Πρακτικά	6ου	Συνεδρίου	Μάϊος 1992
Δελτ. Ελλ. Γεωλ. Εταιρ.	Τομ. XXVIII/3	σελ. 499-514	Αθήνα 1993
Bull. Geol. Soc. Greece	Vol.	pag.	Athens

THE EVOLUTION OF YEMEN BASALT IN RELATION TO THE RIFT DEVELOPMENT AND THE CHEMISTRY OF ITS MINERAL CONSTITUENTS

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ABSTRACT

Tertiary volcanics cover a wide area in Yemen, approximately one tenth of the national territory. They occupy the majority of the western part of the country. Relative crustal thinning (affected by intensive tectonic activity) resulted in continental rifting (Late Oligocene - Early Miocene), through which magmas ascended and formed the Yemen Highlands and Plateaux. The Yemen Trap Series has mainly been controlled by the NW-SE faulting trend, which is parallel with the Red Sea trend, or less commonly (NE-SW) with the Gulf of Aden trend.

The Late Miocene-Quaternary volcanics are located in the coastal plain of the Gulf of Aden and in the central parts of Yemen. Yemen volcanics are composed of basic, to intermediate and acidic rocks.

Basic rocks are represented by basalts, which form the lower part of the volcanic complexes, whereas the acidic types [rhyolites, volcanic glasses and pyroclastics] occupy the upper part of the Yemen Trap Series volcanics.

This paper deals with the chemistry of the basaltic rocks and with the composition of their main constituents (olivine, pyroxene and plagioclase). The basaltic rocks have alkali-subalkali characters. The clinopyroxene phenocrysts show concentric and hour-glass zoning that can be regarded as a good indication of the magma evolution. The composition of the plagioclase ranges between labradorite-bytownite (for the phenocrysts, An_{87-63}) and andesine-labradorite (for the plagioclase in the groundmass, An_{61-40}). The olivine phenocrysts have higher forsterite content (Fo_{90-75}) in their cores; but these values decline at the rims as well as in the groundmass (Fo_{75-40}).

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THE EVOLUTION OF YEMEN BASALT IN RELATION TO THE RIFT DEVELOPMENT AND THE CHEMISTRY OF ITS MINERAL CONSTITUENTS

INTRODUCTION

The origin and evolution of Yemen volcanic rocks is regarded as the result of the rifting (synrift, Late Oligocene-Early Miocene)and postrift (Miocene up to Recent) phases of the formation of the Red Sea and the Gulf of Aden (in which oceanic accretion started).

In the Late Eocene, a widespread emergence of the greater part of the Arabian platform occurred. It was probably at that time that Gulf of Aden rifting was initiated, as the Indian Ocean spreading center propagated eastward (Haitham, *et al.*, 1990).

This study was carried out to investigate the mineralogy, petrology, and structural geology of Yemen volcanics. Our study covers both the Yemen Trap Series (YTS, Late Oligocene-Early Miocene), and the Yemen Volcanic Series (YVS, Late Miocene-Recent) and their evolution in relation to the rift development (Fig. 1). In this paper we deal only with the basic rocks and their analyses related to the chemical composition of the basalts and their main constituents (olivine, pyroxene and plagioclase). We have also correlated the generation and development of these volcanic complexes by using the data obtained from seismic and drilled wells in the coastal plains of the Red Sea and the Gulf of Aden. By using microprobe, chemical and optical analyses *etc.*., we attempt to evaluate the chemical characters and the magma evolution of the investigated volcanics.

STRATIGRAPHY, TECTONIC SETTING AND GENESIS

The volcanic rocks of Yemen can be divided into two series *i.e.* Yemen Trap Series (YTS) and Yemen Volcanic Series (YVS).

The YTS had been developed through the period from Late Oligocene to Miocene (synrift-Shihr group).

It is composed of thick volcanic rocks (lava flows, dikes, sills *etc.*) mainly of basaltic composition, which form the lower part of the series, with intercalations of volcanoclastic deposits.

Genetically, the YTS had been associated with Tertiary continental and oceanic rifting and with the geodynamic of the Afro-Arabian lithosphere plates.

Numerous Tertiary intrusive bodies, mainly of alkali granites and syenites, have also been reported in many localities (particularly in the western part of the study area // with the Red Sea main trend) and they are closely associated with the volcanic complexes.

In Early Miocene, differentiated alkaline volcanic complexes poured out on to the continental (W-SW) part of the country. The thickness of these volcanic complexes ranges from some metres in the eastern part of YTS to 2000 m in the western part or more in the central part of the area.

Huge amounts of basaltic flows built the lower part of the volcanic complexes as a consequence of continental crustal extension.

In the Red Sea coastal plain, faults caused strong subsidence in Oligocene time, which generated W-dipping blocks. Tilted blocks in the Gulf of Aden dip S. They have been affected by intensive tectonism (fault system) of ESE-WNW and NNE-SSW orientation and are filled with volcanic rocks mainly of synrift traps (Fig. 2).

The YVS is found on the coastal plain of the Gulf of Aden from the west (southeastern part of the Red Sea) Perim Island, Jabal-Kharaz passing onto Imran - Little Aden - Aden to the east (Shuqrah and Bir Ali *etc.*.). It was generated and developed through the postrift stage (upper part of Shihr Group) and it is considered to be of Late Miocene to Recent time. It is also found in other localities throughout the country (Sanaa-Amran, Dhamar-Rada and Sirwah-Marib). Volcanic cones, domes, sheets and lava flows are the characteristic features of this series. It is composed mainly of basaltic lava flows and pyroclastics, except the Al-Lisi volcano (5 km E of Dhamar city), which is completely consisting of acidic lava flows (rhyolite, rhyolitic glass and ash). There is a sharp unconformity between the two series.

In the coastal plain of the Gulf of Aden (*e.g.* Imran well) thick continental basaltic traps occur, outpoured during aerial deposition, dated 18 ± 6 Ma (Elf, 1990) with the same characteristic features of those known onshore. Such trap series is generated by synrift extensional fractures, which poured out huge amounts of lavas during a short time respectively. Partly we agree with the idea related to the mode of this magma

