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PETROGRAPHIC AND CHEMICAL VARIATIONS IN THE RIFT-RELATED BASIC DYKES OF THE MALKA AREA (LOWER SWAT), N. W. F. P., PAKISTAN

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ABSTRACT

This paper deals with the petrography, mineral chemistry and rock chemistry of dolerite dykes of Malka area (Lower Swat). These dykes intrude Late Palaeozoic Utla granite and consist of variable amounts of plagioclase ($An_{53-59\%}$), clinopyroxene (augite), illmenite, hornblende, biotite, apatite. Altered varieties show amphibole (calcic), plagioclase (An_{21-23}), Fe-Ti oxides, chlorite and epidote.

Clinopyroxene, amphibole (both primary & secondary) and plagioclase have been studied in detail. Chemical composition of these rocks exhibts transitional character between alkaline and sub-alkaline basaltic composition. Major oxides verses S.I. indicate evolved composition for these rocks. Whereas CMAS model of O'Hara (1968) show the fractionation control of plagioclase and clinopyroxene. Compositions of these dolerite dykes indicate their association with rifting of the northern margin of Indo-Pak plate.

INTRODUCTION

Mafic dykes in Peshawar plain alkaline igneous province and adjoining areas

Mafic dykes and sills intrude rocks of Peshawar Plain Alkaline Igneous Province (PPAIP) and inspite of their spatial insignificance, these constitute an important lithological component of PPAIP. Besides PPAIP, mafic dykes are also reported from Attock- Cherat Ranges (Tahirkheli, 1970), southern Hazara (Calkins et al., 1975), Mansehra (Shams et al., 1968) and Malakand (Chaudhry et al., 1976). In PPAIP mafic dykes are reported from Shewa-Shahbazgarhi (Ahmad, 1986) and Ambela (Rafiq, 1987).

In Attock-Cherat Ranges, the mafic dykes are doleritic in composition. These intrude Precambrian slates, Siluro-Devonian limestones and phylites, and Permian limestones in the form of swarms (Yeats & Hussain, 1987). Best exposures occur in the vicinity of Ziarat Kaka Sahib, Dang Dang, Katti Miana and Kund villages (Karim & Sufyan, 1987).

In the Khyber agency mafic dykes are present in almost all the Paleozoic Formations, e.g., Landikotal Formation, Shagi Lime stone, Ali Masjid Formation and Khyber Limestone (Khan et al., 1970; Shah & Sidiqui, 1980), though rarer in some units. Khyber Limestone, Carboniferous to Permian in age (Shah & Sidiqui, 1980), is heavily intruded by basic dykes and sills. The dykes are 4.56 to 6.08 m thick and are mostly altered (Shah and Sidi qui, 1980). Dolerite dykes are also present in various parts of the Tarbela Alkaline Complex; generally intruding the basic rocks and metasedimentary sequence (Jan et al., 1981).

Dykes and sills of doleritic composition occur extensively in the Manshera-Amb state area of Hazara Division (Shams and Ahmed, 1968; Le Fort et al., 1980). With a maximum thickness of upto 40 m and with an east- west extension, the individual dykes are traceable for about half a kilometer. In Hazara Division, dykes and sills intrude Manshera granite and tourmaline granite of Hakale, and have been subjected to varying degree of metamorphism (from unaltered dolerites to garnet amphibolites Ahmed, 1985).

Dolerite dykes are also reported intruding the riebeckite gneiss and aegirine reibeckite porphyry of Shewa-Shabazgarhi complex, Mardan (Ahmad, 1986). Rafiq (1987) described dolerite, hornblen dite and lamprophyre dykes from the Ambela granitic complex. According to his report, dolerites (hornblende rich) are the most extensively developed dykes in this area. Individual dykes vary in thickness from 50 cm to 7 m and run for distances ranging from few meters to hundreds of meters.

Dolerite dykes are also present in the Gadoon area of Swabi district and adjacent Lower Swat-Buner region. These are extensively distributed in a 6 km wide belt between Utla in the south and Nagri in the north (Fig. 1).

In the present study, dolerite units within a three sq. km area around Malka village, between latitude 34° 15' 28" to 34° 15' 68" and longitude 72° 45' 68" to 72° 45' 74" on toposheet # 43B/11, were mapped on 1 " = 1000 m scale in June 1990 (Fig. 2). Samples from 13 dolerite dykes were obtained for petrographic and chemical studies.

Emphasis has been placed on implying the petrochemical indices of the studied samples as genetic indicators and tectonic fingerprints. Correspondence with the available data from dolerites in the adjoining area (e.g., Attock-Cherat Range) and equivalent rocks in similar environment has also been discussed.

