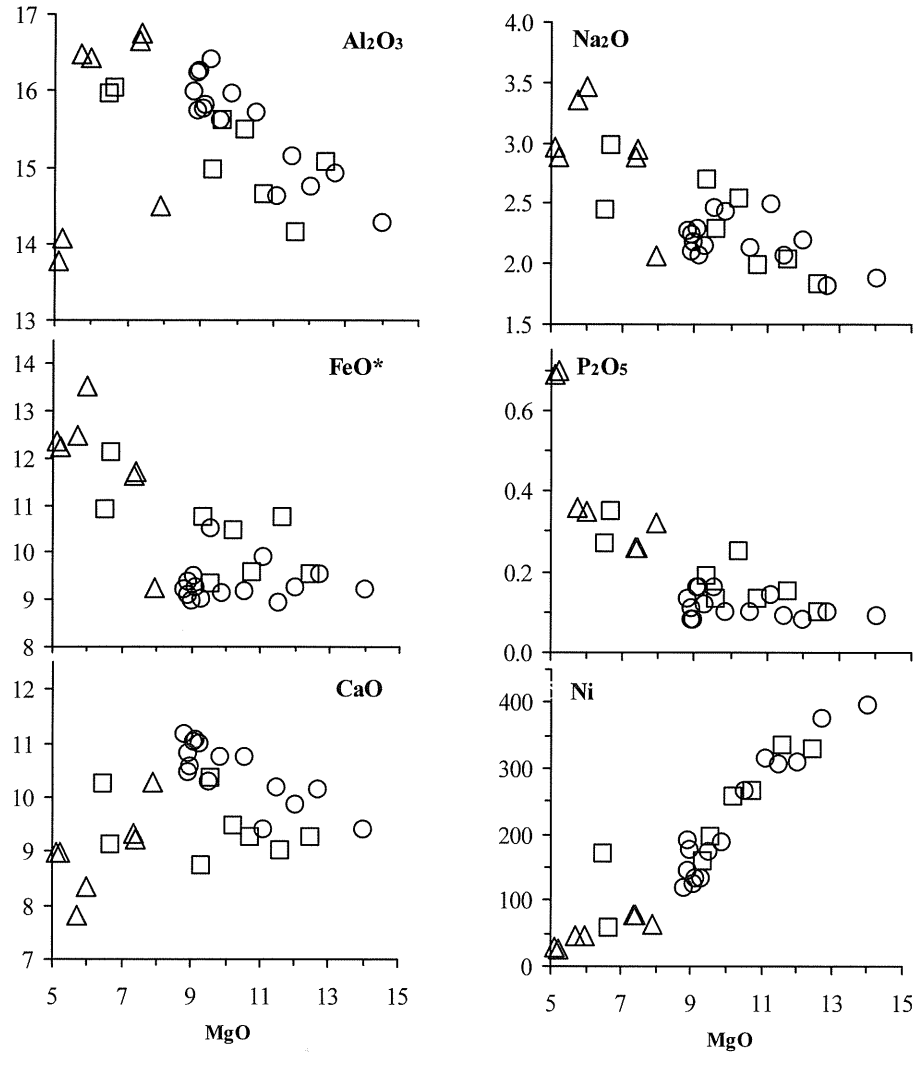

Fig. 4 – Variation diagrams of MgO vs. selected major and trace elements. Symbols as in Figure 2.

lithophile (LIL) elements with marked positive Ba anomalies, and depletions in high field strength (HFS) elements (Fig. 6a).

The basalts from Ona and Durko are, by contrast, more alkaline and relatively evolved rocks with lower magnesium number (45-72), particularly the basalts from Durko (Mg# = 45-63). These basalts are characterized by relatively high TiO_2 (0.89-3.57 %), P_2O_5 (0.10-0.70 %), FeO* (9.24-13.52 %), K_2O (0.18-1.11 %), HFS elements (e.g. Nb 10-29 ppm, Zr 41-142 ppm) and LIL elements (e.g. Rb 25-35 ppm, Ba 190-2235 ppm) (Figs. 4 and 5, Table 1). Unlike the Menguda basalts, Ona/Durko basalts do not show depletions in high field strength (HFS) elements (Fig. 6b).

