SINET: Ethiop. J. Sci., 20(1):49–72, 1997
© Faculty of Science, Addis Ababa University, 1997 **ISSN: 0379–2897**

MAGMA-CRUST INTERACTION DURING EMPLACEMENT OF CENOZOIC VOLCANISM IN ETHIOPIA: GEOCHEMICAL EVIDENCE FROM SHENO-MEGEZEZ AREA CENTRAL ETHIOPIA

Gezahegn Yirgu

Department of Geology and Geophysics, Addis Ababa University
PO Box 1176 Addis Ababa, Ethiopia

ABSTRACT: The Ethiopian Cenozoic volcanic province constitutes a thick succession dominated by fissural basalts and subordinate silicic products spread over an area measuring several hundred thousand square kilometres. Major and trace element analyses are presented for a suite of basic to acid rocks from sections around Sheno-Megezez area, north-east of Addis Ababa. The analyzed basic rocks belong to the plateau-forming Aiba Formation, sampled near Sheno village, and the shield-forming Termaber Formation, sampled at Megezez mountain. The silicic samples, stratigraphically found between the two basaltic formations, represent the Alaji Rhyolite Formation. The basalts exhibit variable degrees of evolution and are generally transitional between tholeiitic and alkaline. They display comparable major element compositions but show significant internal variations in some incompatible element ratios such as Rb/Nb and Rb/Ba. The data presented in this work is best interpreted in terms of magmatic processes involving combined fractional crystallization (FC) and interaction with a component of acid composition (AFC). The acidic products appear to be derived from parental basaltic magmas by fractional crystallization. The component of acid composition interacting with mantle-derived basaltic magmas could derive either from rhyolitic melt generated by FC or from material of crustal origin. It, therefore, appears that mantle-derived magmas could have undergone important geochemical modifications at intracrustal levels. This observation, together with similar findings from other regions in the Ethiopian volcanic province, puts significant constraints on utilizing geochemical signatures of basalts to infer mantle source heterogeneity before critically evaluating the effects of crustal interaction.

Key words/phrases: Basalt, crust, Cenozoic, Ethiopia, geochemistry, fractional crystallization

INTRODUCTION

Continental flood basalt volcanism is often associated with rifting, as in the case of the Afar-Red Sea-Gulf of Aden area. Ideas on the origin of these basalts have developed rapidly during the last two decades.The erupted volcanics in these areas display compositional variations both in time and space, which are now believed to reflect largely the involvement of different mantle sources beneath the regions of magmatic activity (e.g., Hart *et al.*, 1989, Deniel *et al.*, 1994). However, a number of other authors argue that some of the geochemical variations in the mafic magmas may be the result of low-pressure evolutionary processes not directly related to source heterogeneity (Cox and Hawkesworth, 1988; Huppert and Sparks, 1985; Devey and Cox, 1987). It is, therefore, necessary that the role of evolutionary processes in modifying magma compositions be assessed before inferring the nature of the mantle source from basalt geochemistry. One of the possible processes that may impose modifications on mantle-derived magmas is crustal contamination as magmas make their way through continental crust.

The Ethiopian Cenozoic volcanic province constitutes one of the largest intracontinetal magmatic provinces. It developed entirely during Cenozoic with emission of huge amounts of flood basalts and interbedded ignimbrites. The flood lava sequence is overlain, in part, by shield volcanoes of the so-called Termaber formation. The complex evolution of magmatism in space and time makes this region a favourable area to investigate the origin and evolution of large-volume volcanics. In this work new major and trace element data are presented on a suite of basic to acid volcanic rocks collected from the Ethiopian Central Plateau and a shiled volcano in the region of Debre-Berhan town. The aim of this study is to report new analytical data on the Cenozoic volcanics and investigate on possible processes responsible for the geochemical characteristics of the erupted magmas, with particular emphasis on the role of continental crust in the petrogenesis of the volcanics.

Geological setting

The Ethiopian volcanic province, which covers an area of greater than 600, 000 km^2, is dominated by up to 300,000 km^3 of generally fissure-fed basaltic lavas forming the volcanic plateaus that bound the Afar and Ethiopian Rifs (Mohr, 1983; Ebinger *et al.*, 1993). The volcanic products lie directly on metamorphic rocks of Precambrian age or on Mesozoic sedimentary sequence. A number of studies in this province have contributed to the understanding of the major tectonic and magmatic events and deep mantle processes responsible for them (Zanettin *et al.*, 1974; Merla *et al.*, 1979; Davidson, 1983; Mohr, 1983; Hart *et al.*, 1989, among others). These authors have provided valuable data on stratigraphy, radiometric ages and petrological and geochemical composition of the Ethiopian volcanics.

These studies have allowed to recognize two major phases of magmatic activity. A first phase was responsible for the eruption of lavas that built thick successions, up to nearly two kilometres, of fissural basalts (known as Ashange and Aiba Basaltic Formations) and later emplacement of a thick series, up to 500 meters, of silicic lavas mainly in the form of ignimbritic sheets (Alaji Rhyolitic Formation). This fissural magmatic stage was followed by the building up of huge shield-like volcanic complexes from central vents with the predominance of basalts over evolved volcanics (Termaber Basalt Formation). Earlier K/Ar radiometric age determinations reported by several authors in the Ethiopian Northern Plateau region (see Merla *et al.*, 1979; Mohr and Zanettin, 1988; for review) indicate an age of about 55 Ma for the emplacement of the oldest Ashange basalt flows, an age of 34 to 13 Ma for the Alaji Formation and an interval of 28 to 5 Ma for the Termaber Formation. These results are now being revised in light of much recent data from carefully studied sections using better and modern techniques. Preliminary age determinations, based on $^{40}Ar/^{39}Ar$ method, complemented by palaeomagnetic studies, indicate that the main fissural outpourings on the Ethiopian Central Plateau region occurred at about 30 Ma and were probably emplaced in a short time interval (Hoffman *et al.*, 1995).

A second phase of magmatic activity in the Ethiopian region was mainly located in the Afar depression and along the Main Ethiopian Rift, where it is active at present (Gibson, 1974; Di Paola, 1972; Barberi *et al.*, 1980). This activity is associated with the opening of the interconnected Red Sea- Afar- Gulf of Aden young oceanic rift system and the continental East African rift.

Sampling and petrography

The studied area is located about 80 km northeast of Addis Ababa, in the region of the town of Debre-Berhan, to the south and east of Sheno village (Fig. 1). The outcropping rocks in this area belong to the Aiba, Alaji and Termaber Formations, according to Merla *et al.* (1979). The plateau flood basalts of the Aiba formation have been sampled along the Inkoy river and Amari Wiha river gorges (tributaries of Kesem river), south of the town of Sheno. The samples of the Termaber formation have been collected from various localities on the Megezez shield volcano. The silicic rocks of the Alaji formation have been sampled both from the top of the plateau series (overlying Aiba basalts) and from the base of the Meghezez volcano (underlying the shield-forming basalts).