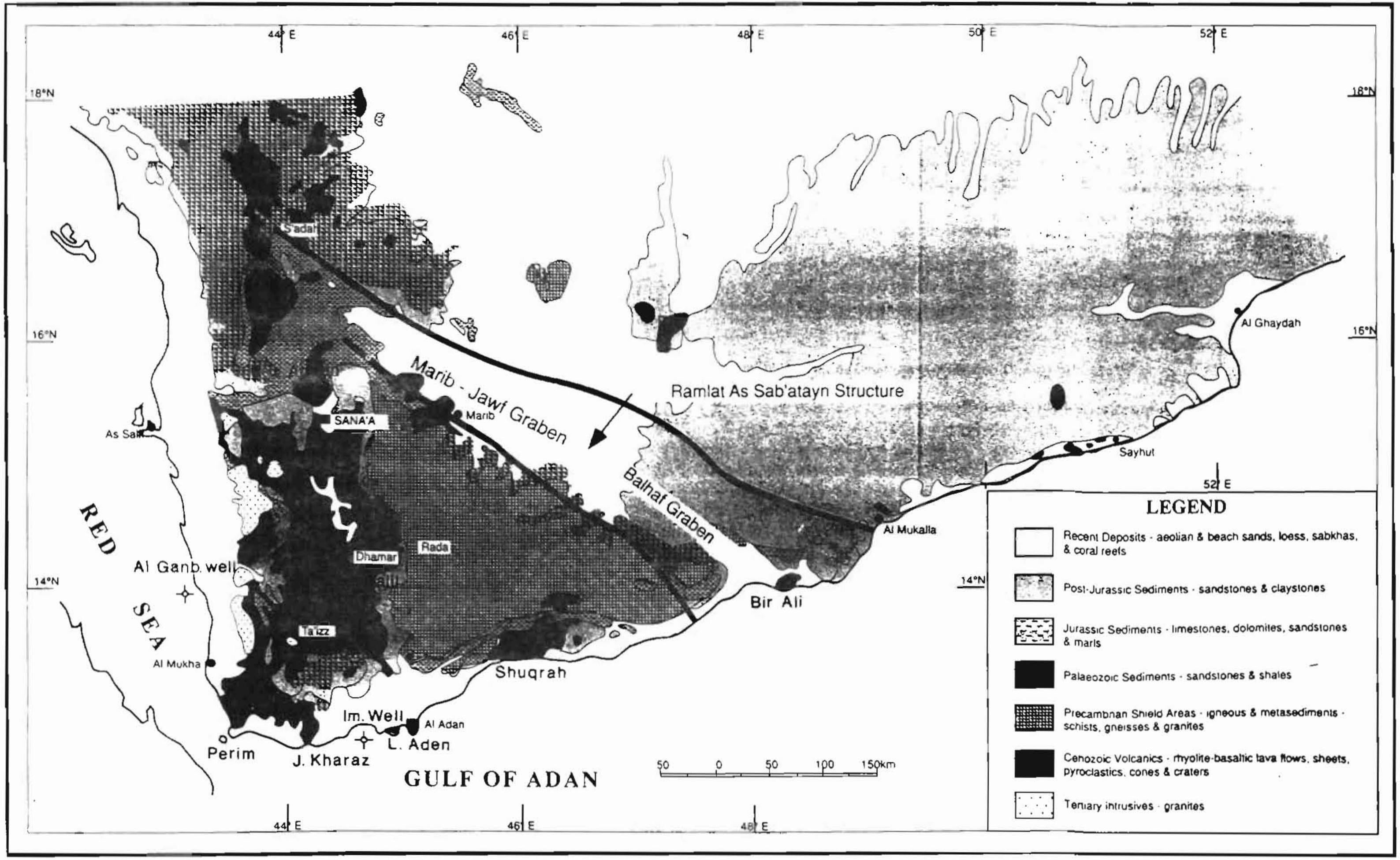

FIGURE 1 - SIMPLIFIED GEOLOGICAL MAP OF YEMEN

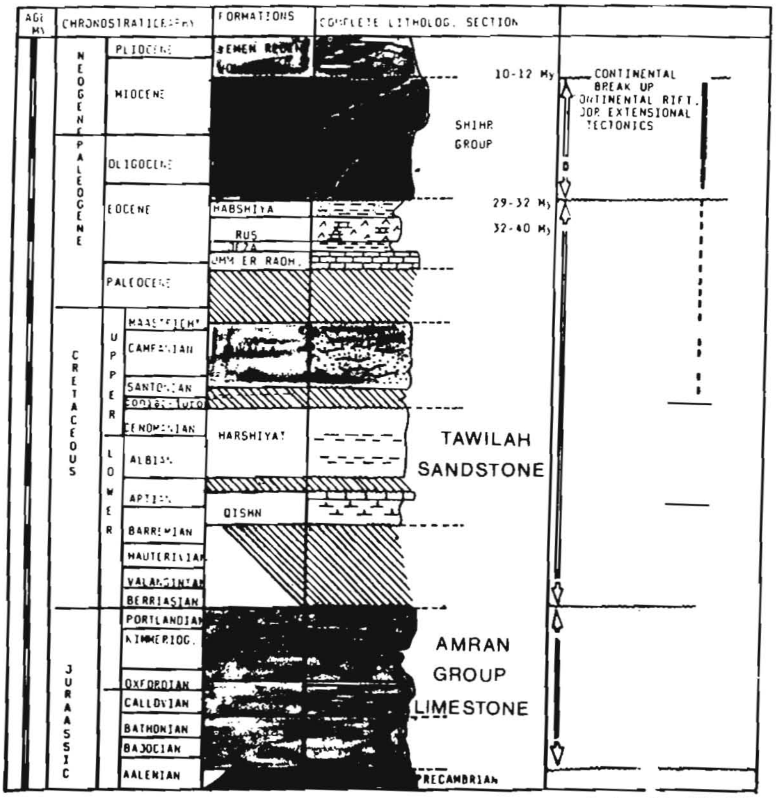

Fig. 2 Stratigraphic column illustrates Yemen Trap and Yemen Volcanic Series (Modified from Elf 1990).

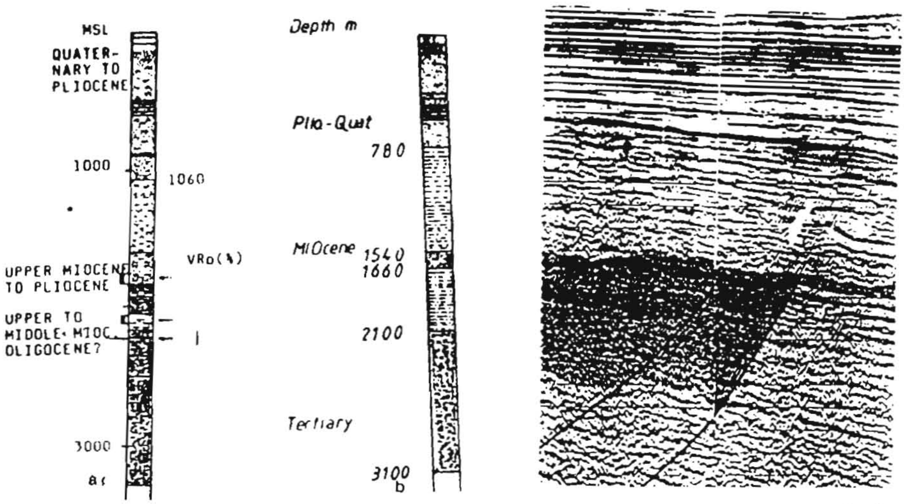

Fig. 3 Geological sections correlate the distribution of Yemen volcanics in the offshore of the Gulf of Aden (a) and the Red Sea (b). The distribution of the volcanic rocks is also shown from the seismic data of drilled well in the Gulf of Aden offshore (c).

eruption but on the other hand there are some field evidences which also prove the central volcanic activity. The dyke swarms within the YTS have the same mineral composition with the adjacent outcrops, and the large extents of the pyroclastics (*e.g.* ignimbrites) without lateral variation in their thicknesses suggest fissural eruption. On the other hand the difference in the mineral constituents between the basaltic lava flows and the adjacent basaltic dikes and the presence of radial dike swarms support central volcanic activity (*e.g.* Final Report, 1988). Therefore, both fissural and central eruption can be assumed.

There is a tectonic contact between a continental crust block and the synrift deposits. During the Tertiary extensional phase, the continental crust had been stretched and broken. The resulting fault worked as a great crustal fault during the synrift stage.

Based on the data obtained from two wells offshore of the Gulf of Aden (Imran well) and Red Sea (Al-Janbiyah well) the thickness of the volcanic units may attain several kms, probably >3 kms (Fig. 3).

The upper part of the trap series is represented by the stratigraphic level of the break-up of the continent [(12-10 Ma)(Fig. 4) (After Elf Aquatine, 1990)]. Traps (Late Oligocene) are deposited on a first synrift sedimentary units.

An increase in heat flow happened which can be related to the beginning of the Tertiary rifting stage (40-12 Ma) and started decreasing from 12 Ma up to recent time (Fig. 4 After Elf Aq., 1990).

Based on isotope age data reported by many authors (*e.g.*, Civette *et al.*, 1978; Capaldi et al., 1983, 1987; Final Report, 1988; Chiesa *et al.*, 1989) and also based on our radiometric age data [(16.6 ± 1.8 Ma for the upper part of Jabal-Rabbiy (Ibb); 27.5 ± 2 Ma for the basalt of Al-Dalil village; 31.6 Ma for the basalt of Al-siian village SW from Ibb city); 1992 this paper] it can be inferred that the volcanic activity in the YTS started about 30 Ma ago and continued for 11 Ma, during which differentiated rock types were erupted in different phases.

YTS can partly be correlated with some Oligocene-Miocene volcanic sequences of Alaji, Termaber, Galile, and Trap Series, in Ethiopia (Zanattin *et al.* 1980a; Zanattin 1992); and also with the continental alkali basalt flows of Harrat As Sirat and Harrat Hadan in Saudi Arabia (Fleck *et al.* 1973; Arno *et al.* 1980a). Such a correlation is including both age and chemical affinities.

After a long interval (Late Miocene-Quaternary) the extension continued and a widespread volcanic eruption was created along the coastal plain of the Gulf of Aden and in some other localities throughout the country (*e.g.* Sanaa-Amran, Sirwah-Marib, Dhamar-Rada *etc.*.). This series was concentrated between 10 Ma and 5 Ma, *e.g.* Jabal-Kharaz gave 8.8 Ma (Final Report, 1988). Such eruptions were central-vent composite stratovolcanoes, *e.g.*, Jabal Kharaz, and Jabal Shamsan at Aden city. The respective wide hiatus (9-10 Ma) allows us to make such a nomenclature division between the above mentioned series.

Further volcanic complexes are known as recent volcanic activities such as those found in Bir Ali, and AL-Lisi volcano in the vicinity area of Dhamar Province. Furthermore historical volcanoes have also been reported.

NATURE OF OCCURRENCE AND PETROGRAPHY OF THE BASALTS

Among the volcanic rocks of Yemen, basalts are predominant. They occur as 2-5 m lava flows. Columnar joints are also found, and in some localities exceed 50 m (*e.g.* Al-Dalil village). They also occur as dikes ranging from 0.1 m to 1-2 m in thickness and may attain several hundred metres in length. Thick basaltic lava flows, can be found in several places, *e.g.*, in Dhala , Museimir, Am-Shatt *etc.*., but the maximum thickness (200 m) was observed in the central part of Sanaa.

Basalts are characterized mostly by porphyritic textures (holocrystalline, ophitic and pilotaxitic) and massive structures, but amygdaloidal and vesicular (porous) structures are also reported. Amygdules are filled by zeolites, calcedony, carbonate, chlorite. In some cases the porous structures are devoid of any secondary minerals; particularly in the volcanics of the younger stages (*e.g.* Shuqrah, Marib *etc.*) they can attain up to 40% of the rock volume .