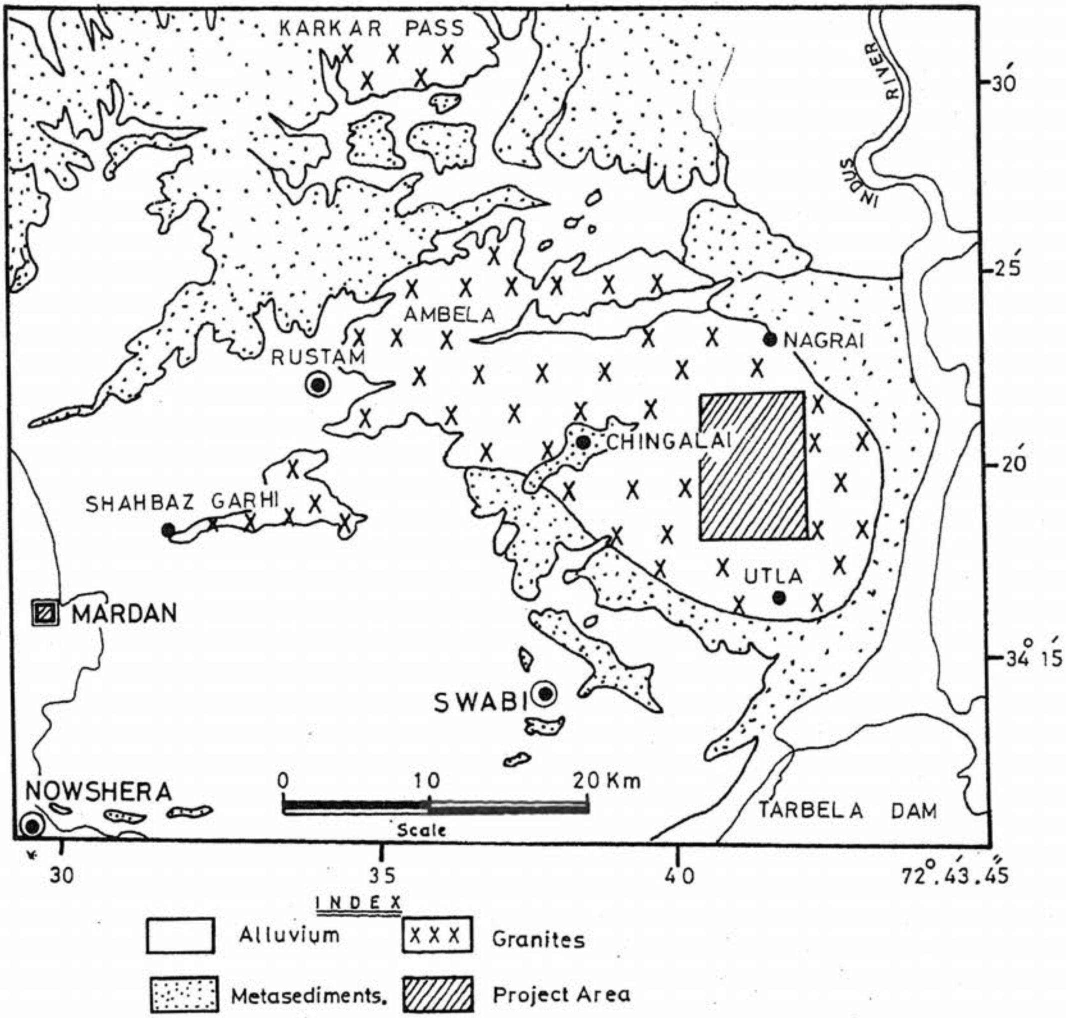

Fig. 1. Index map of Pakistan showing the location of the studied area (modified after Rafiq, 1987).

PETROGRAPHY

Dolerites from the studied area are mostly medium grained. These intrude the Utla granite which is porphyritic and coarse granied. In these rocks, the most abundant minerals are plagioclase and clinopyroxene. However, in altered varieties amphibole and plagioclase are the dominant minerals. Plagioclase constitutes 20 to 60 % by volume in these rocks. It is mostly subhedral to anhedral and medium to fine grained. It is twinned and zoned. Zoning is of continuous as well as osillatory types. In most of the thin sections, the plagioclase is partially altered to epidote or clay minerals.