As for the Menguda basalts, Cr and Ni abundances decrease with decrease in MgO, but to a greater degree that suggests a more extensive

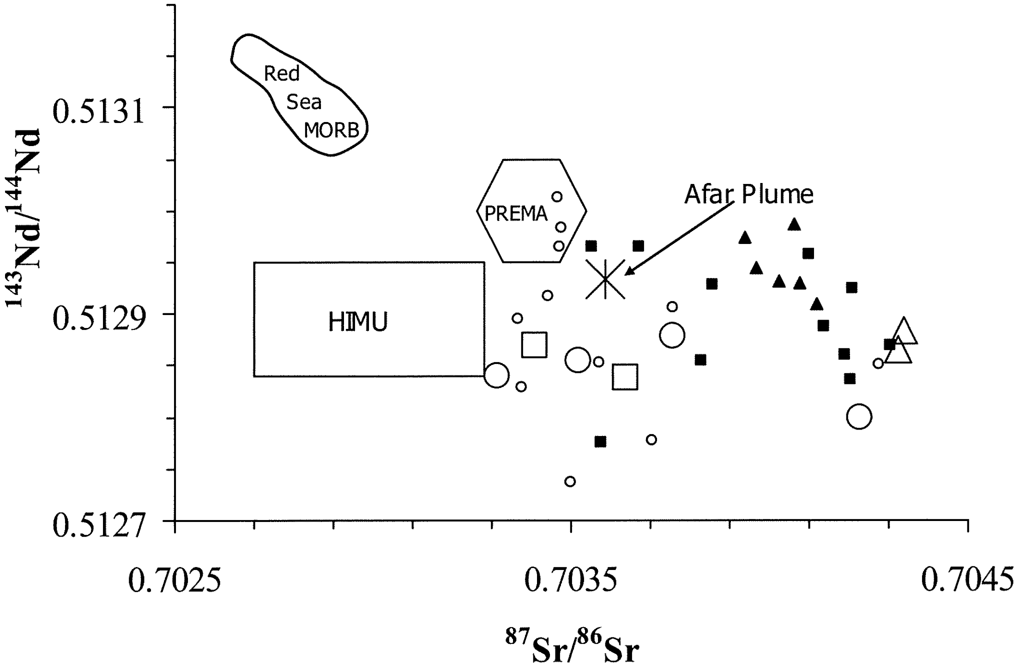

Fig. 7 – Sr-Nd isotopic composition of the flood basalts of Eritrea compared with the NW Ethiopian plateau basalts, Red Sea/Gulf of Aden MORB, the Afar plume and mantle components. Symbols as in Figure 3. Comparative data from: NW Ethiopian plateau basalts, Pik *et al.* (1999); Red Sea/Gulf of Aden MORB, Volker and McCulloch (1993); Afar plume, Baker *et al.* (2002); mantle components (HIMU, PREMA), Zindler and Hart (1986).

isotopic array with relatively constant ^{143}Nd/^{144}Nd ratios (Fig. 7). Although all Eritrean basalts have similar ^{143}Nd/^{144}Nd ratios, there is a systematic variation of ^{87}Sr/^{86}Sr with degree of fractionation indicative of progressive crustal contamination (Fig. 8).

DISCUSSION

Tholeiitic low-Ti basalts on the Central Eritrean Highlands were erupted before transitional to alkaline high-Ti basalts on the southern highlands (see also Zanettin *et al.* 1999). This requires modification of Pik *et al.*'s (1998) distribution map of low-Ti and high-Ti basalts on the NW Ethiopian plateau. Higher degrees of partial melting (and/or shallower melting depth) for the Menguda tholeiitic basalts is implied, from low FeO* and incompatible element contents and high CaO/Al$_2$O$_3$, than for the Ona/Durko alkaline basalts. Thus melting deepened and became less voluminous with time under the Oligocene Eritrean plateau.

All analysed basalts carry the chemical signature of crustal contamination, exemplified in higher Ba/Nb and Ba/La ratios than in primitive mantle melts. However, Menguda basalts, despite sharing similar Sr-Nd isotopic compositions with the Ona/Durko basalts, have relatively low abundances of incompatible elements and different ratios of some elements of a similar degree of incompatibility (e.g. Rb/Ba vs. Nb/K, Fig. 9). Fractional crystallization and/or degree of melting cannot explain these ratio differences, as incompatible element ratios theoretically do not change greatly during either process. Nor can the ratios be explained in terms of differing degrees of crustal contamination, as they do not relate to Sr and Nd isotopic ratios. Hence, the Menguda basalt magmas must have been derived from a relatively incompatible element-