PETROCHEMISTRY OF THE YTS BASALT

Chemical classification (Final Report, 1988; Chiesa *et al.* 1989; Mattash *et al.*, 1990) of the Yemen volcanic rocks is illustrated on the total alkali versus silica (TAS) diagram (after Le Bas *et al.*, 1986)(Fig. 5a). It reveals that samples from Yemen Trap Series and Yemen Volcanic Series, lie along a trend of alkalic differentiation. The samples are plotted in the basalt field. According to the field boundary of Irvine and

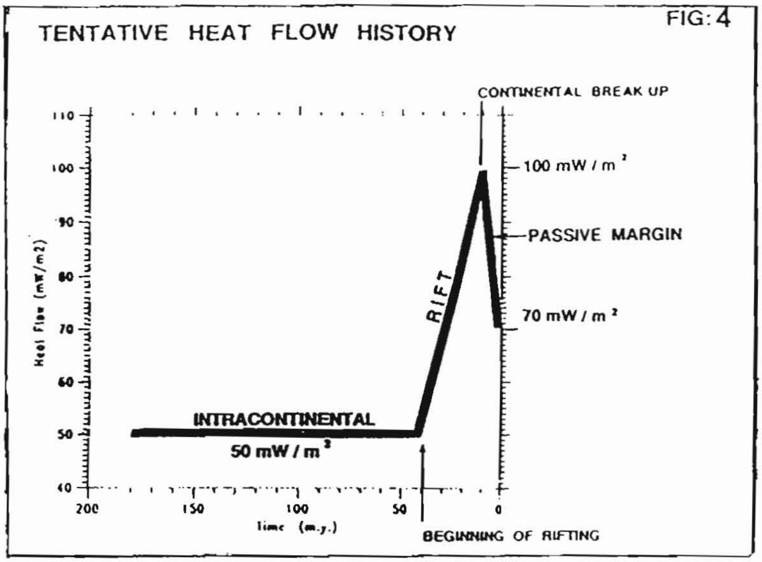
FIG: 4

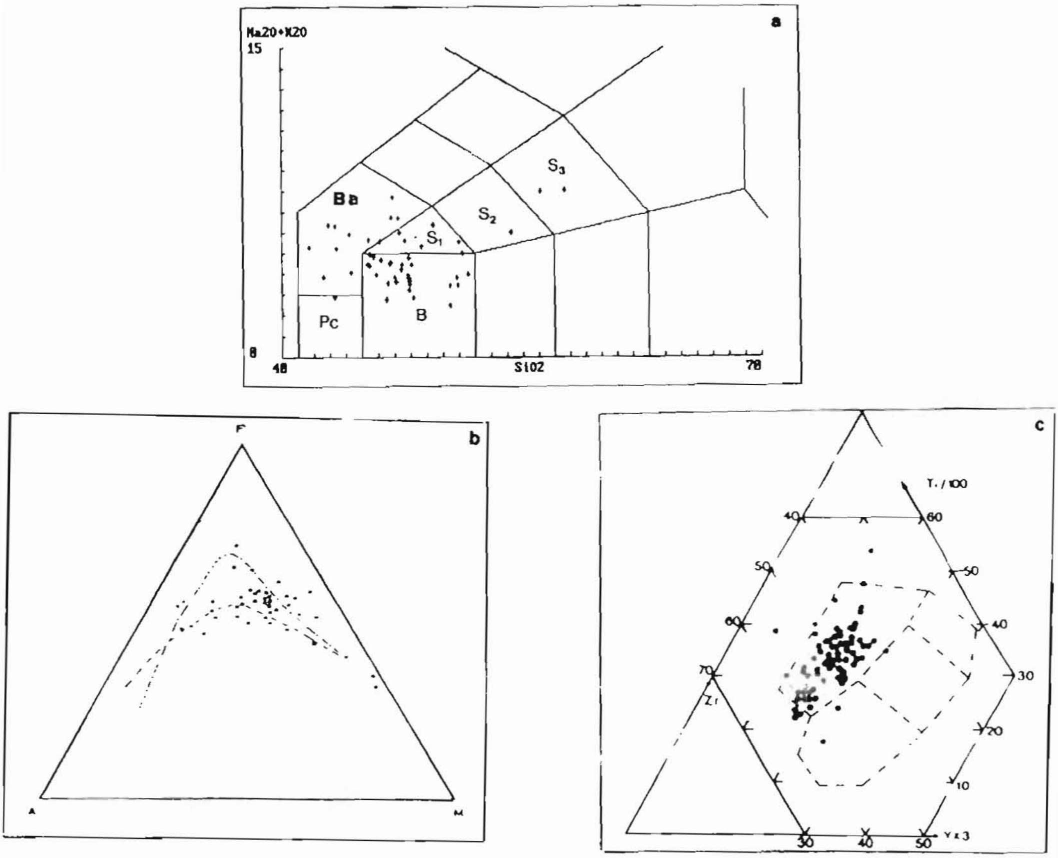

Fig.5 The petrochemistry of YTS basalts is plotted in (a) the total alkali-versus silica diagram (after Le Bas et al. 1986), (b) AFM diagram after Macdonald and Katsura, 1964. -.-.-.-.-.-. Hawaiian tholeiitic trend, - - - - - - Hawaiian alkalic trend, and (c) Ti-Zr-Y diagram.

Barager (1971), basic members of Yemen volcanic rocks are characterized by alkali basalt (most of the samples of the northern regions), and by subalkaline basalt (most of the samples of the southern regions); only few samples occur along this field boundary. The more differentiated samples (undersaturated) are plotted in the tephrite - basanite field (Ba), in which they characterize the volcanics of the north regions and restricted to them only. This is also proved by AFM diagram (Fig. 5b), in which rocks from northern regions of YTS point out some differences in the alkali content in comparison with rocks from the southern part. On the other hand few samples are plotted in the hawaiite field (S_1); but the more differentiated rocks form a trend line from mugearite (S_2 field), to benmorite (S_3 field). The samples which lie on the basalt - hawaiite and tephrite - hawaiite fields are considered here as hawaiite.

Basalts from both mentioned localities are plotted in the Ti-Zr-Y diagram, the plotted values fall within plate basalt (WPB) field except few samples of transitional character (Fig. 5c).

MINERAL COMPOSITION

Olivine, pyroxene and plagioclase are the most abundant constituents and freqüently form phenocrysts exceeding in some samples 30-50 % of the bulk.

Ilmenite, magnetite, apatite and less frequently biotite are the common accessories. The secondary minerals are represented by chlorite, epidote, serpentine, iddingsite, carbonate, and rarely amphibole (hornblende).

The glass phase is very rare and was only found in a very few samples, particularly in those lavas related to the Q-Recent volcanics.

In this study we are only focusing on the main constituents.

OLIVINE

Based on microprobe analyses (*Table 2*) olivine phenocrysts have higher forsterite content (Fo_{90-75} in their cores); whereas these values decrease at the rims and within the groundmass (Fo_{75-40}). According to the optical study olivines range from 0.1 mm to 5 mm, forming euhedral to subhedral grains. In some samples olivines are partly altered to serpentine (Fig. 6a) and "iddingsite" (Fig. 6b). Olivines have *mg*-numbers ranging from 0.39 to 0.91.

The Mg content of Marib basalts has the highest value (MgO = 49.13%) among the analysed basaltic rocks of Yemen. Their *mg*-numbers (0.91) are also high, therefore, they may be considered to be of deeper origin perhaps from the upper mantle. They are similar in their composition to those olivine xenocrysts described by Kurat (1971) , Dietrich and Poultidis (1985).

Taking into consideration the lowest contents obtained from the Aden area (*mg*-numbers = 0.39), which indicates a shallow magma origin in relation to Marib (*mg*-number = 0.91), the latter can be regarded as an indirect evidence of deeper magma origin, in which the continental crust becoming thinner E-ward (Balhaf, Al-Gawf-Marib *etc.*) .

The *mg*-number values decrease at the rims and in the groundmass.

The NiO content slightly increases with increasing MgO (Fig. 7a), and the CaO, MnO and FeO are decreasing. The MnO content ranges between 0.19-2% (southern part of YTS) and it reaches the maximum in the Fe-enriched olivines and Mg-depleted particularly at the rims of some olivine crystals (*e.g.* Dhala and Am-Shatt areas in the southern part of Yemen Trap Series), but the MnO (0.12-0.63 wt%) decreases (Fig. 7b) through the connecting line between Ibb and Sanaa.

The CaO content in relation to FeO has linear distribution, but this distribution becomes concentrated with decreasing FeO content (Fig. 7c, southern part of Yemen Trap Series)

PYROXENE

Their grain size ranges from 1 mm to 7 mm. Some of the crystals have simple twinning. Zoning commonly occurs, but concentric zoning and hour-glass structure are not uncommon (Fig. 8 a,b,c,d).