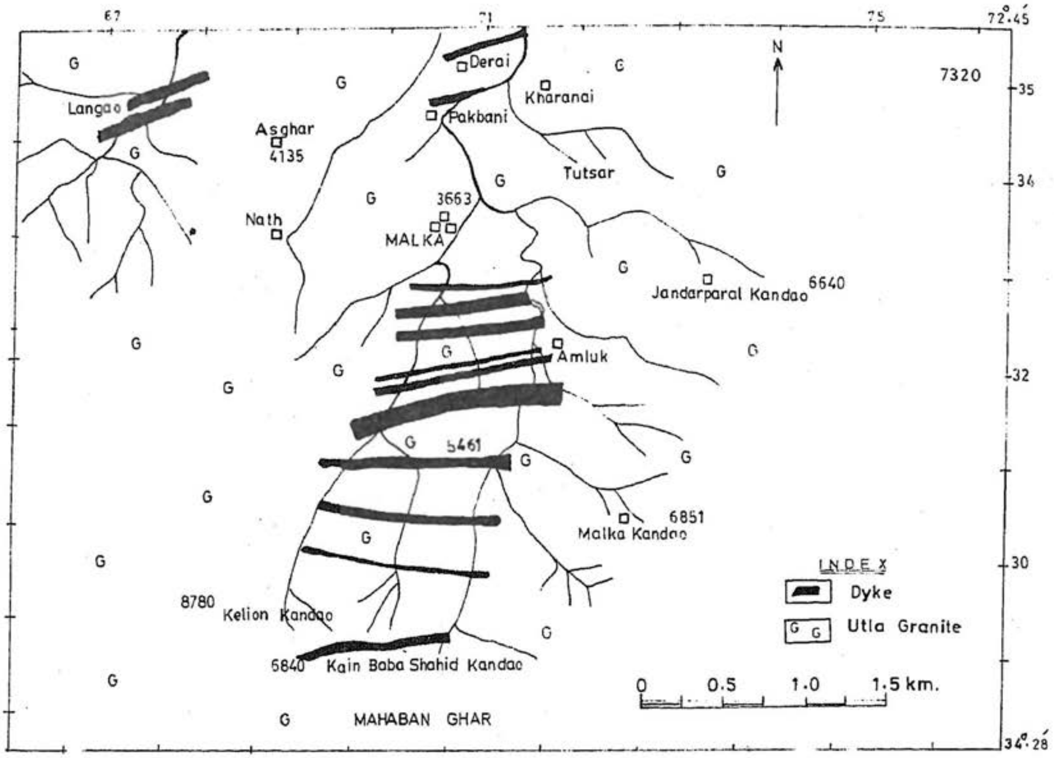

Fig. 2. Map of Malka area showing outcrops of dolerites.

In fresh sections of dolerites, clinopyroxene is next to plagioclase in abundance. It is mostly granular, but anhedral to subhedral crystals are also common. Clinopyroxene is usually altered to chlorite, epidote and amphiboles. Some zoned crystals of clinopyroxene show a homogeneous core, surrounded by a continuously normal zoned mantle. Clinopyroxene ranges from traces to about 34% by volume in these sections (Table 1).

Both primary and secondary (pseudomorphic) magnetite and illminite are the most common opaque minerals (Fe- Ti oxides) in these rocks. These are mostly skeletal in form but longitudinal and bladed crystals are also not uncommon. Two types of amphibole grains have been identified. Primary amphibole, usually brown hornblende, and fibrous amphibole (± chlorite and epidote) which has developed due to the alteration of clinopyroxene. Sphene, biotite and apatite are present as accessory minerals. Some samples also show glass in thin sections. A variety of textures are seen in thin sections of the studied samples. The most common textures are: 1) ophitic, 2) subophitic, 3) spherulitic, 4) intrafasiculate, and 5) cumulate.

TABLE 1. MODAL COMPOSITION OF DOLERITES (MOSTLY FRESH) (VISUAL ESTIMATES)

	M5	M6A1	M6A2	M9A	M11B	M12	Y	M2
Plagioclase	50	48	50	48	55	56	55	45
Clinopyroxene	33	30	33	25	34	31	34	10
Fe-Ti Oxides	5	5	6	4	12	12	6	5
Amphibole*	-	5	5	16	-	-	-	27
Chlorite	4	4	3	4	1	-	2	8
Epidote	4	5	1	1	-	-	1	5
Myrmekite	-	2	1	1	-	1	1	-
Apatite	1	1	1	1	-	Tr	Tr	Tr
Biotite	3	Tr	-	Tr	Tr	-	1	Tr
Quartz	Tr	-	-	-	-	-	-	-

	M9	M9C	M10	M11	X	Z	AS1
Plagioclase	44	40	37	40	50	40	46
Clinopyroxene	11	18	14	12	19	8	24
Fe-Ti Oxides	8	8	9	4	7	8	7
Amphibole*	22	19	12	31	8	32	12
Chlorite	5	5	16	5	5	5	2
Epidote	8	8	8	6	5	5	4
Myrmekite	-	-	1	1	-	1	Tr
Clay	-	-	3	Tr	6	1	4
Apatite	2	2	Tr	Tr	Tr	Tr	1
Biotite	Tr	-	-	1	-	Tr	Tr
Quartz	Tr	-	Tr	-	Tr	-	-

*mostly brown hornblende but also includes fibrous amphibole (secondary).