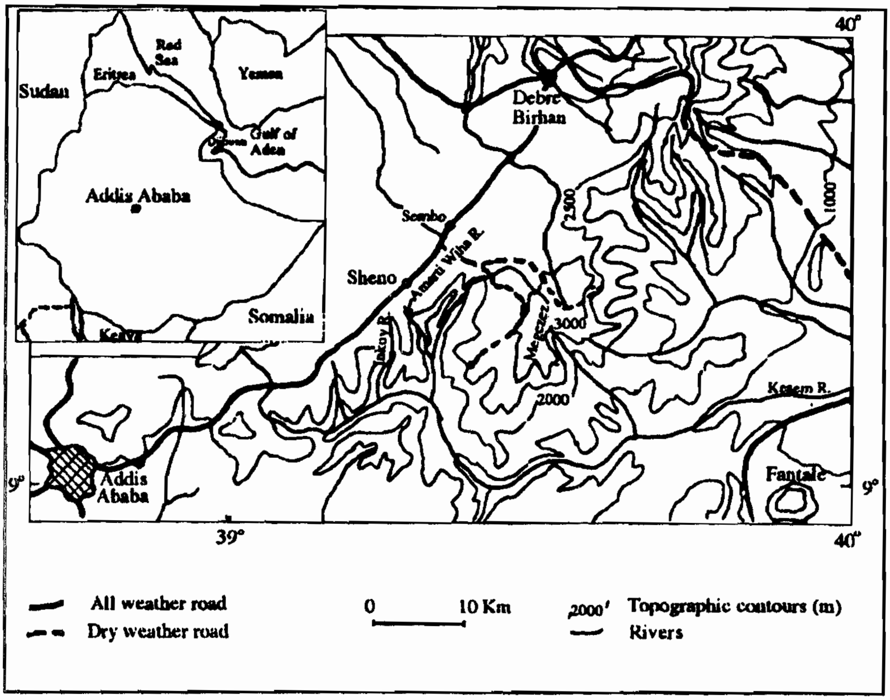

Fig. 1. Location map of the studied area.

The analyzed rocks range petrographically from basalt to rhyolite. Aiba samples from Sheno are all basaltic while those of Megezez consist of basalts and intermediate varieties. Basic and intermediate rocks are variably porphyritic with total phenocryst contents ranging from about 40% to less than 5% of the total rock volume. Plagioclase is invariably the main phenocrystal phase and is accompanied by minor clinopyroxene and, in a few cases, by scarce olivine and magnetite microphenocrysts. Aiba basalts are commonly aphyric and rarely porphyritic or glomero-porphyritic while those of Megezez are characterized by the presence of up to 5 mm large plagioclase phenocrysts and less common aphyric basalts. Plagioclase shows complex zoning and in some cases is strongly resorbed. Some phenocrysts show evidence of secondary transformation. Clinopyroxene is present in well preserved euhedral crystals. Olivine occurs as small altered crystals. The groundmasses of basalts and intermediate rocks are generally microphytic or intergranular and consist of the same mineral phases as the phenocrysts, with opaque minerals (Fe-Ti oxides) and some altered glass.

The Alaji acid rocks, found mainly in the form of ignimbritic sheets, are generally scarcely porphyritic with phenocrysts of sanidine, and quartz set in a cryptocrystalline groundmass. Rare alkali amphiboles, and aegerine-augite are sometimes present. Fe-Ti oxides commonly occur as microphenocrysts and in the groundmass. Phenocrysts are generally broken and strongly fractured. Sanidine is commonly euhedral while quartz is often resorbed with rounded margins and embayed edges. Groundmasses are devitrified and, in some cases, show phantoms of eutaxitic texture.

GEOCHEMISTRY

Analytical methods

Major and trace elements have been determined at the Institute of Earth Sciences, University of Messina, Italy. Major elements have been analyzed by combined wet chemical methods and X-ray fluorescence (XRF) procedures (Franzini *et al.*, 1972). The trace elements Cr, V, Ni, Co, Rb, Sr, Y, Nb, La, Ce, Ba and Zr have been analyzed by XRF on pressed powder pellets. Several international rock standards have been used for curve calibration. Precision is better than 10% for all the trace elements, except Rb and Sr which have precisions better than 5%. Some selected samples have been analyzed by Instrumental Neutron Activation Analysis (INAA) for the Rare Earth Elements (REE), Sc, Cr, Co, Th, U, Cs, Ta and Hf. Precision is better than 10% for most of these elements at the concentration level of the studied samples. The elements obtained by both INAA and XRF compare quite well, except for La, Ce and Co which show consistently higher values in XRF determinations.

Major and trace elements

Abundances of major and trace elements are reported in Table 1. The Total Alkali-Silica (TAS) classification diagram (Le Bas *et al.*, 1986) shows that the suite of rocks analyzed range in composition from basalt through trachyandesite to rhyolite (Fig. 2). Basaltic rocks dominate over the salic ones with only few samples of intermediate compositions. Such a distribution of volcanic rocks is not an artifact of sampling but reflect the relative volumes of erupted volcanics as observed in the field. Both the plateau and the Megezez basalts plot along the boundary separating the alkaline from the sub-alkaline series of Irvine and Baragar (1971) (Fig. 2 inset) and are best characterized as transitional basalts, following the nomenclature of Piccirillo *et al.* (1979) for Ethiopian volcanics. It is important to note here that the Termaber Basalt Formation has so far been regarded as an alkalic type in previous works on Ethiopian volcanics (Mohr and Zanettin, 1988). The present data confirm that the Termaber formation also contains transitional volcanics and, thus is more variable than previously thought.

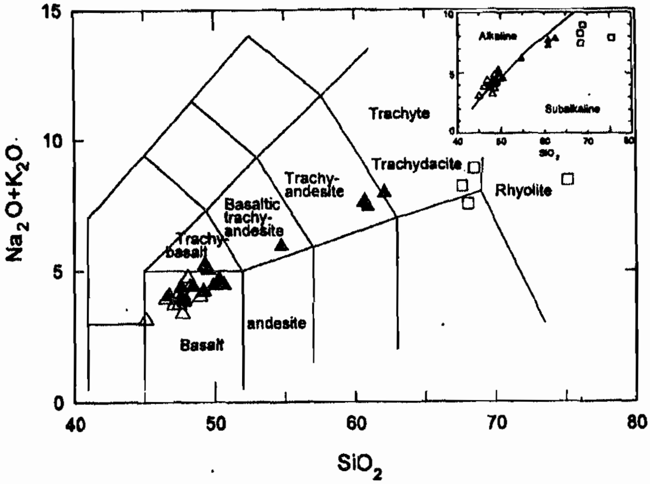

Fig. 2. TAS classification diagram (Le Bas *et al.*, 1986) for the analyzed volcanics (recalculated on hydrous basis). Δ, fissural plateau lavas; ▲, Megezez shield volcanics; □, Alaji silicics. Inset: Plot in the alkaline-sub-alkaline diagram of Iryine and Baragar (1971).

Variations of major elements as a function of SiO_2 wt% for the analyzed samples are shown in Fig. 3. The plateau basalts show a narrow range of silica contents but rather wide variations of some major elements, especially Na_2O, TiO_2, P_2O_5, and, to a less extent, Al_2O_3. The Megezez volcanics span a relatively wider compositional range of silica contents. The rocks from the Alaji formation are acid in composition and exhibit restricted variations. K_2O and Na_2O exhibit a regular increase with SiO_2 in the Megezez rocks, whereas MgO, CaO, FeO_{total} , Al_2O_3, P_2O_5 and TiO_2 decrease with increase in SiO_2 with some scattering in the basic samples. The Alaji acid rocks plot on the same trends as the Megezez suite, except for Na_2O, which is lower in the Alaji rocks than in the most evolved Megezez volcanics. Overall, the major element trends of the Megezez rocks mimic a liquid line of decent and are consistent with a fractional crystallization path of magma evolution. These variation trends correlate with the assemblage of minerals in the studied samples and suggest that these minerals significantly governed the compositional path of liquids during magmatic differentiation. On the contrary, the plateau lavas display marked elemental variations at a fairly constant silica content. These variations are not related to textural features of the rocks, such as the amounts of phenocrystal phases and must be considered as inherent to the composition of magmas.