Based on microprobe analyses (*Table 1*), pyroxenes show a compositional variation from diopsidic to salitic and to augitic (Fig. 9a).

In the light of the diagram drawn by Leterrier *et al.* (1982), the majority of our pyroxenes compositions plot within the alkali basaltic clinopyroxene (Fig. 9b). According to their Cr, Mg, Fe and Al contents they can also be subdivided as follows: Chromian Ferroan DIOPSIDE, Aluminian Chromian Ferroan DIOPSIDE,

Table 1. Representative microprobe analyses (average of 150 point analyses) of clinopyroxene from Yemen volcanics.

	1	2	3	4	5	6	7	8
	MT-2	MT-5	MT-6	MT-14	MT-15	MT-18	MT-19	MT-27
MgO	13.80	11.75	13.44	12.88	13.06	13.79	14.92	14.95
Al_2O_3	3.73	5.35	2.80	4.57	8.26	5.38	5.13	2.88
SiO_2	48.49	46.28	48.90	47.39	46.57	47.89	47.50	49.76
CaO	24.17	24.15	20.30	24.67	22.26	22.35	24.07	20.32
TiO_2	1.87	2.96	1.65	2.38	1.67	1.57	1.77	1.25
MnO	0.00	0.09	0.21	0.00	0.10	0.11	0.00	0.34
FeO	7.77	9.25	12.92	8.44	7.67	8.50	6.72	10.62
Cr_2O_3	0.25	0.00	0.00	0.00	0.05	0.15	0.52	0.00
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	100.08	99.83	100.22	100.33	99.64	99.74	100.63	100.12
T site								
Si^{4+}	1.805	1.746	1.842	1.767	1.734	1.786	1.744	1.855
Al^{IV}	0.144	0.238	0.124	0.201	0.266	0.214	0.222	0.127
Fe^{3+}	0.031	0.016	0.034	0.032	0.000	-	0.034	0.018
TOTAL:	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
M1 site								
Al^{VI}	-	-	-	-	0.097	0.023	-	-
Fe^{3+}	0.083	0.086	0.065	0.099	0.074	0.098	0.143	0.076
Ti^{4+}	0.052	0.084	0.047	0.067	0.047	0.044	0.049	0.035
Cr^{3+}	0.007	-	-	-	0.001	0.004	0.015	-
Mg^{2+}	0.766	0.661	0.754	0.716	0.725	0.767	0.793	0.831
Fe^{2+}	0.092	0.169	0.134	0.118	0.056	0.064	-	0.058
TOTAL:	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
M2 site								
Mg^{2+}	-	-	-	-	-	-	0.024	-
Fe^{2+}	0.036	0.021	0.174	0.014	0.109	0.103	0.029	0.179
Mn^{2+}	-	0.003	0.007	-	0.003	0.003	-	0.011
Ca^{2+}	0.964	0.976	0.819	0.986	0.888	0.893	0.947	0.811
TOTAL:	1.000	1.000	1.000	1.000	1.000	0.999	1.000	1.001
CAT#:	4.038	4.034	4.033	4.044	4.025	4.03[illegible]	4.060	4.032
OXNUM:	5.999	6.000	6.001	6.000	6.000	5.9[illegible]	6.000	6.002

IMA name:

MT-2 - aluminian Ferroan DIOPSIDE
MT-5 - aluminian subsilicic Ferroan DIOPSIDE
MT-6 - aluminian (Magnesium-rich) AUGITE
MT-14 - aluminian Ferroan DIOPSIDE
MT-15 - aluminian subsilicic Ferroan DIOPSIDE
MT-18 - aluminian Ferroan DIOPSIDE
MT-19 - aluminian chromian subsilicic Ferroan DIOPSIDE
MT-27 - aluminian (Magnesium-rich) AUGITE

MT-15 - aluminian subsilicic Ferroan DIOPSIDE
MT-18 - aluminian Ferroan DIOPSIDE
MT-19 - aluminian chromian subsilicic Ferroan DIOPSIDE
MT-27 - aluminian (Magnesium-rich) AUGITE

	9	10	11	12	13	14	15	16
	THAM	2247b	2557	2246b	2409	2367	2576	2627
MgO	13.54	13.41	13.78	13.77	13.02	15.14	13.48	13.20
Al_2O_3	5.85	5.77	3.19	4.51	1.97	3.44	3.55	3.73
SiO_2	46.79	47.04	50.82	48.91	51.24	50.89	49.56	49.30
CaO	23.84	23.94	21.18	23.21	20.92	22.53	21.47	21.84
TiO_2	2.04	2.19	0.98	1.60	0.79	1.04	1.73	1.96
MnO	0.09	0.05	0.39	0.13	1.02	0.16	0.28	0.25
FeO	7.44	7.60	9.03	6.66	11.12	6.38	9.27	9.29
Cr_2O_3	0.17	0.14	0.00	0.27	0.15	0.28	0.03	0.02
Na_2O	0.00	0.00	0.46	0.51	0.58	0.50	0.67	0.69
Sum	99.76	100.14	99.83	99.57	100.81	100.36	100.04	100.28
T site								
Si^{4+}	1.743	1.748	1.894	1.816	1.909	1.866	1.845	1.833
Al^{IV}	0.257	0.252	0.106	0.184	0.086	0.134	0.155	0.143
Fe^{3+}	-	-	-	0.000	0.005	-	-	0.004
TOTAL:	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
M1 site								
Al^{VI}	-	0.001	0.034	0.014	-	0.015	0.001	-
Fe^{3+}	0.138	0.124	0.050	0.109	0.084	0.090	0.105	0.104
Ti^{4+}	0.057	0.061	0.027	0.045	0.022	0.029	0.048	0.055
Cr^{3+}	0.005	0.004	-	0.008	0.004	0.008	0.001	0.001
Mg^{2+}	0.752	0.743	0.766	0.762	0.723	0.827	0.748	0.732
Fe^{2+}	0.048	0.067	0.123	0.062	0.167	0.031	0.097	0.106
TOTAL:	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
M2 site								
Fe^{2+}	0.046	0.045	0.108	0.036	0.090	0.075	0.087	0.073
Mn^{2+}	0.003	0.002	0.012	0.004	0.032	0.005	0.009	0.008
Ca^{2+}	0.952	0.953	0.846	0.924	0.835	0.885	0.856	0.870
Na^{+}	-	-	0.033	0.037	0.042	0.036	0.048	0.050
TOTAL:	1.001	1.000	0.999	1.001	0.999	1.001	1.000	1.001
CAT#:	4.046	4.042	4.017	4.037	4.030	4.030	4.035	4.037
OXNUM:	6.001	5.999	5.999	6.001	5.999	6.002	6.000	6.001

IMA name:

THAM - aluminian subsilicic Ferroan DIOPSIDE
2247b - aluminian subsilicic Ferroan DIOPSIDE
2557 - aluminian (Magnesium-rich) AUGITE
2246b - aluminian Ferroan DIOPSIDE
2409 - (Magnesium-rich) AUGITE
2367 - aluminian Ferroan DIOPSIDE
2576 - aluminian Ferroan DIOPSIDE
2627 - aluminian Ferroan DIOPSIDE

2409 - (Magnesium-rich) AUGITE
2367 - aluminian Ferroan DIOPSIDE
2576 - aluminian Ferroan DIOPSIDE
2627 - aluminian Ferroan DIOPSIDE

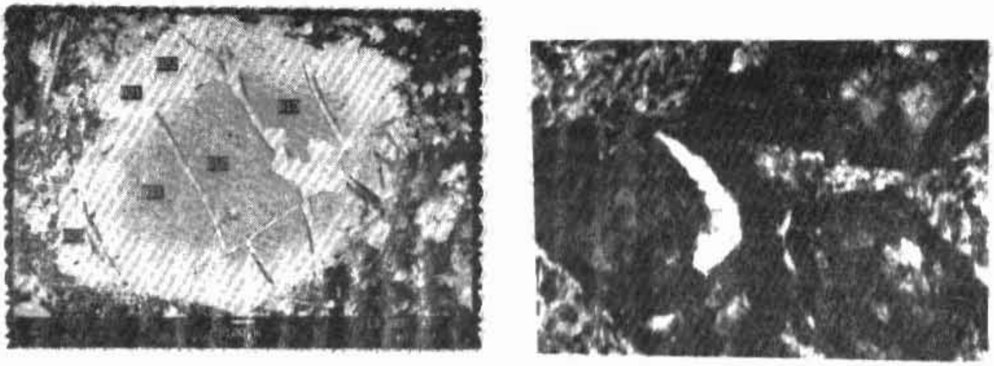

Fig.6 Scanning electron images of olivine phenocrysts. The alteration to serpentine can be seen through the cracks as well as at the rims. Fo$_{81}$ the average content in the core, Fo$_{61}$ the average content at the rim (a), and (b) shows the alteration of olivine to iddingsite. Magnification: 54X, +N.