Based on the degree of alteration, following 2 types of dolerites are distinguished.

Dolerites Type 1

Sections, (M5, M9A, M11B, M12 and Y, Table 1) are the best representatives of the fresh dolerites from the studied area. These rocks have fresh plagioclase and clinopyroxene. Primary amphibole (brown hornblende) is also present. Minor alteration of clinopyroxene to epidote, chlorite and amphibole is, however, commonly seen in sections (M2, M9, M9C, M10, M11, X, Z and AS1, Table 1) which are regarded as slightly altered varieties.

TABLE 2. MODAL COMPOSITION OF ALTERED DOLERITES (VISUAL ESTIMATES)

	M3B1	M3B2	M3B3	M4	M6B1	M6B2	M6C	AS2
Amphiboles*	50	52	50	48	50	40	40	46
Plagioclase	20	25	24	28	28	44	40	28
Fe-Ti Oxides	8	5	6	5	4	2	4	4
Clinopyroxene	-	-	-	-	Tr	-	Tr	Tr
Chlorite	12	11	12	9	11	8	11	12
Epidote	8	5	6	6	4	4	3	6
Myrmekite	-	Tr	Tr	2	Tr	Tr	-	1
Clay	-	1	1	2	2	1	-	1
Apatite	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Biotite	-	Tr	-	Tr	-	-	-	-
Quartz	2	1	1	Tr	1	Tr	2	2
Sericite	-	Tr	-	Tr	-	-	-	-

*mostly fibrous with traces of primary amphibole.

Altered Dolerites, Type 2

Rocks of this group are dominantly composed of amphibole, plagioclase, chlorite and epidote (Table 2). Clinopyroxene is altered to amphibole, chlorite and epidote. Fresh clinopyroxene occurs in some sections but only in traces. The brown hornblende is also changed into fibrous form of amphibole. Plagioclase occurs as a mosaic of shapeless grains or as large idioblasts (sections M3B1, M3B2 and M3B3), enclosing strings of amphibole or epidote. It is mostly untwinned. Chlorite is of green colour and varies from (1 to 12 %) by volume in these rocks. Dyke rocks exposed near the Malka village (Fig. 2) are mostly altered while the fresh dolerite samples were obatained from the exposers in the northern slope of Mahaban Ghar.

MINERAL CHEMISTRY

Clinopyroxene, plagioclase and amphiboles are the major phases within the fresh and altered dolerites from the studied area. These were analysed with a Jeol Superprobe (Jcx-733), using wavelength dispersive mode.

Clinopyroxene and plagioclase were analysed from dolerite samples M9A and M5, both fresh, green amphibole (secondary) from sample M3B1 (altered dolerite) and brown amphibole (primary) from sample M10 (see Table 2).

Clinopyroxene

Analyses obtained from clinopyroxene grains in fresh dolerites, as shown in Table 3, are confined to the augite field with only one point in salite field (Fig. 3) in the pyroxene quadrilateral.

In the unit cell $Mg + Fe + Mn + Ti + {}^{VI}Al > 1$ and $Ca + Na < 1$.

This shows that the M1 sites are completely occupied by Mg, Fe, Mn, Ti and Al, while Ca and Na occur at the M2 site. The deficiency in the M2 site can be compensated by the excess cation at M1 site.

Amphibole

As discussed in petrography section, amphiboles from the Malka dolerites are of two types, e.g., brown amphibole (primary) as in section (M10) and green amphibole (secondary) as in section (M3B1). A total of 19 amphibole grains have been analysed. Results are presented in Table 4. Fe^{3+} in the analyses is determined through a method devised by Robinson et al. (1982). Analyses 13 to 19 from dolerite sample M10 are of brown amphibole while analyses 1 to 12 represent compositions of green amphibole from altered dolerites. The list of cations per 23 oxygens in Table 4 shows that (Na+Ca) 1.34 and NaB 0.67; accordingly these are calcic amphiboles (Hawthorne, 1985). Analytical data from Table 4 when plotted in Figure 4, indicate that amphiboles of altered dolerites (analysis 1 to 12) are ferroan pargasite, magnesio-hornblende, actinolitic hornblende, actinolite and ferro-actinolite in composition. The brown amphibole (analyses 13 to 19) are mostly paragasite in composition.