Table 1. Major element (wt%) and trace element (ppm) data for the Sheno-Megezez volcanics. Asterisks indicate X-ray fluorescence trace element data. Other trace elements have been analyzed by INAA.

	SHENO SECTION (Aiba and Alaji forms)						
	M-G	TM-B	TM-J	TM-D	TM-I	TM-E	TM-K
SiO_2	45.13	46.55	47.11	47.35	47.50	47.70	47.74
TiO_2	2.43	2.62	4.14	2.48	4.19	2.63	2.48
Al_2O_3	16.87	15.58	14.54	17.32	14.49	17.06	17.62
Fe_2O_3	3.55	7.68	5.18	7.41	3.99	5.21	4.55
FeO	8.86	7.00	9.26	4.82	10.72	6.14	7.51
MnO	0.19	0.19	0.21	0.19	0.20	0.24	0.19
MgO	6.51	4.32	4.48	3.26	4.57	3.79	4.33
CaO	10.67	8.37	9.16	9.03	8.08	9.26	9.72
Na_2O	2.53	3.02	2.68	3.32	2.68	3.35	2.93
K_2O	0.60	0.88	0.99	0.69	1.02	0.71	0.43

Table 1. (Contd.)

	SHENO SECTION (Aiba and Alaji forms)						
	M-G	TM-B	TM-J	TM-D	TM-I	TM-E	TM-K
P_2O_5	0.75	0.53	0.55	0.65	0.49	0.69	0.54
LOI	2.01	3.25	1.07	3.31	1.31	2.67	1.96
Mg#	53.11	39.44	40.3	37.31	40.11	42.33	43.9
La*	11	14.8	31	11	28	10	13
Ce*	33	34	81	21	69	25	32
V*	307	334	407	290	422	293	293
Cr*	16	37	25	9	19	7	27
Co*	41	39	43	25	45	29	37
Ni*	31	18	34	12	31	13	19
Rb*	9	20	26	9	25	12	4
Sr*	580	390	470	491	468	503	480
Y*	28	46	55	34	51	36	41
Zr*	72	153	334	118	329	114	126
Nb*	11	12	44	11	41	12	10
Ba*	514	364	271	385	280	322	267
Th*	2.3	1.7	7	4.6	4.3	2.3	0.8
La		14					13
Ce		34					32
Nd		21					20
Sm		5.3					5
Eu		2.1					2
Tb		0.9					1
Yb		2.9					2.6
Lu		0.4					0.4
Cs		0.1					0.1
Th		0.9					0.8
U		0.1					0.1
Ta		0.8					0.6
Hf		4.4					3.5
Cr		37					27
Sc		35					32
Co							37

Table 1. (Contd.)

	M-AT	TM-F	TM-C	TM-M	TM-H	TM-L
SiO_2	47.84	47.91	48.12	48.26	48.98	75.05
TiO_2	2.27	2.52	2.76	2.79	3.67	0.29
Al_2O_3	17.81	16.06	18.13	17.77	15.28	10.92
Fe_2O_3	4.11	4.78	2.34	2.32	2.33	2.19
FeO	7.94	8.51	8.11	8.19	10.82	1.62
MnO	0.20	0.19	0.19	0.19	0.19	0.12
MgO	4.18	4.61	3.87	4.04	4.62	0.19
CaO	9.03	8.69	9.27	9.02	8.51	0.21
Na_2O	3.18	3.15	3.93	3.59	2.88	3.89
K_2O	0.66	0.78	0.81	0.80	1.13	4.51
P_2O_5	0.61	0.63	1.01	1.07	0.50	0.03
LOI	2.19	2.16	1.36	1.36	1.08	0.97
Mg#	42.96	43.01	44.28	47.32	42.86	9.99
La*	11	15	20	20	35.7	124
Ce*	21	32	51	42	77	213
V*	282	387	176	179	385	1
Cr*	25	31	4	5	11	0.5
Co*	32	40	23	25	44	2
Ni*	18	18	5	6	27	11
Rb*	9	8	14	13	29	115
Sr*	446	404	838	755	501	6
Y*	37	43	35	36	47	135
Zr*	119	143	122	124	296	1225
Nb*	10	13	22	20	38	128
Ba*	279	326	166	452	298	22
Th*			3	2	4	18
La					35.7	124
Ce					77	213
Nd					40	115
Sm					8.8	21
Eu					3.1	1
Tb					1	3.5
Yb					2.8	12.1
Lu					0.4	1.8
Cs					0.1	0.3
Th					4	18
U					1	1.8
Ta					2.3	7.3
Hf					6.5	29
Cr					11	0
Sc					25	5
Co					44	0.9

Table 1. (Contd.)

	MEGEZEZ (Termaber formation)							
	MZ-8	MZ-4	MZ-11	MZ-16	MZ-3	MZ-18	MZ-2	MZ-9
SiO_2	46.76	47.61	47.70	48.47	49.23	49.35	49.55	49.91
TiO_2	2.39	2.86	2.64	2.34	2.55	3.07	3.23	2.26
Al_2O_3	18.00	18.03	17.81	19.29	18.01	15.17	14.99	21.86
Fe_2O_3	7.43	4.75	5.18	3.99	5.89	3.79	8.58	1.67
FeO	5.00	6.37	6.51	6.09	5.01	8.53	3.77	5.96
MnO	0.16	0.16	0.15	0.14	0.16	0.18	0.18	0.12
MgO	3.91	3.35	3.79	3.65	3.42	4.18	3.58	2.48
CaO	8.02	9.33	9.11	8.84	9.14	7.86	6.84	9.09
Na_2O	3.08	3.26	2.99	3.35	3.02	3.58	3.46	3.47
K_2O	0.95	1.09	0.93	1.04	1.19	1.64	1.58	0.96
P_2O_5	0.45	0.59	0.45	0.55	0.50	0.76	0.65	0.55
LOI	3.25	2.06	2.75	2.25	1.61	1.89	3.58	0.87
Mg#	41.24	39.76	41.57	44.16	41.03	42.34	39.52	41.07
La*	18	18	13	16	19	30	46	17
Ce*	38	44	41	38	47	85	90	32
V*	304	228	316	197	278	249	268	173
Cr*	34	7	14	7	0	3	0	26
Co*	42	31	41	29	31	31	33	19
Ni*	37	20	26	27	17	7	8	12
Rb*	16	17	16	16	22	30	32	15
Sr*	647	765	560	776	567	499	497	918
Y*	33	34	34	29	40	34	70	26
Zr*	165	190	172	162	210	301	305	136
Nb*	18	24	14	19	26	34	37	14
Ba*	298	363	263	319	490	475	560	395
Th*	2.5	4.8	5.5				3.3	
La	18		19.2				46.8	
Ce	38		41				90	
Nd	20		23				54	
Sm	4.9		5.3				12	
Eu	1.8		2				4	
Tb	0.7		0.9				1.9	
Yb	1.9		1.8				4.3	
Lu	0.3		0.3				0.7	
Cs	0.1		0.1				0.7	

Table 1. (Contd.)