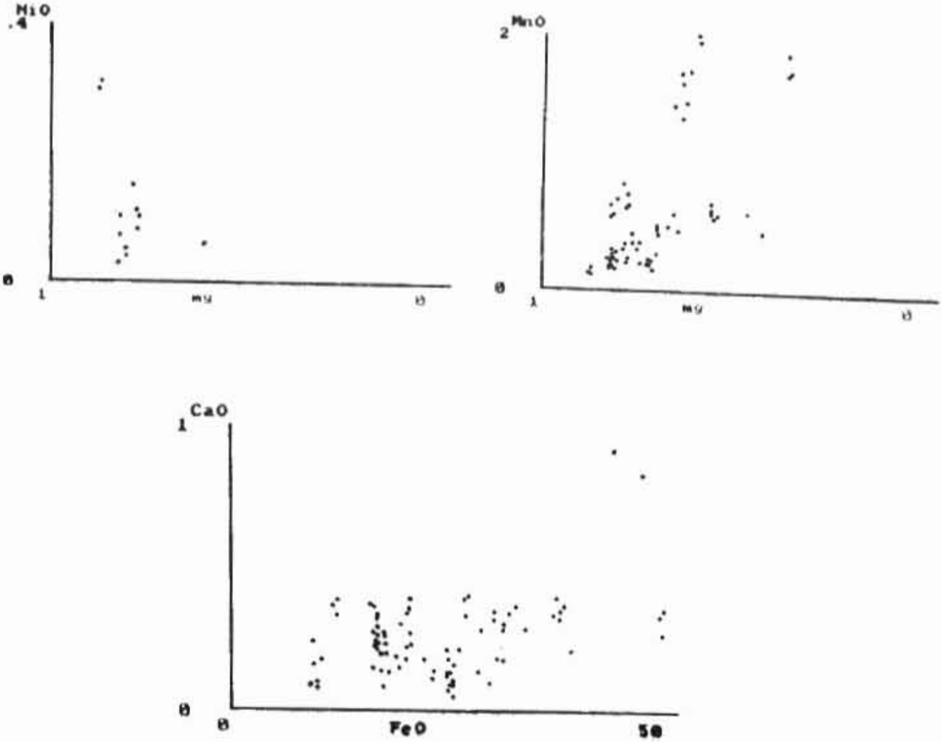

Fig.7 Variation of NiO (a) and MnO (b) versus mg-number and (c) shows the variation of CaO versus FeO, in the olivines of Yemen alkali basalts.

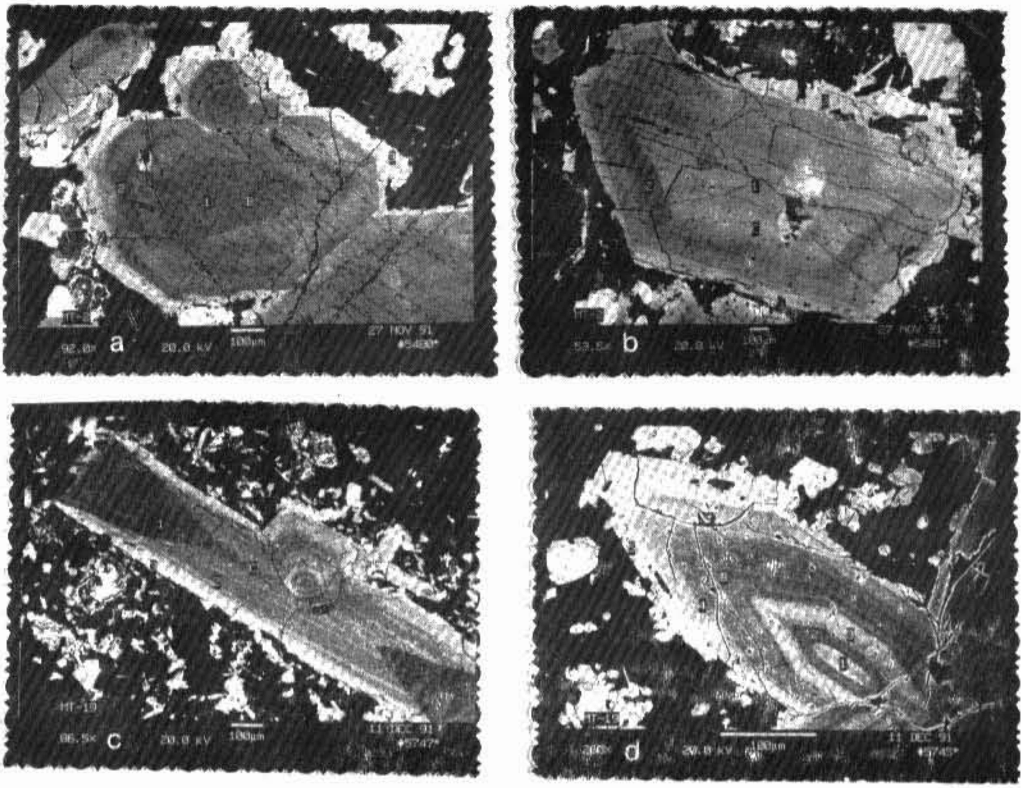

Fig.8 Scanning electron images of zoned (a,b) and hour-glass structure (c,d) of clinopyroxene phenocrysts. The numbers shown on the crystals indicate the points analysed by microprobe.

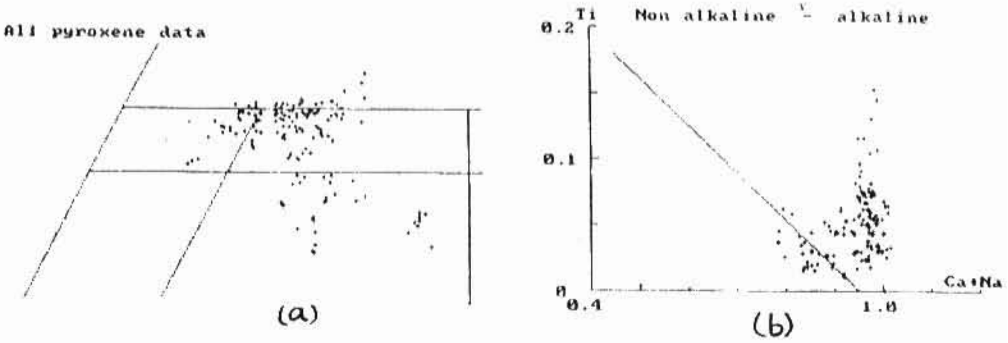

Fig.9 Composition of clinopyroxenes of Yemen alkali basalts (a) and (b) shows that the analysed phenocrysts are plotted within the alkali basaltic clinopyroxene (see text).

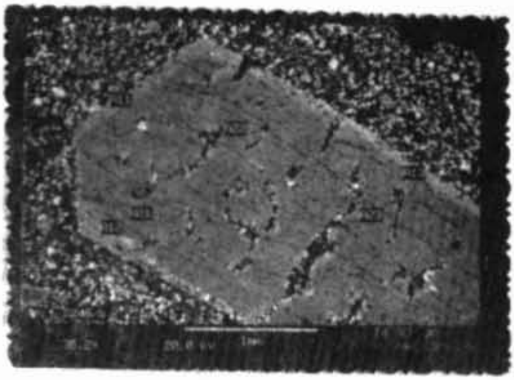

Fig. 10 Scanning electron images of titanaugite phenocryst. The average content of the TiO_2 in the core is 1.07%, and the average at the rim is 2.23%.