The difference in colour between brown and green amphibole is attributed to variation in TiO_2 concentration as suggested by Lamoen (1980). Brown amphibole is characterized by having TiO_2 in the range of 2.71 to 3.74 %, Whereeas green coloured varieties exhibit 0.16 to 1.55 % of TiO_2 in the analyses.

TABLE 3. CHEMICAL COMPOSITION OF CLINOPYROXENE FROM THE DOLERITES OF MALKA AREA

						M9A				
	1	2	3	4	5	6	7	8	9	10
SiO_2	48.35	48.65	49.74	47.94	48.54	45.92	49.08	48.27	48.64	47.56
TiO_2	1.96	1.96	1.89	1.30	2.15	2.61	3.75	1.76	1.61	2.54
Al_2O_3	4.91	4.71	3.61	5.25	5.41	5.54	4.37	5.07	4.53	5.80
FeO	8.38	8.26	8.22	7.62	6.52	8.12	9.78	9.96	9.53	10.26
MnO	0.09	0.08	0.12	0.07	0.07	0.20	0.15	0.13	0.09	0.13
MgO	14.60	14.25	14.70	14.01	13.71	12.87	14.42	14.28	14.28	13.89
CaO	19.98	20.35	19.62	20.50	20.60	20.79	19.08	19.72	19.96	18.88
Na_2O	0.49	0.44	0.49	0.48	0.44	0.78	0.41	0.41	0.39	0.49
Total	98.76	98.70	98.39	97.17	97.44	96.83	101.04	99.60	99.04	99.55
CATIONS PER 6 OXYGENS										
Si	1.82	1.84	1.88	1.82	1.83	1.76	1.82	1.81	1.84	1.79
Ti	0.06	0.05	0.05	0.06	0.07	0.11	0.10	0.06	0.05	0.07
Al	0.22	0.21	0.16	0.24	0.24	0.25	0.19	0.22	0.02	0.26
Fe^{3+}	0.06	0.04	0.07	0.04	0.02	0.30	0.04	0.06	0.06	0.05
Fe^{2+}	0.21	0.22	0.25	0.20	0.23	0.19	0.27	0.25	0.24	0.27
Mn	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00
Mg	0.82	0.80	0.82	0.79	0.77	0.74	0.81	0.80	0.80	0.78
Ca	0.81	0.82	0.79	0.83	0.83	0.85	0.77	0.79	0.81	0.76
Na	0.04	0.03	0.04	0.04	0.03	0.06	0.03	0.06	0.03	0.04
^{iv}Al	0.18	0.16	0.13	0.18	0.17	0.24	0.15	0.19	0.16	0.21
^{vi}Al	0.04	0.05	0.03	0.05	0.07	0.01	0.04	0.04	0.04	0.05
Mg#	0.80	0.79	0.77	0.80	0.77	0.79	0.75	0.76	0.77	0.74
Al_z	8.80	8.15	6.65	9.05	8.40	11.95	7.50	9.45	8.10	10.40

Plagioclase

The plagioclase of dolerites is mostly in the compositional range of An $_{53-69\%}$ i.e., labrodorite. Few samples fall in the compositional range of andesine. However, the plagioclase in altered dolerites is oligoclase An$_{21.6-22.3\%}$.

GEOCHEMISTRY

A total of 14 samples of dolerites including four from the altered variety, were selected for analyses. The samples were washed, dried and finally ground within a tungston carbide ring mill and solutions made with HF. For SiO_2 and Al_2O_3, separate solutions through fusion method were prepared.

Major elements were determined with an SP191 PYE Unicam Atomic Absorption spectrophotometer and SP - 400 UV spectrophotometer using USGS samples BCR, W2, AGV1 and G2 as internal standards. FeO was determined through the A.M.V method of Wilson (1960). Results are presented in Table 5 along with C.I.P.W. norms.

TABLE 3 (continued)