	MEGEZEZ (Termaber formation)							
	MZ-8	MZ-4	MZ-11	MZ-16	MZ-3	MZ-18	MZ-2	MZ-9
Th	1		1.8				3.3	
U	0.4		0.5				0.9	
Ta	1.1		1.1				2	
Hf	3.5		4.7				7.6	
Cr	34		14					
Sc	19		23				22	
Co	42		42				33	

Trace element variations as a function of SiO_2 are shown in Fig. 4. The plateau basalts display large variations in the compatible trace elements as well as in Ba and Sr contents against a negligible range in SiO_2. The steep trends in Cr, Co, Ni and Sc can be directly related to the removal of the mafic minerals also present in the basalts.The absence of relations between Ba and Sr on one hand and SiO_2 on the other, however, indicates that the variations did not result from a differentiation process which would have also affected silica markedly. This is supported by the absence of relation between Ba and Sr contents and the porphyricity index of the samples, that may suggest that the scattering is a product of phenocryst accumulation. Furthermore, none of the phenocrystal phases could incorporate appreciable amounts of Ba, which indicates that the observed trace element variations in the basalts are pristine geochemical characteristics of magmas. The incompatible trace elements Rb, Ba, Light Rare Earth Elements (LREE), and others exhibit positive correlations with SiO_2 in the Megezez volcanics, with scattering of Sr and Ba in the mafic range. The positive relations may be correlated with plagioclase and alkali feldspar phenocrysts abundantly found in the rocks suggesting that differentiation was significantly controlled by these minerals.The ferromagnesian elements (Co, Cr, Sc) show a sharp decrease to very low values within the Megezez mafic samples and drop down to very low concentrations in the evolved products. Ba and Sr drop to low concentrations in the Alaji acid rocks.

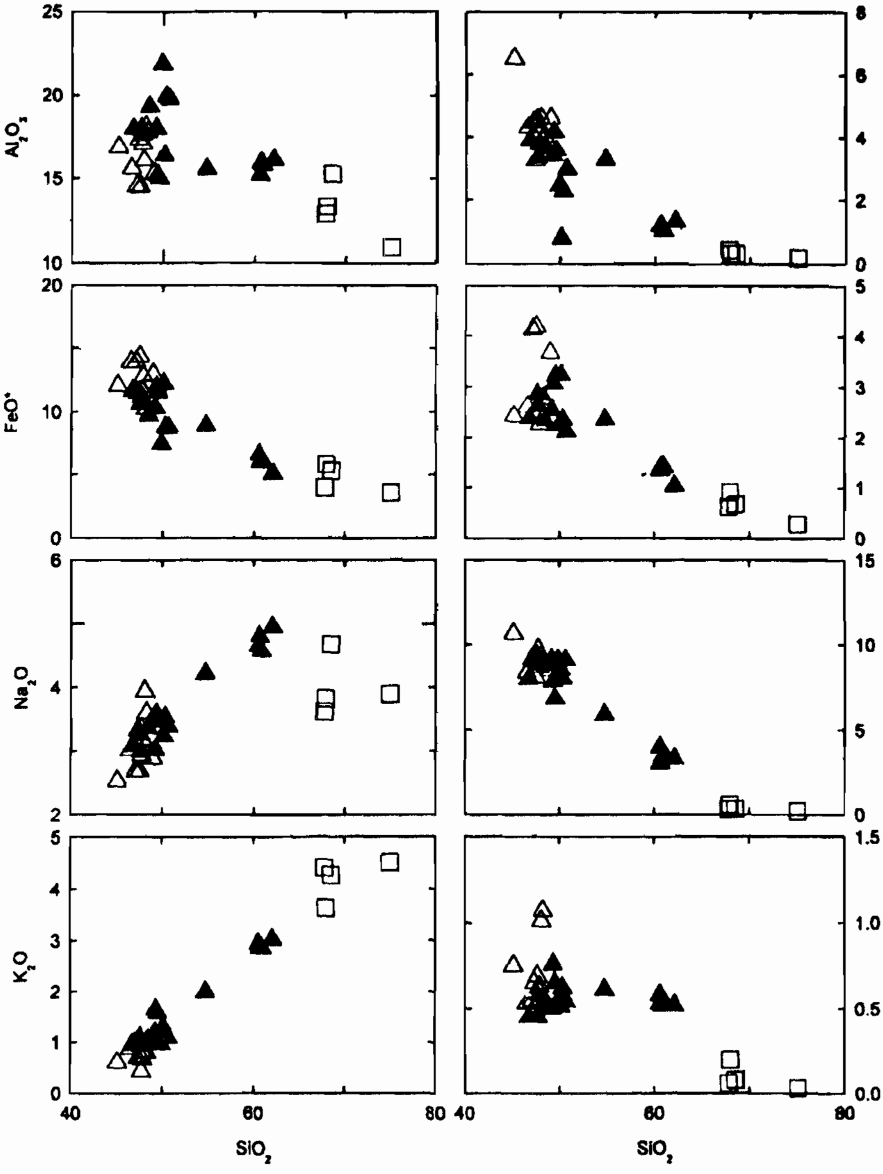

Fig. 3. Variation diagrams of major element abundances (Wt.%) as a function of SiO_2 content. Symbols as in Fig. 2.