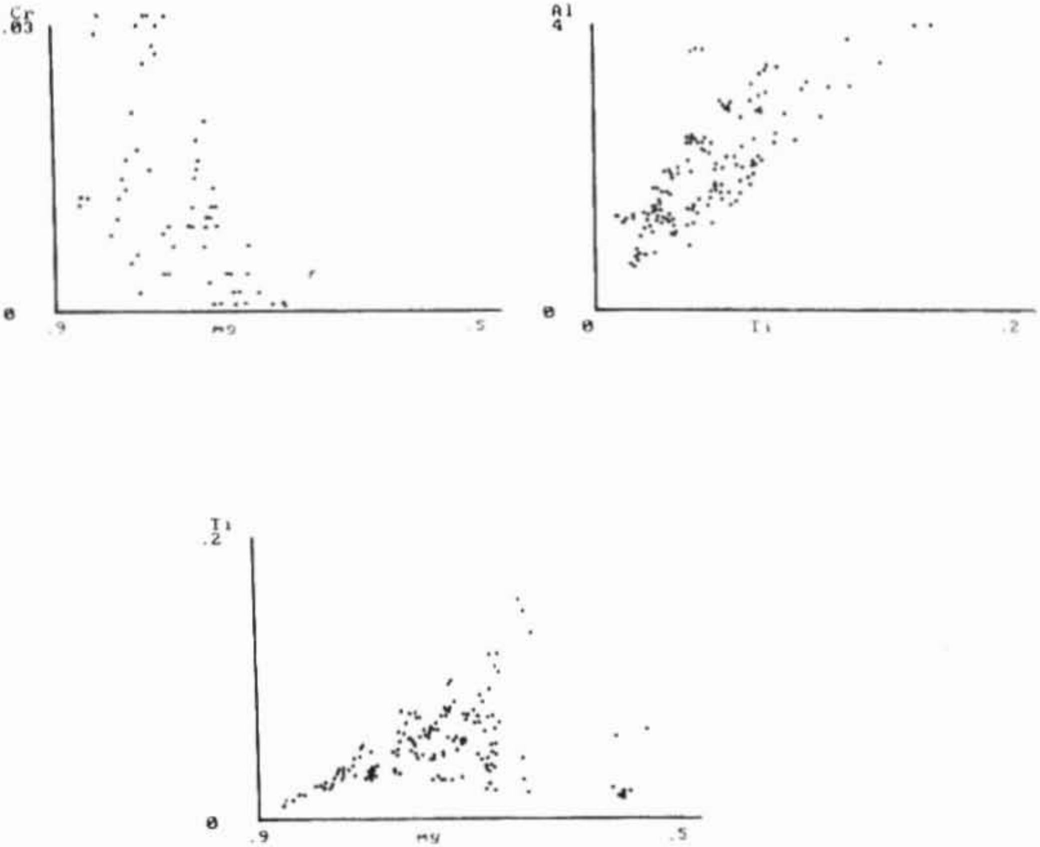

Fig. 11 (a) The variation of Cr versus mg-nuber, (b) shows the Al/Ti content and (c) illustrates the Ti versus mg-number.

Aluminian Chromian Subsilicic Ferroan DIOPSIDE, Aluminian Ferroan DIOPSIDE, Aluminian subsilicic Ferroan DIOPSIDE, Aluminian Titanian Subsilicic Ferroan DIOPSIDE, [Magnesium-rich] Augite and Aluminian [Magnesium-rich] Augite. It is worth to mention that the augite is the most common and it is mostly euhedral. Titanaugite was also observed mainly at the rims of the pyroxene grains (Fig. 10). In some samples, pyroxene has been partly altered to chlorite, carbonate, epidote, and rarely uralitized (hornblende).

The Cr content of the clinopyroxene increases with increasing *mg*-numbers and attains the maximum value through the interval (0.7-0.9 *mg*-numbers). The Cr_2O_3 content in the core of some pyroxene crystals (Aluminian Chromian Ferroan DIOPSIDE) ranges up to 1.09 wt%, but the Cr_2O_3 content decreases at the rims and within the groundmass (Fig. 11a).

However, Dobosi *et al.* (1991) in their study found that the Cr content increases in those sectors having Ti-enrichment. The results found in our study are not in conformity with their findings, since our analyses showed that the Cr content decreases with increasing Ti. Some of our pyroxenes (Ti-poor sectors) are also having more Si, Mg and less Fe and Al.

Al_2O_3 and TiO_2 have wide variation ranging between 0.40-5.34% for TiO_2 and 1.39-8.88% for Al_2O_3. The relationship between Al and Ti distribution is given in (Fig. 11b). It shows that the Al content increases with increasing Ti .

The Ti/Al ratio can be considered as an approximation for a qualitative indication of the pressure prevailing during crystallization (Clark *et al.*, 1962; Kushiro, 1969). According to most of our analyses of the pyroxenes, the Ti/Al ratio varies between 0.1-0.2, which indicates high pressure origin. This ratio is higher at the rims of the pyroxene crystals rather than in their cores, a particular characteristic of the titanaugite varieties, indicating lower pressure than that of the above mentioned pyroxene cores. On the other hand, the high Al^{vi} content and high Al^{vi}/Al^{iv} ratio also indicates high pressure origin (Aoki and Kushiro, 1968; Wass,1979). This ratio in our samples is between 0.30 and 0.40 in the cores and <0.26 at the rims and within the groundmass. The latter value indicates lower pressure respectively. The majority of the Ti contents are increased with decreasing *mg*-numbers, with exception of few samples (Fig. 11c).

PLAGIOCLASE

Their grain sizes range from 1 mm to 8 mm. Albite, carlsbad and pericline twinns are characteristic features. Zoning is also common (Fig. 12 c,d).

Based on microprobe analyses (*Table 3*), the plagioclase composition ranges between labradorite-bytownite. The highest An contents in our studied samples reached An_{87-63}, in which the lower value characterizes the An content at the rims (Fig. 12 a,b).

Plagioclase within the groundmass has an average composition of laboradorite-andesine (An_{61-40}), but in some samples the An content declines (andesine composition). The plagioclase has partly been altered into carbonate and epidote.

The groundmass also consists of augite (being strongly altered into chlorite) and euhedral crystals of olivine ± opaque minerals (ilmenite ± magnetite).

CONCLUSIONS

Yemen volcanics are parts of an extensive elongate outcrops associated with the Red Sea, Gulf of Aden and Afar (Ethiopia) rifts. They have been generated in the Late Oligocene-Early Miocene (synrift phase) and in the Late Miocene to Recent (postrift phase), and are mainly composed of basaltic rocks. The YTS emplaced in Oligocene and reached the maximum activity in Early Miocene times, in which both fissural and central eruptions took place. These volcanic complexes had been affected by faulting mainly of NW trend (Red Sea trend) and E-NE trend (Gulf of Aden trend). According to the available radiometric age data the Tertiary intrusive bodies (alkali granite, syenite *etc.*.) are closely associated with the Tertiary volcanics (YTS).

Yemen alkali olivine basalts have generated by fractional crystallization (differentiation). Duda and Schmincke, 1985; Bedard *et al.*, 1988; Dobosi, 1989 showed in their study that zoned pyroxenes are the best records of magma evolution. In our samples, zoning and hour-glass structure are common and characteristic features of the analysed pyroxenes, this gives good information about the evolution of the basaltic magma. The chemical composition of the pyroxenes proves that the magma had been crystallized and developed in deep (elevated pressure) and shallow magma chambers. The ratio of Al to Ti in the clinopyroxenes, the wide

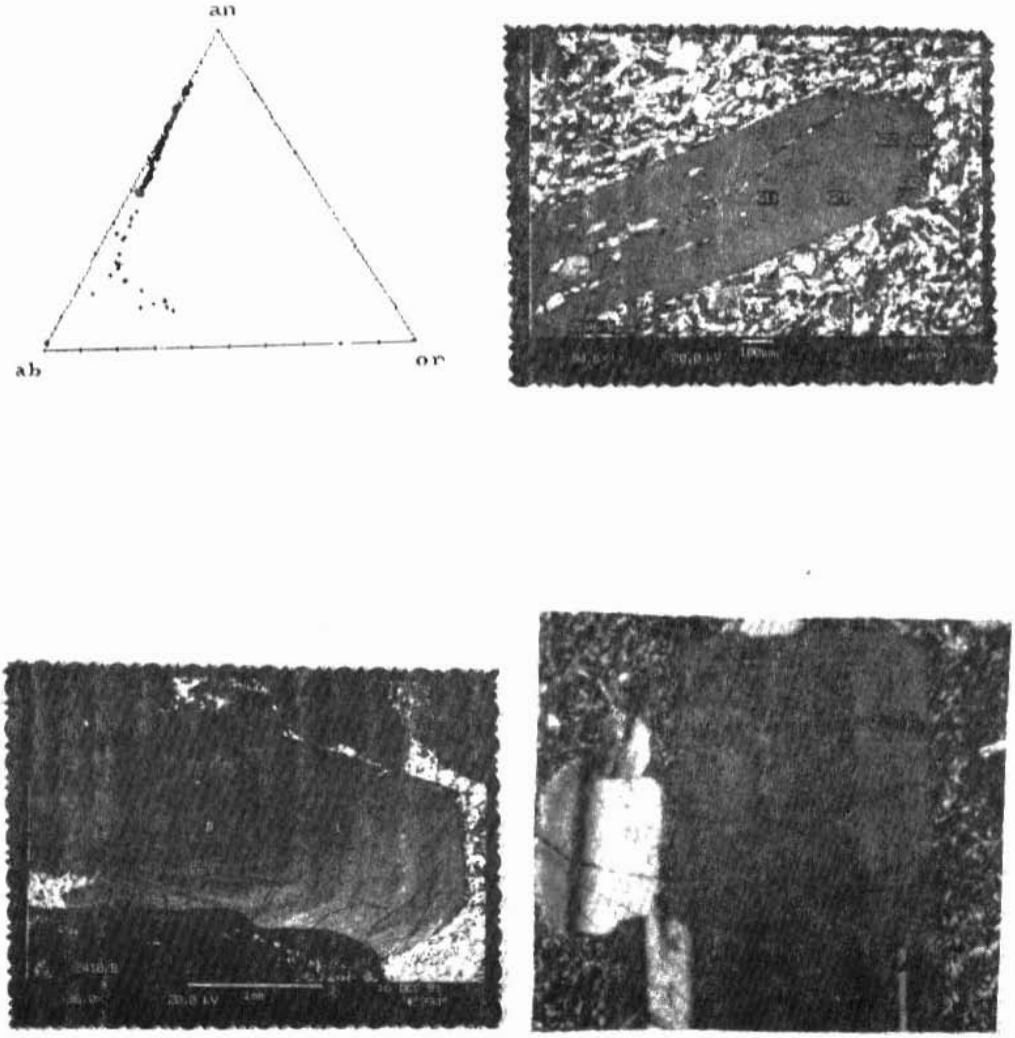

Fig.12 (a) An-Ab-Or ternary diagram illustrates the composition of the feldspars from Yemen alkali basalts,(b) scanning electron images of feldspar phenocryst having an average content of An_{78} *in the core and* An_{63} *at the rim. Zoning is also shown by the scanning electron images (c) and by theoptical microscope (d). Magnification : 34X + N.*