						M5				
	11	12	13	14	15	16	17	18	19	20
SiO_2	51.78	49.09	52.85	50.95	50.35	51.01	50.57	51.54	50.90	51.44
TiO_2	0.48	2.13	0.41	0.73	0.73	0.54	0.44	0.59	0.74	0.52
Al_2O_3	2.35	4.85	2.05	3.16	3.87	3.16	3.01	2.64	2.97	2.70
FeO	7.81	9.88	9.19	9.08	7.15	7.81	7.35	8.32	9.21	6.79
MnO	0.14	0.24	0.23	0.14	0.14	0.15	0.44	0.17	0.18	0.11
MgO	16.64	14.24	17.54	15.66	15.74	15.71	16.33	16.66	15.73	16.51
CaO	20.59	20.95	19.46	19.81	20.32	19.90	20.32	20.64	21.03	20.70
Na_2O	0.25	0.54	0.23	0.31	0.24	0.31	0.31	0.23	0.22	0.26
	100.04	101.92	101.96	99.84	98.54	98.59	98.77	100.79	100.98	99.03
			CATIONS		PER	6	OXYGENS			
Si	1.92	1.81	1.92	1.90	1.89	1.91	1.90	1.90	1.88	1.91
Ti	0.01	0.06	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02
Al	0.10	0.21	0.09	0.14	0.17	0.14	0.13	0.12	0.13	0.12
Fe^{3+}	0.06	0.09	0.06	0.05	0.03	0.03	0.07	0.07	0.08	0.04
Fe^{2+}	0.18	0.22	0.22	0.23	0.19	0.22	0.16	0.18	0.21	0.17
Mn	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.00
Mg	0.92	0.78	0.95	0.87	0.88	0.88	0.91	0.91	0.87	0.92
Ca	0.82	0.83	0.76	0.79	0.82	0.80	0.82	0.81	0.83	0.83
Na	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
^{iv}Al	0.08	0.19	0.08	0.10	0.11	0.09	0.10	0.10	0.12	0.09
^{vi}Al	0.02	0.02	0.01	0.04	0.06	0.05	0.03	0.01	0.01	0.03
Mg#	0.83	0.78	0.81	0.79	0.82	0.90	0.85	0.83	0.81	0.85
Al_z	4.20	9.45	3.90	5.15	5.70	4.40	5.20	5.10	5.85	4.30

$Al_z = {}^{iv}Al * 100 / 2$; $Mg\# = Mg_2 / Mg_2 + Fe_2$

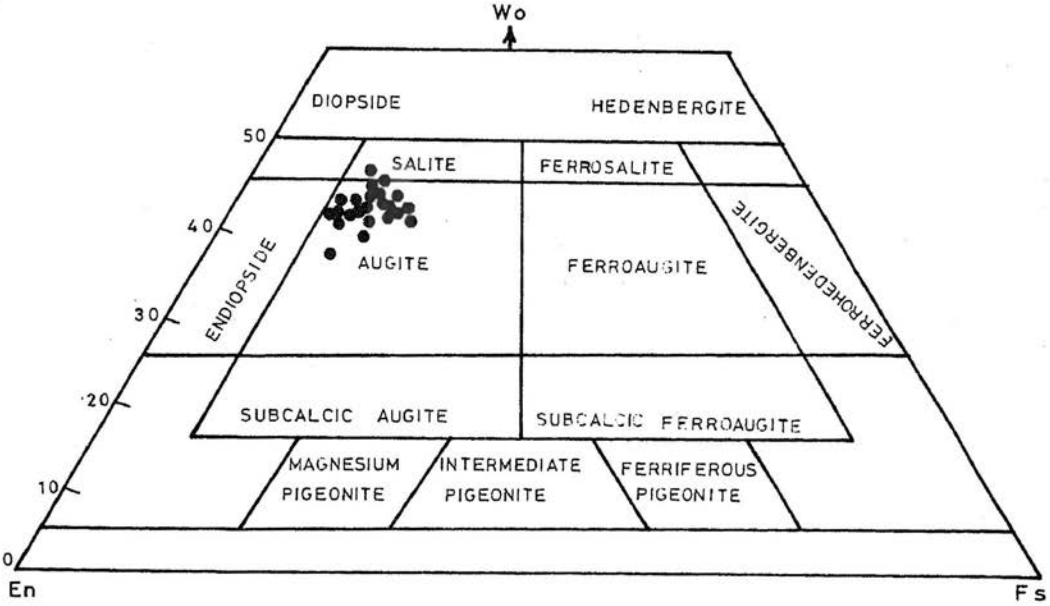

Fig.3. Composition of clinopyroxene from the Malka Dolerites (after Poldervaart et al., 1951).

TABLE 4. CHEMICAL COMPOSITION OF AMPHIBOLES FROM THE DOLERITES OF MALKA AREA.