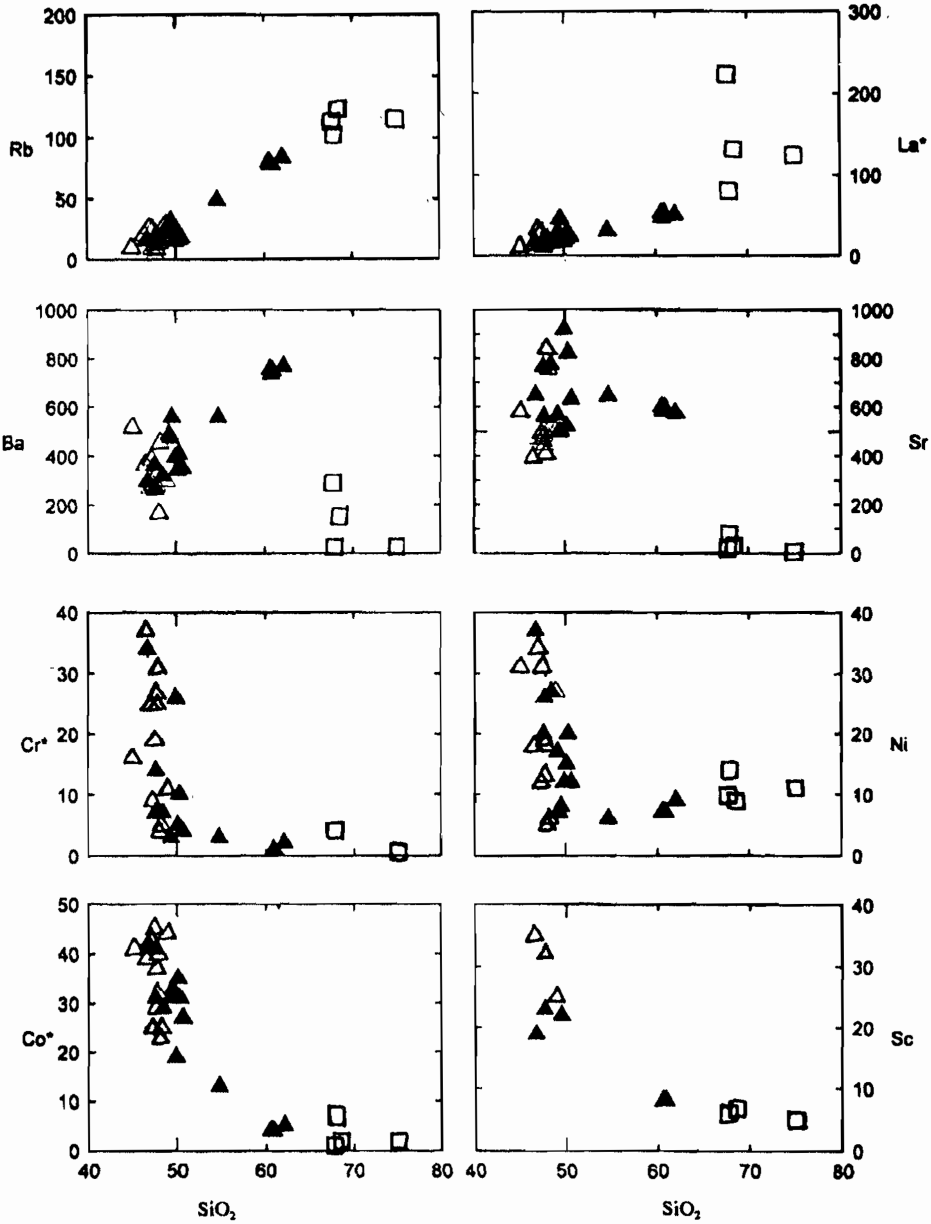

Fig. 4. **Variation diagrams of trace element abundances (ppm) as a function of SiO_2 content.** Symbols as in Fig. 2.

Rare earth (REE) and incompatible elements

The contents of the REE determined on selected rocks is reported in Table 1. REE patterns plotted by normalizing with respect to chondrites (Nakamura, 1974) are reported in Fig. 5. It can be observed that plateau and Megezez basalts exhibit very similar REE patterns both in abundance and fractionation. The Alaji silicic samples are distinctly enriched in both the LREE and the Heavy Earth Elements (HREE) relative to the basalts and are characterized by a significant negative Eu anomaly which may be related to the fractionation of plagioclase.

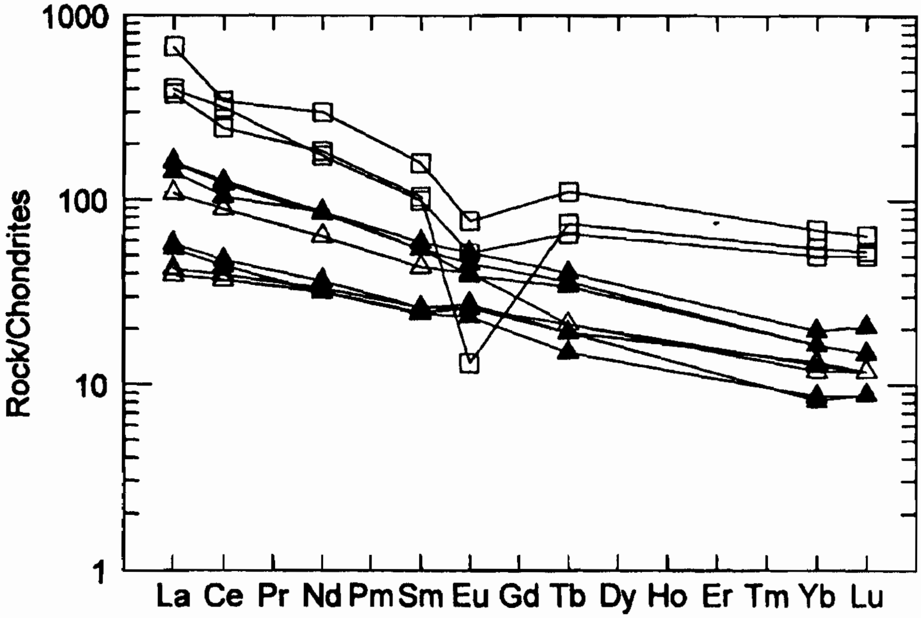

Fig. 5. Chondrite-normalized Rare Earth Element patterns for the analyzed rocks. Symbols as in Fig. 2.

Incompatible element patterns of the analyzed samples are shown in Figure 6. The plateau and the Megezez basalts display similar incompatible element patterns with relative enrichment in the highly incompatible trace elements. Some Megezez basalts show relative enrichment in Ba with respect to Rb and

Th and relative depletion in Ti. Plateau basalts are overall relatively less enriched than Megezez basalts and exhibit relative enrichment in Nb and Ba with marked negative anomalies in U in some samples.

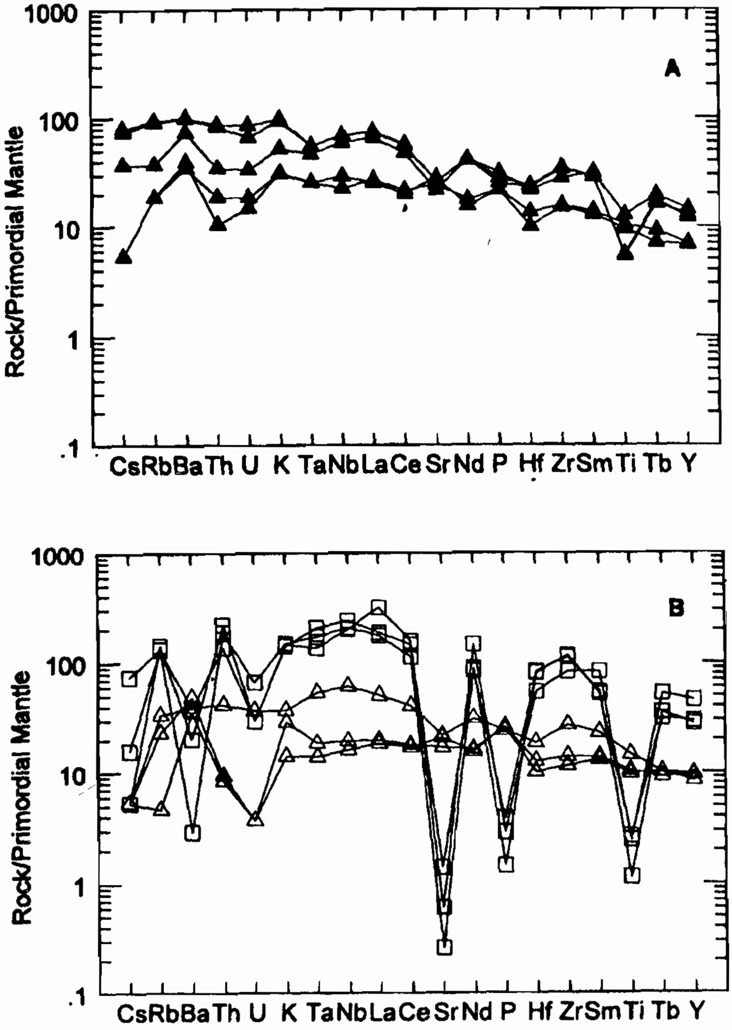

Fig. 6. Incompatible element patterns normalized to Primordial Mantle composition (Wood *et al.*, 1979). A) Megezez volcanics; B) Plateau and Alaji volcanics. Symbols as in Fig. 2.