	1 o-1	2 o-2	3 o-3	4 o-4	5 o-5	6 o-6	7 o-7	8 o-8	9 o-9	10 o-10	11 o-11	12 o-12	* 13 o-13	14 o-14	15 o-15	16 o-16	17 o-17	18 o-18	19 o-19	20 o-20
SiO_2	39.43	39.48	39.33	39.36	39.46	38.37	38.34	38.41	38.29	39.82	38.43	36.02	35.56	33.53	36.13	36.22	36.41	36.23	36.27	36.27
Al_2O_3	0.43	0.37	0.44	0.46	0.38	0.43	0.39	0.47	0.30	0.43	0.47	0.25	0.36	0.35	0.61	0.51	0.38	0.32	0.39	0.47
FeO	16.18	16.25	17.16	17.30	17.19	19.77	19.74	19.93	18.86	16.38	16.20	30.27	32.94	33.00	29.32	29.46	27.98	30.53	31.04	30.51
MnO	0.30	0.44	0.31	0.31	0.31	0.75	0.63	0.64	0.83	0.30	0.59	1.33	1.95	2.08	1.43	1.70	1.45	1.48	1.73	1.47
MgO	43.09	43.05	42.18	42.17	41.97	40.42	40.36	40.16	41.21	43.31	42.90	33.33	29.35	29.28	31.87	31.94	32.76	31.26	32.03	31.30
CaO	0.29	0.22	0.27	0.28	0.23	0.33	0.34	0.39	0.30	0.33	0.32	0.18	0.29	0.37	0.35	0.32	0.28	0.28	0.34	0.30
NiO	0.03	0.03	0.05	0.00	0.04	0.11	0.08	0.10	0.15	0.07	0.10	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Sum.:	100.37	100.66	100.34	100.43	100.18	100.40	99.96	100.18	100.19	100.22	99.29	100.48	100.35	117.71	100.11	100.15	99.46	100.18	100.95	100.40
	olivine cation number on the basis of 4 oxygens										olivine cation number on the basis of 4 oxygens									
Si	1.002	0.998	0.996	0.998	1.000	0.988	0.989	0.996	0.983	0.986	0.986	0.977	0.981	1.006	0.981	0.983	0.986	0.987	0.983	0.985
Al	0.012	0.011	0.019	0.013	0.017	0.012	0.011	0.014	0.015	0.012	0.014	0.008	0.011	0.014	0.019	0.016	0.018	0.010	0.010	0.011
Fe	0.340	0.343	0.362	0.363	0.364	0.421	0.425	0.429	0.404	0.346	0.347	0.687	0.760	0.752	0.670	0.668	0.634	0.696	0.701	0.693
Mn	0.007	0.014	0.015	0.015	0.013	0.016	0.014	0.014	0.018	0.007	0.013	0.031	0.045	0.037	0.037	0.039	0.032	0.034	0.039	0.033
Mg	1.616	1.622	1.592	1.596	1.586	1.551	1.552	1.541	1.580	1.639	1.623	1.308	1.203	0.964	1.290	1.292	1.323	1.270	1.254	1.270
Ca	0.004	0.003	0.007	0.005	0.006	0.009	0.009	0.010	0.008	0.008	0.008	0.005	0.008	0.008	0.010	0.009	0.008	0.008	0.009	0.008
Ni	0.000	0.000	0.001	0.000	0.000	0.002	0.002	0.002	0.003	0.001	0.002	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
CATI:	2.998	2.993	2.993	2.992	2.988	3.001	3.001	3.000	3.009	3.004	3.003	3.014	3.008	2.003	3.007	3.007	3.002	3.005	3.003	3.004
mg:	0.83	0.83	0.81	0.81	0.81	0.79	0.79	0.78	0.80	0.83	0.82	0.66	0.62	0.62	0.66	0.66	0.68	0.65	0.64	0.65
Fa:	17.38	17.46	18.57	18.61	18.67	21.43	21.50	21.78	20.36	17.43	17.53	34.44	38.72	38.09	34.18	34.08	32.40	35.40	35.93	35.30
Fo:	82.62	82.54	81.43	81.39	81.33	78.57	78.50	78.22	79.64	82.57	82.47	65.56	61.28	61.91	65.82	65.92	67.60	64.60	64.08	64.70
CATI-Si:	1.99	2.00	2.00	1.99	1.99	2.01	2.01	2.00	2.03	2.02	2.02	2.04	2.03	1.42	2.02	2.02	2.02	2.02	2.02	2.02

Table 2. Microprobe analyses of olivine from Yemen Trap Series and Yemen Volcanic Series.

	21 k-21	22 k-22	23 k-23	24 k-24	25 k-25	26 k-26	27 k-27	28 k-28	29 k-29	30 k-30	31 at-13	32 at-13	33 at-19	34 at-19	35 at-19	36 at-18	37 at-18	38 at-18	39 at-18	40 at-18
SiO_2	51.38	55.80	55.46	54.84	50.87	50.85	50.89	47.84	48.79	47.77	4.03	4.12	4.70	4.12	4.96	2.96	1.00	1.98	4.30	4.73
Al_2O_3	29.88	26.97	26.93	27.70	30.81	29.78	30.15	32.67	32.16	32.13	28.76	28.35	28.54	28.87	27.62	29.73	30.18	29.63	28.83	28.30
FeO	1.17	1.00	1.34	1.14	0.74	0.79	0.73	0.57	0.61	0.79	51.33	50.38	51.70	50.60	52.03	49.30	49.29	49.43	50.49	51.02
CaO	13.45	10.52	10.46	10.75	13.83	13.75	13.63	17.05	16.75	16.11	0.27	0.28	0.37	0.30	0.36	0.29	0.28	0.28	0.25	0.34
Na_2O	3.77	5.50	5.23	4.87	3.82	3.68	3.52	2.09	2.26	2.70	15.87	15.35	14.14	14.53	13.29	15.92	16.30	15.61	14.81	14.37
K_2O	0.21	0.49	0.53	0.47	0.30	0.33	0.33	0.18	0.19	0.27	0.96	0.79	1.01	1.23	0.96	0.52	0.48	0.38	0.83	1.02
Sum.:	99.86	100.16	99.96	99.27	99.32	99.18	99.23	99.33	99.65	99.76	101.74	99.36	100.41	99.81	99.15	99.70	100.25	99.31	100.71	100.23
	feldspar cation number on the basis of 8 oxygens										feldspar cation number on the basis of 8 oxygens									
Si	2.371	2.525	2.517	2.503	2.326	2.345	2.340	2.179	2.226	2.208	0.356	0.369	0.417	0.387	0.444	0.353	0.329	0.338	0.378	0.423
Al	1.581	1.436	1.439	1.463	1.623	1.617	1.634	1.782	1.711	1.730	1.546	1.542	1.541	1.569	1.596	1.625	1.629	1.621	1.553	1.550
Fe	0.042	0.037	0.050	0.043	0.028	0.030	0.028	0.029	0.024	0.030	2.341	2.344	2.348	2.330	2.408	2.284	2.271	2.294	2.332	2.348
Ca	0.665	0.499	0.500	0.525	0.681	0.679	0.671	0.844	0.804	0.798	0.021	[illegible]	0.018	0.017	0.021	0.017	0.011	0.016	0.014	0.019
Na	0.322	0.482	0.461	0.431	0.340	0.325	0.313	0.187	0.196	0.242	0.773	0.777	0.691	0.719	0.634	0.798	0.804	0.776	0.725	0.716
K	0.010	0.028	0.034	0.027	0.017	0.019	0.019	0.020	0.010	0.023	0.033	0.038	0.058	0.067	0.057	0.029	0.018	0.014	0.031	0.059
CATI:	5.010	5.007	5.003	4.992	5.027	5.013	5.003	5.025	5.002	5.043	5.077	5.074	5.076	5.077	5.078	5.087	5.082	5.079	5.071	5.095
mg:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al4:	0.6279	0.4738	0.4836	0.4970	0.6640	0.6330	0.6600	0.8210	0.7740	0.7920	0.6598	0.6560	0.6229	0.6629	0.3920	0.7160	0.7790	0.7060	0.6470	0.6120
Al6:	0.9529	0.9610	0.9560	0.9660	0.9610	0.9620	0.9740	0.9575	0.9760	0.9500	0.8870	0.8870	0.9990	0.9870	0.9140	0.9070	0.9100	0.9150	0.9060	0.8990
Or:	1.7734	2.7730	2.0000	2.7467	1.6279	1.8573	1.8913	[illegible]	0.7537	1.4218	1.8261	1.3829	1.3992	1.5138	1.8767	1.4655	0.9529	1.3913	1.2313	1.4408
Ab:	32.7091	47.7701	46.1461	[illegible]	32.7222	32.7692	31.2964	17.9791	19.4444	22.9384	30.9563	31.8928	36.9332	34.4613	39.6782	30.4310	29.3361	31.1304	35.0044	36.5285
An:	65.5172	49.4569	50.8509	[illegible]	65.1669	66.3734	66.8993	81.1172	79.7619	75.6298	67.2174	66.7293	61.6783	64.0249	58.4450	68.1035	69.6707	67.4783	63.7643	61.8307

Table 3. Representative microprobe analyses of plagioclase from Yemen volcanics.

range of Mg content of the olivine phenocrysts, and the gap of the An content among the plagioclase phenocrysts indicate deep and shallow magma origin respectively.