Sample						M3B1				
Analysis#	1	2	3	4	5	6	7	8	9	10
SiO_2	40.87	47.66	53.51	51.67	48.15	49.90	49.17	52.66	39.64	40.65
TiO_2	0.31	1.55	0.27	0.16	0.22	0.27	0.28	0.28	0.38	0.54
Al_2O_3	14.02	7.74	2.95	4.27	7.28	5.27	5.42	7.31	14.61	14.27
Fe_2O_3	9.78	8.56	4.56	8.11	9.11	7.22	6.45	2.00	12.00	12.89
FeO	12.54	9.70	9.19	7.08	7.65	7.39	9.64	12.29	10.38	10.27
MnO	0.13	0.14	0.12	0.12	0.11	0.12	0.14	0.15	0.08	0.10
MgO	8.06	12.24	15.96	15.10	13.31	14.51	13.13	13.84	7.62	8.00
CaO	11.36	11.36	12.41	11.42	11.29	11.37	11.26	12.33	10.41	10.51
Na_2O	1.95	1.16	0.47	0.77	1.20	0.82	0.90	1.11	1.61	1.65
K_2O	0.43	0.00	0.00	0.00	0.00	0.08	0.07	0.15	0.96	1.02
Total	99.45	100.11	99.44	98.70	98.32	96.95	96.46	102.12	97.69	99.90
			CATIONS		PER	23	OXYGENS			
Si	6.07	6.82	7.55	7.35	6.95	7.24	7.23	7.28	5. 97	5.99
Ti	0.04	0.17	0.03	0.02	0.02	0.03	0.03	0.03	0.04	0.06
Fe3	1.09	0.92	0.48	0.87	0.99	0.79	0.71	0.21	1.36	1.43
Fe2	1.56	1.16	1.08	0.84	0.92	0.90	1.19	1.42	1.31	1.27
Mn	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01
Mg	1.78	2.61	3.35	3.20	2.86	3.14	2.88	2.85	1.71	1.76
Ca	1.81	1.74	1.88	1.74	1.75	1.77	1.78	1.83	1.68	1.66
Na	0.56	0.32	0.13	0.21	0.34	0.23	0.26	0.30	0.47	0.47
K	0.08	0.00	0.00	0.00	0.00	0.02	0.01	0.03	0.18	0.19
Al4	1.93	1.18	0.45	0.66	1.05	0.76	0.77	0.72	2.03	2.01
Al6	0.52	0.12	0.04	0.06	0.19	0.14	0.17	0.47	0.57	0.47
Mg*	0.53	0.69	0.76	0.79	0.76	0.78	0.71	0.67	0.57	0.58

Table 4 (continued)

Sample	M3B1		M10						
Analysis	11	12	13	14	15	16	17	18	19
SiO_2	49.43	53.30	41.83	41.65	41.72	41.20	41.03	42.76	41.75
TiO_2	0.28	0.18	2.71	3.50	3.42	3.74	3.72	3.30	3.64
Fe_2O_3	6.33	0.11	5.45	5.89	6.11	4.11	2.89	3.11	4.33
FeO	9.87	13.76	8.50	8.64	8.36	8.94	10.80	11.28	9.44
MnO	0.10	0.17	0.09	0.09	0.12	0.09	0.09	0.14	0.10
MgO	13.34	7.04	12.73	12.51	12.78	12.71	12.22	11.28	9.44
CaO	11.54	12.57	11.12	11.19	11.07	10.93	11.34	11.19	11.01
Na_2O	0.89	0.82	2.66	2.12	2.60	2.68	2.53	2.45	2.55
K_2O	0.14	0.00	0.47	0.40	0.41	0.45	0.48	0.14	0.39
Total	97.55	101.04	97.07	96.56	97.69	95.96	95.89	95.71	96.38
		CATIONS			PER	23	OXYGENS		
Si	7.20	7.80	6.20	6.22	6.16	6.18	6.20	6.40	6.24
Ti	0.03	0.02	0.30	0.39	0.38	0.42	0.42	0.37	0.41
Al	0.97	0.53	2.01	1.86	1.93	1.96	1.92	1.78	1.87
Fe3	0.69	0.01	0.61	0.66	0.68	0.46	0.33	0.35	0.49
Fe2	1.20	2.91	1.05	1.08	1.03	1.12	1.37	1.41	1.18
Mn	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01
Mg	2.90	1.54	2.82	2.78	2.81	2.84	2.75	2.67	2.80
Ca	1.80	1.97	1.77	1.79	1.75	1.76	1.84	1.79	1.76
Na	0.25	0.23	0.76	0.61	0.74	0.78	0.74	0.71	0.74
K	0.03	0.01	0.09	0.08	0.08	0.09	0.09	0.03	0.07
Al4	0.80	0.20	1.80	1.79	1.84	1.82	1.80	1.60	1.76
Al6	0.17	0.33	0.21	0.07	0.08	0.14	0.12	0.18	0.11
Mg*	0.71	0.35	0.73	0.72	0.73	0.77	0.67	0.65	0.70

The general average, average dolerite (fresh) and average altered dolerites are compared in Table 6. The average compositions in Table 6 exhibit differences mostly in Ti contents and oxidation state. The average altered dolerite (column 4) is characterized by relatively high TiO_2 and Fe_2O_3 and low FeO. The average dolerite (fresh, col. 2) however, shows slightly low Fe_2O_3 in comparison with other averages.