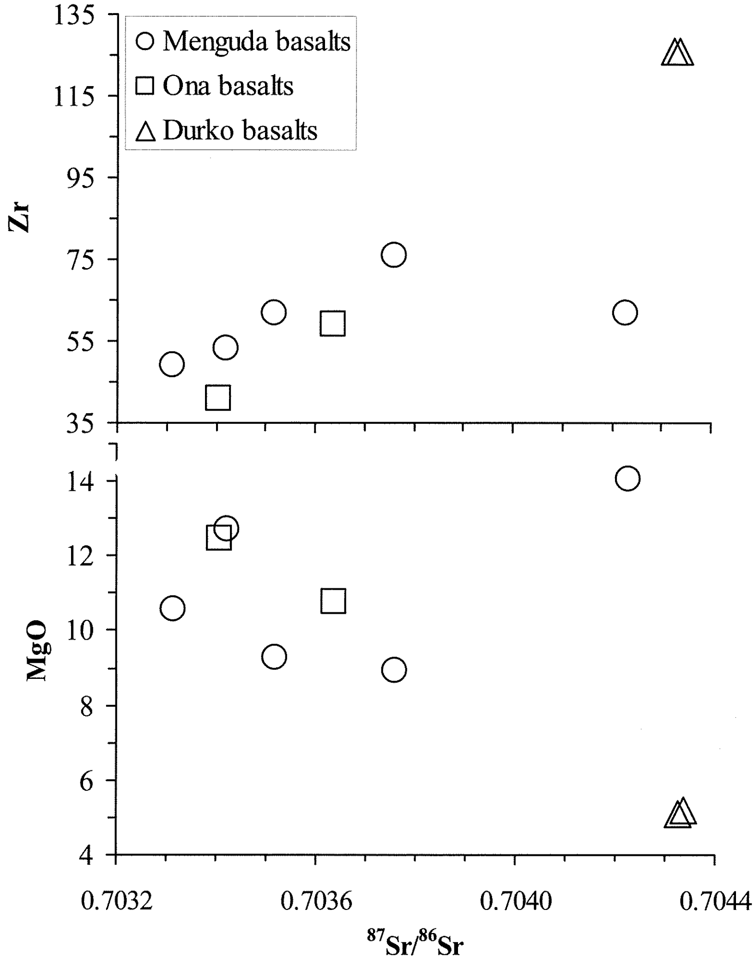

Fig. 8 – $^{87}Sr/^{86}Sr$ variations with fractionation indices (MgO, Zr).

depleted source compared with the sources for the Ona/Durko basalt magmas.

A recycled and strongly depleted oceanic crustal component in the Afar plume has been identified from a previous geochemical study of Eritrean flood basalts (Teklay *et al.* 2002). It can now be suggested that the Menguda basalts, representing the earliest volcanism in Eritrea, resulted from an interaction of magmas derived from depleted Afar-plume mantle with the continental crust. The Ona/Durko basalts resulted from an interaction of an enriched component of the Afar plume - as for the HT2 basalts of NW Ethiopia (Pik *et al.* 1999) - with continental crust and/or the depleted component of the Afar plume.

All the basalts show higher LIL/HFS and LIL/LREE ratios than MORB and OIB suggesting an interaction with continental crust and/or enriched Pan-African lithospheric mantle.

CONCLUSIONS

The earlier lavas on the Eritrean Central Highlands are low-Ti tholeiitic basalts, while later lavas on the Southern Highlands are high-

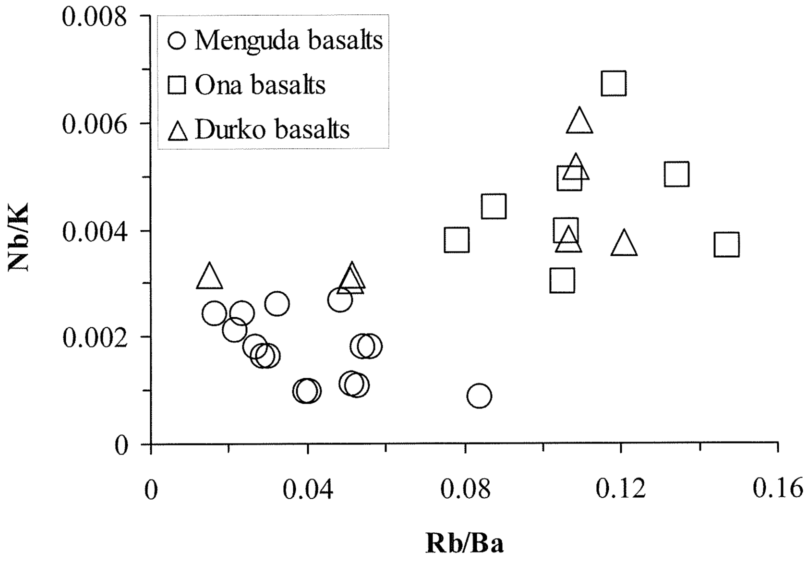

Fig. 9 – Variations of highly incompatible trace elements ratios in Menguda and Ona/Durko basalts.

Ti transitional to alkaline basalts. The magmatic plumbing system evolved from one with higher degrees of partial melting, possibly at shallower depths, to one with a lesser degree of melting, possibly at increased depths, the change accompanied by a shift southward. Isotopic data indicate the effects of crustal contamination in all the basalts analysed.

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