The acid rocks of the Alaji formation display distinctly higher enrichment in incompatible elements, but with patterns basically similar to the plateau and Megezez basalts. However, the Alaji acid samples possess strong negative anomalies of Ba, Sr, P and Ti. These negative spikes testify the important role of plagioclase for Sr, alkali feldspar for Ba, apatite for P and Ti-magnetite forTi in the genesis and/or evolution of these rocks, in good agreement with the observed mineral assemblage in the rocks. Furthermore, the similarity of abundance patterns between basaltic terms and Alaji silicics suggests a direct genetic relationship of the acid rocks with the basalts through a differentiation process controlled by crystal fractionation, as suggested also by major and trace element abundance patterns.

DISCUSSION

Field, petrological and geochemical data on volcanic rocks from Sheno-Megezez area indicate that the plateau lavas consist only of basaltic rocks while those of Megezez volcanics consist of a larger range of compositions from basalts to intermediate-acid rocks. The two series are separated by acid volcanics of the Alaji formation. The basalts are of transitional type, with a mildly alkaline affinity in some samples, while the acidic rocks are alkaline to peralkaline, in agreement with observed petrographic features. The rock series in this area is characterized by a lack of samples with high Mg#, Ni and Cr, which indicate non-primitive geochemical characteristics. Most of the analyzed basalts have MgO < 6.51%, Mg # (42–67) and Ni (7–37 ppm), which testifies to significant differentiation during uprise to the surface. In general terms, the plateau basalts, although having a relatively small range in contents of SiO_2, record significant variations in trace and some major elements.

Some of the main observations that require thorough discussion and adequate explanations in light of the available results include:

1. Significance of the geochemical variations within the plateau and the Megezez basalts;
2. Genetic relationships between basalts and the intermediate rocks in the Megezez suite; and
3. The genesis of the Alaji acid rocks.

The plateau lavas show small variations in silica and MgO, but a large range in the abundances of several incompatible elements. In particular, TiO_2 displays a variation that allows to distinguish high-Ti and low-Ti groups of basaltic rocks within the studied samples. Such a distinction has been found in other areas of intracontinental basaltic volcanism (e.g. Paranà) as well as in similar plateau sequences in Ethiopia. In addition to TiO_2, there are significant variations of other major and trace elements, such as Na_2O, Al_2O_3, Ba, Sr, Nb, and other incompatible element abundances and ratios. The main problem related to these basalts is to understand whether these variations reflect pristine compositions of primary melts or are the effect of low pressure evolution that occurred during magma uprise to the surface.

Inter-elemental relationships demonstrate that TiO_2 is positively correlated with a number of elements and elemental ratios such as Fe, V, Zr, Nb, Y, La/Y and Rb/Sr and negatively correlated with Al_2O_3. Most of these elemental variations can be explained by fractional crystallization (e.g. Ti vs. Fe and V) while other correlations such as Ti vs. Nb and Zr require the combination of fractional crystallization and interaction with the upper crust. As the upper crust is characterized by low Ti, Zr and Nb (Taylor and McLennan, 1985), interaction between the high-Ti basaltic magma and the upper crust would result in a decrease of all these elements. This interaction should also produce a decrease in Co, Ni, Cr and other compatible elements. However, low-Ti and high-Ti basalts have comparable concentrations of Co, Cr and Ni. Moreover, positive correlations between TiO_2 and Rb/Sr ratios argue against assimilation processes. It is, hence, concluded that the variable Ti contents in the plateau basalts reflect the characteristics of primary magmas which suggest derivation from compositionally different sources. Alternatively, variable degrees of partial melting could be invoked to have produced the observed effects. However, as it will be argued later, there are other elemental variations that favour the role of evolutionary processes in modifying magma characteristics.

The Megezez volcanics have a more complex evolution than the plateau lavas, with significant elemental variations within the mafic rocks. Accordingly, it is necessary to understand 1) the processes that generated the elemental variations within the basalts, and 2) the processes that generated the evolved volcanics. A semi-quantitative geochemical modelling approach has been followed to help elucidate these problems.

Fig. 7 shows Rb vs. Rb/Nb variations within the plateau, Megezez and Alaji volcanics. It can be observed that the Megezez basalts cluster around a Rb/Nb value of unity. The intermediate Megezez volcanics, instead, have higher Rb and Rb/Nb values. Since both Rb and Nb are strongly incompatible elements, the increase in Rb/Nb cannot be due to the effect of fractional crystallization alone. Alternatively, an AFC process must be assumed. The geochemical modelling demonstrates that the intermediate rocks from the Megezez volcano can be obtained by AFC processes starting from the associated basalts and assuming moderate amounts of assimilation of upper continental crustal material (with a ratio of crystallized to assimilated material, r = 0.2-0.5).

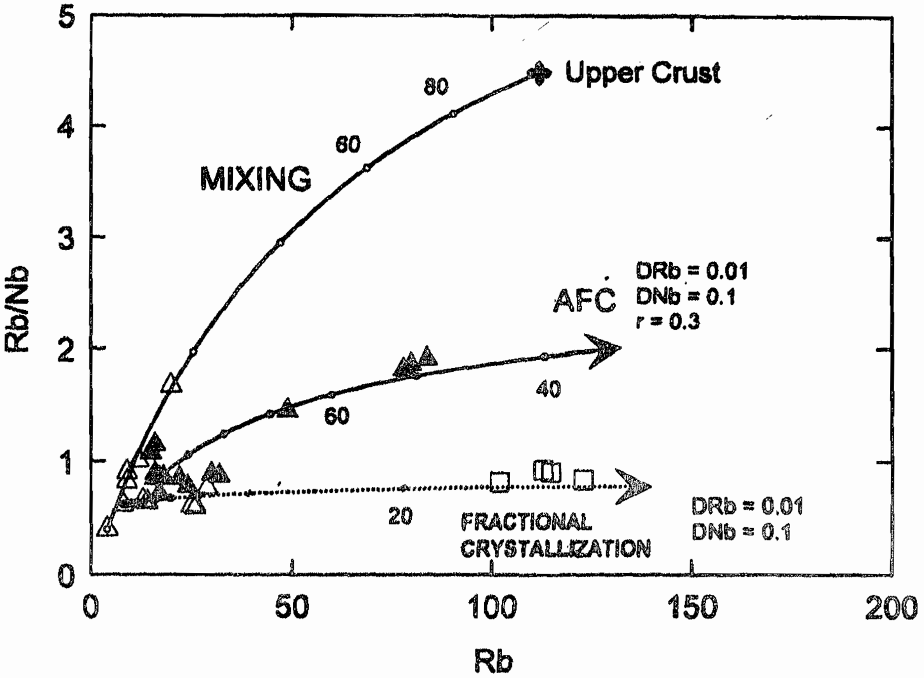

Fig. 7. **Fractional Crystallization (FC) and Assimilation Fractional Crystallization (AFC) models for the investigated rocks. The letter "r" indicates the ratio between mass of assimilated and crystallized material. Numbers along the lines are the amounts of residual liquid. Cross symbol represents average upper crust composition according to Taylor and MacLennan (1985) which has been used as assimilant. Symbols as in Fig. 2.**

The diagram reported in Fig. 7 further shows that the basalts from the plateau sequence also display significant variations of Rb/Nb. This variation fits a calculated trend of mixing between the least evolved analyzed plateau basalt and upper crust (Taylor and McLennan, 1985). Accordingly, Rb/Nb variations suggest that the plateau lavas have also interacted significantly with the upper crust. The Alaji rhyolites have similar Rb/Nb ratios as the basalts from both the plateau and Megezez volcano. This suggests a derivation of the Alaji acid rocks from basaltic magmas by processes dominated by fractional crystallization.