According to the recent data obtained from seismic and drilling through the coastal plain (offshore) of the Gulf of Aden (Elf Aqu., 1990), and of the eastern side of the Red Sea (Total, 1989), it can be concluded that the thickness of the volcanics (mainly of basaltic composition) may attain more than 3000 m below the sea level.

YTS can partly be correlated in both age and chemical characters with some younger volcanic sequences of Late Oligocene-Miocene in Ethiopia and Saudi Arabia. On the other hand the Late Miocene - Quaternary volcanics of Yemen (YVS) are corresponding to those volcanics reported from Afar volcanic field (Ethiopia) and to those volcanic fields reported from the southern and western parts of Saudi Arabia. They are in accordance in age and in chemical trends.

According to the optical study of many basaltic samples, the presence of olivine in a stable form, and the availabality of titanaugite indicate an alkaline character for these rocks. In general the Yemen volcanics mostly show an alkaline trend, but tholeiitic affinity is partly represented by some basaltic rocks of the YTS e.g. the south-westernmost area (Am-Shatt). It is the nearest part (of the YTS) to the Gulf of Aden, which is probably affected and generated at that time in which the western part of the Gulf of Aden (rift phase) had been generated.

ACKNOWLEDGEMENT

We are indebted to Mr. Saleh Abubaker Bin-Hussainoon Minister of Oil and Mineral Resources, Yemen; to the Chairman and Depuety Chairman of the Mineral Exploration Board, to the General Director of the Geology and Mineral Exploration Department and to Mr. Hussain Ali Mattash for their continuous assistance and advices. Thanks are also due to Professor Dr. Imre Kubovics Head of the Petrology and Geochemistry Department, Melinda Janosi and to all the researchers and workers at the Mineralogical Dept., Petrology and Geochemistry Dept., for their valuable suggesions. We would also like to express our thanks to Dr. Bill Heins (Michigan State University) for his help in reviewing this paper and for his valuable comments.

REFERENCES

AOKI, K. and KUSHIRO I. (1968). Some clinopyroxenes from ultramafic inclusions in Dreiser Weiher, Eifel. Contrib Mineral Petrol 18:326-337 .

ARNO, V., BAKASHWIN, M. A., BAKOR, A. Y., BARBERI, R., BASAHEL, A.,A., DI PAOLA, G. M., FERRARA, G., GAZZAZ, M. A., GIULIANI, A., HEIKEL, M., MARINELLI, G., NASSIEF, A. O., ROSI, M., and SANTACROCE, R., 1980a. Recent volcanism within the Arabian plate: Preliminary data from Harrats Hadan and Nawasif-Al Buqum, in Geodynamic evolution of the Afro-Arabian rift system: Rome, Italy, Accademia Nazionale dei Lincei, p.629-634.

BEDARD, JHJ., FRANCIS, DM., LUDDEN, J.(1988). Petrology and Pyroxene chemistry of Monteregian dykes : the origin of basalts and lamprophyres. Can J Earth Sci 25:2041-2058.

CAPALDI, D., MANATTI, P. and PICCARDO, G. B. (1983). Preliminary investigations on volcanism of the Sadah region Yemen Arab Republic.Bull. Volcanol. 46 (4), 413-427.

CHIESA, S., CIVITTA, L., De FINO, M., La VOLPE, L., ORSI, G. (1989) The Yemen Trap Series: Genesis and evolution of a continental flood basalt province. J. Volc. and Geotherm. Res. 36, 337-350.

CIVITTA, L., La VOLPE, L. and LIRER, L. (1978). K-Ar ages of the Yemen plateau. J. Volcanol. Geoth. Res., 4, 307-314.

CLARK, SP., SCHAIRER, JF., de NEUFVILLE, J. (1962). Phase relations in the system $CaMgSi_2O_6$-$CaAl_2SiO_6$ at low and high pressure . Carnegie Inst Washington year b 61:59-68.

DIETRICH, H. and POULTIDIS, H. (1985). Petrology of ultramafic xenoliths in alkali basalts from Kloch and Stander Kogel (Styria, Australia) . N Jb Min Abh 151: 131-140.

DOBOSI, G. (1989). Clinopyroxene zoning patterns in the young alkali basalts of Hungary and their petrogenetic significance . Contrib Mineral Petrol 101:112-122 .

DOBOSI, G., SCHULTZ-GUTTLER, R., KURAT, G., and KRACHER, A. (1991). Pyroxene Chemistry and Evolution of Alkali Basaltic Rocks from Burgenland and Styria, of Austria Mineralogy and petrology 43: 275-292 .

DUDA, A. and SCHMINCKE, HU. (1985). Polybaric differention of alkali basaltic magmas : evidence from greeacore clinopyroxenes (Eifel,Frg). Contrib Mineral Petrol 91:340-353.

ELF AQUITAINE PETROLEUM - BP EXPLORATION. LASMO.(1990). Republic of Yemen. Aden-Abyan Contract Area. Well Amran-1. Geological Well Report , Aden.

FINAL REPORT (1988). On the Integrated Geological Mapping of the western part of P.D.R.of Yemen. In the scale 1:100000. Geology and Mineral Exploration Dept., Aden-Yemen, Strojexport Prague Czechoslovakia.

FLECK, R. G., COLMEN, R. G., CORNWALL, H. R., GREENWOOD, W. R., HADLEY, D. G., PRINZ, W. C., RATTE, J. C., AND SCHMIDT, D. R., 1973. Potassium-argon geochronology of the Arabian Shield, Kingdom of Saudi Arabia. U. S. Geological Survey Saudi Arabian Project Report 165, 40 p.

HAITHAM, F. M. S. and NANI, A. S. O. (1990). The Gulf of Aden Rift : Hydrocarbone potential of the Arabian sector . Ministry of Oil and Mineral Resources .YEMEN 15p.

IRVINE, T. N. AND BARAGER, W. R., 1971. A guide to the chemical classification of the common volcanic rocks Canadian Journal of Earth Sciences v. 8, p. 523-548.

KURAT,G. (1971). Granat-spinell-Websterit und Lherzolith aus dem Basalttuff von Kapfenstein, steier mark. Tschermaks Mineral Petrogr Mitt 16:192-214 .

KUSHIRO, I. (1969). Clinopyroxene solid solutions formed by reactions between diopside and plagioclace at high pressure . Mineral Soc Amer Spec pap 2: 179-191 .

LE BAS, M. J., LE MAITRE, R. W., STRECKEISEN, A. AND ZANETTIN, B. (1986): A chemical classification of volcanic rocks based on the total alkali-silica diagram. J of Petrology, 27, 745-750p.

LETERRIER, D., MAURY, R. C., THONON, P., GIRARD, D., MARCHAL, M. (1982). Clinopyroxene composition as a method of identification of the magmatic affinities of paleo-volcanic series . Earth Planet Sci. Lett. 59: 139 -154 .

MATTASH, M. A. and BILIK, I. (1990). Volcanic Rocks of Yemen. (IESCA-90) International Geological Conference . Izmir - Turkey.Vol.II: 397-410.

PAUL, C. HESS (1989).Origin of Ignous Rocks. Harvard University Press. Cambridge, Massachusetts. London, England. 263-275.

TOTAL (1989), Janbiyah -1, Final Well Report. Ministry of Oil and Mineral Resources. Sanaa - Yemen.

WASS, SY. (1979). Multiple origin of clinopyroxenes in alkali basaltic rocks . Lithos 12:115-132 .

ZANATTIN, B., JUSTIN VISENTIN E., NICOLETTI M., PICCIRILO E.M., 1980a. Correlation among Ethiopian volcanic formations with special reference to the chronological and stratigraphical problems of the <<Trap Series>>. Atti Convegni Lincei, 47: 231- 252.

ZANATTIN, B., 1992. Evolution of the Ethiopian volcanic province. Mem. Fis. Lincei. s 9, v. 1: 153-181.