Rb vs. Rb/Ba diagram in Figure 8 shows that the Megezez suite can be modelled by assuming an AFC process with significant amounts of assimilation of upper continental crust ($r = 0.3$). On the other hand, the Rb/Ba variations within the plateau basalts are consistent with a process of mixing between continental crust and the least evolved analyzed mafic magma. The range of Rb/Ba variations in the mafic rocks can be also explained in part in terms of mixing interaction between the least evolved plateau basalt and Alaji acid liquids.

A plot of Rb/Ba vs Rb/Nb is shown in Fig. 9. Comparison between modelled and observed patterns suggests that, most probably, mixing of primitive basaltic magma with upper continental crust as well as with differentiated acid liquids played a role in the evolution of plateau basalts. This is observed in the diagram where some of the plateau samples plot on the mixing curve between upper crust and the most mafic plateau basalt, and other samples fit the mixing line between the mafic and acid magmas. The diagram further shows that Megezez volcanics are genetically related to one another through AFC processes.

As a whole, the variations in elemental ratios considered above agree in indicating that the Alaji rhyolites were most probably derived from basalts by fractional crystallization. The steep increase in Rb/Ba in Fig. 9 testifies to the leading role played by alkali feldspar fractionation. This is in fact the only mineral that is capable to incorporate Ba and produce, at the same time, a rapid decrease in the same element during the most advanced stages of magmatic differentiation. Considering the available trace element data for the rhyolites, especially their lower Rb/Nb (< 1) (Fig. 7), compared to the higher Rb/Nb ($>$ 10) for rhyolites inferred to have originated by crustal melting, the possibility that Alaji rhyolites originated by partial melting of the continental crust could not be favoured.

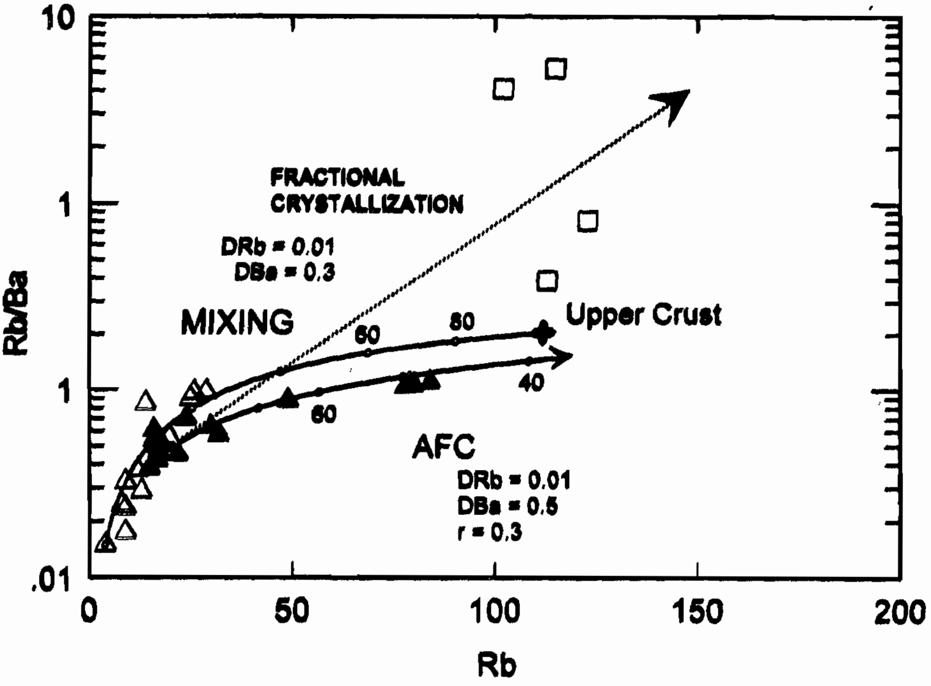

Fig. 8. Rb versus Rb/Ba FC and AFC models. The letter "r" indicates the ratio between mass of assimilated and crystallized material. Numbers along the lines are the amounts of residual liquid. Composition of upper crust is from Taylor and McLennan (1985). Symbols as in Fig. 2.

The idea that the Alaji silicic rocks could be differentiated products from basaltic parents does not, however, explain the bimodal nature of the volcanic suite. It is, therefore, suggested that these rhyolites are possibly derived by partial melting of a basaltic source material, followed by fractional crystallization. Further studies using isotopic data are required to understand better the genesis of the rhyolites as well as the scarcity of intermediate volcanics in the entire Ethiopian flood lava sequence.

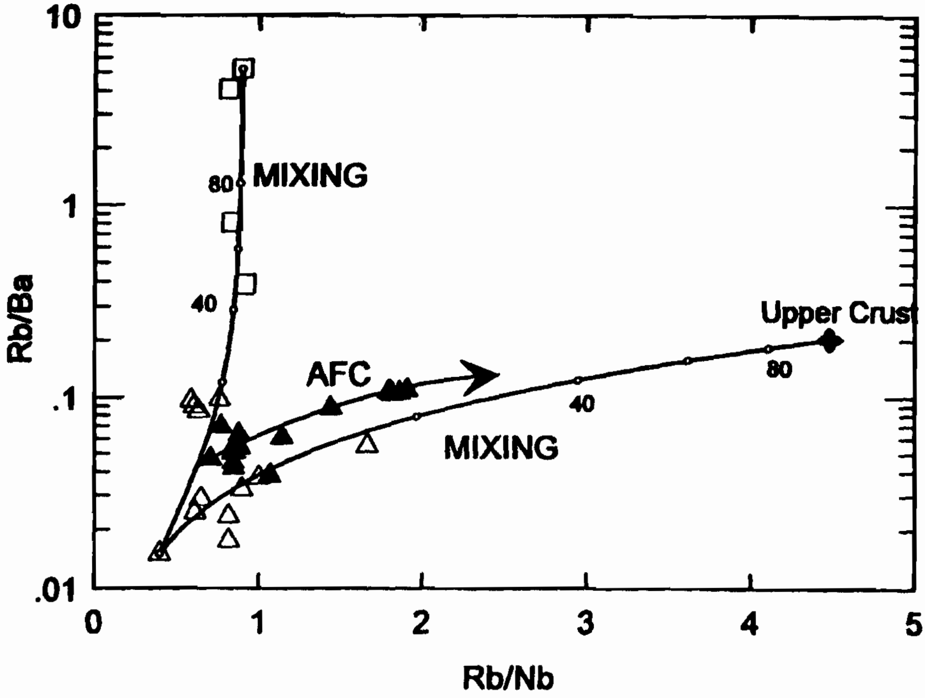

Fig. 9. **Plot of Rb/Nb against Rb/Ba for the analyzed volcanics and modelled variation curves for AFC processes.** D values for Rb, Nb and Ba as in Figs. 7 and 8. Numbers along the lines are the amounts of residual liquid. Upper crust composition from Taylor and McLennan (1985). Symbols as in Fig.2.

CONCLUSIONS

The present study has shown that the basaltic rock suite from the plateau sequence of the Sheno area displays compositional variability in terms of several element abundances and ratios. Based on Ti abundances, high-Ti and low-Ti varieties have been distinguished. These two groups are likely related either to compositionally different sources or to the same source affected by different degrees of partial melting. However, the investigated plateau basalts also display significant variations of elemental ratios such as Rb/Nb and Rb/Ba that indicate that these magmas have interacted significantly with the upper crust and with acid liquids having a composition similar to the Alaji acid rocks.

The rocks from the Megezez volcano range in composition from basalts to trachyandesite. Geochemical modelling suggests that this compositional range has been effected through AFC processes starting from mafic magmas.

Finally, the Alaji acid volcanics show compositional characteristics that suggest a derivation from basaltic parents by low-pressure evolutionary processes dominated by fractional crystallization. However, additional studies, especially isotopic compositions, are required to further constrain or disprove this hypothesis.

As a whole, the data presented here as well as in previous studies on Ethiopian basaltic magmas (Mohr, 1983; Mohr and Zanettin, 1988; Hart *et al*., 1989; Gasparon *et al*., 1993; Peccerillo *et al*., 1995) strongly argue in favour of the possibility that marked modifications in basalt compositions could result from the involvement of a component of acidic composition during the evolution of mantle-derived basaltic magmas. The origin of the acid end- members could be rhyolitic melts formed from basalts by fractional crystallization, crustal material itself or a combination of the two. In conclusion, the available geochemical data from Sheno-Megezez rocks as well as from other Cenozoic mafic suites from Ethiopia suggest that basaltic magmas have undergone important intracrustal geochemical modifications en route to the surface. These modifications have been superimposed on primary magma variations which themselves resulted either from heterogeneous sources or from variable degrees of partial melting of a homogeneous source. It is, therefore, suggested that caution must be taken in considering basalt compositions as indicators of sub-crustal processes, and that the effects of crustal contamination and magma mixing must be critically evaluated before making inferences on source composition.

ACKNOWLEDGEMENTS

I wish to extend special gratitude to Prof. Angelo Peccerillo for his help while collecting the samples and carrying out the laboratory analyses, and for providing constructive suggestions on the initial version of the manuscript. I am also grateful to anonymous reviewers of *SINET* for their thorough and constructive review of the manuscript that lead to a substantial improvement of the paper. I also thank the

Technical Unit of the Italian Cooperation in Addis Ababa for the support given during the fieldwork.

REFERENCES

1. Barberi, F., Civetta, L. and Varet, J. (1980). Magmatic evolution in Afar. *Atti Conv. Lincei, Geodynamic Evolution of the Afro-Arabic Rift System*, Rome. 455–562.
2. Cox, K.J. and Hawkesworth, C.J. (1985). Geochemical stratigraphy of the Deccan traps at Mahabaleshwar, Western Ghats, India. Implications for open system magmatic processes. *J. Petrol.* **26**:355–377.
3. Davidson, A. (1983). Reconissance geology and geochemistry of parts of Illubabor, Kefa, Gemu Gofa and Sidamo, Ethiopia. *Ethiopian Inst. Geol. Survey Bull.* **2**., Ministry of Mines and Energy, 89 pp.
4. Deniel, C., Vidal, P., Coulon, C., Vellutini, P.J. and Piguet, P. (1994). Temporal evolution of mantle sources during continental rifting: the volcanism of Djibuti (Afar). *J. Geophys. Res.* **99**:2853–2869.
5. Devey, C.V. and Cox, K.J. (1987). Relationship between crustal contamination and crystallization in continental flood basalt magmas with special reference to the Deccan traps of the Western Ghats, India. *Erath Planet. Sci. Letters.* **84**:59–68.
6. Di Paola, G.M. (1972). The Ethiopian Rift Valley between 7°00' and 8°40' lat. North. *Bull. Volcano.* **36**:317–356.
7. Ebinger, C.J., Tesfaye Yemane, Giday Woldegabriel, Aronson, J.L. and Walter, R.C. (1993). Late Eocene-recent volcanism and faulting in the southern main Ethiopian Rift. *J. Geol. Soc. London.* **150**:99–108.
8. Franzini, M., Leoni, L. and Saitta, M. (1972). A simple method to evaluate the matrix effect in X-ray fluorescence analyses. *X-Ray Spectrometry* **1**:151–154.
9. Gasparon, M., Innocenti, F., Manetti, P., Peccerillo, A. and Tsegaye Abebe (1993). Genesis of the Pliocene to Recent bimodal mafic-felsic volcanism in the Debre Zeit area, central Ethiopia: volcanological and geochemical constraints. *J. African Earth Sci.* **17**:146–165.
10. Gibson, I.L. (1974). A review of the geology, petrology and geochemistry of the volcano Fantale. *Bull. Volcano.* **38**:791–802.
11. Hart, W. K., Giday Woldegabriel, Walter, R. C. and Mertzman, S.A. (1989). Basaltic magmatism in Ethiopia: constraints on continental rifting and mantle interactions. *J. Geophys. Res.* **94**:7731–7748.

12. Hofmann, C., Feraud, G., Pik, R., Gezahegn Yirgu, Dereje Ayalew, Coulon, C., Deniel, C. and Courtillot, V. (1995). ^{40}Ar/^{39}Ar dating of Ethiopian traps. Europ. Un. Geosc. Congr., Strasbourg 9–13 April 1995, Abstract.

13. Huppert, H.E. and Sparks, R.S.J. (1985). Cooling and contamination of mafic and ultramafic magmas during ascent through the continental crust. *Earth Planet. Sci. Letters*. 74:371–386.

14. Irvine, T.N. and Baragar, W.R.A. (1971). A guide to the elemental classification of common volcanic rocks. *Can. J. Earth Sci*. 8:523–548.

15. Le Bas, M.J., Le Maitre, R.W., Streicksen, A. and Zanettin, B. (1986). A chemical classification of volcanic rocks based on the total alkalis-silica diagram. *J. Petrol*. 27:745–750.

16. Merla, G., Abbate, E., Azzaroli, A., Bruni, P., Canuti, P., Fazzuoli, M., Sagri, M. and Tacconi, P. (1979). A geological map of Ethiopia and Somalia (1973) and comment with a map of major landforms. Consiglio Nazionale delle Ricerche, Firenze Italy.

17. Mohr, P. (1983). The Ethiopian flood basalt province. *Nature*. 303:577–584.

18. Mohr, P. and Zanettin, B. (1988). The Ethiopian flood basalt province. In: *Continental Flood Basalts*, pp. 63–110, (Macdougall, J.D., ed.), Kluwer Acad. Publ. Dordrecht.

19. Nakamura, N. (1974). Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochim. Cosmochim. Acta*. 38:753–773.

20. Peccerillo, A., Gezahegn Yirgu and Dereje Ayalew (1995). Genesis of acid volcanics along the Main Ethiopian Rift: a case history of the Gedemsa volcano. *SINET: Ethiop. J. Sci*. 18(1):23–50.

21. Piccirillo, E. M., Justin-Visentin, E., Zanettin, B., Joron, J.L. and Treuil, M., (1979). Geodynamic evolution from plateau to rift: major and trace element geochemistry of the central-eastern Ethiopian Plateau volcanics. *Neus Jb. Palaont. Abh*. 158:139–179.

22. Taylor, S.R. and McLennan, S.M. (1985). *The Continental Crust: Its Composition and Evolution*. Blackwell, London, pp. 323.

23. Wood, D.A., Joron, J.L., Treuil, M., Norry, M. and Tarney, J. (1979). Elemental and Sr isotopic variations in basic lavas from Iceland and the surrounding ocean floor. *Contr. Mineral. Petrol*. 70:319–339.

24. Zanettin, B., Gregnanin, A., Justin Visintin, E., Mezzacasa, G. and Piccirillo, E.M. (1974). Petrochemistry of the volcanic series of the central-eastern Ethiopian plateau and relationship between tectonics and magmatology. *Mem. Ist. Miner. Univers. Padova*. 31:1–35.