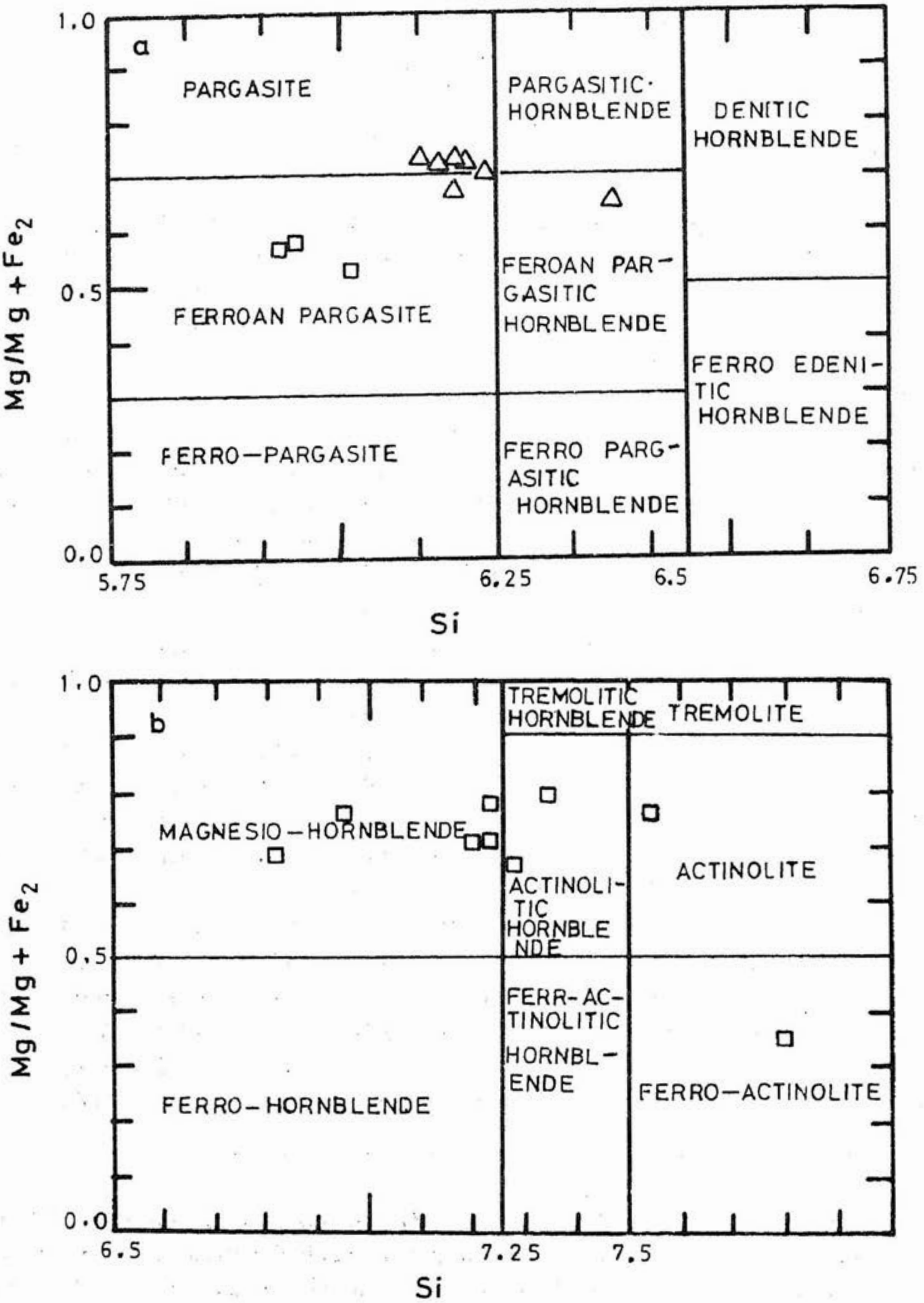

Fig. 4. Composition of amphiboles from Malka Dolerites (after Leak, 1978). Symbols:| = green amphibole, Δ = brown amphibole.

Table 5 shows that the dolerites are transitional from hypersthene normative to nepheline normative. The hypersthene normative samples also contain 1.38 to 4.26 percent normative quartz.

The analyses in the Na_2O + K_2O verses SiO_2 and K_2O versus SiO_2 plots (Fig. 5, a and b; boundaries after Cox. et. al., 1979, and Middlemost, 1975) exhibit a spread of the data points from sub-alkaline to alkaline fields. Similar trend, supporting the transitional basaltic character of the studied samples is distinct on the AFM diagram and Al_2O_3 versus An diagram of Irvine and Baragar, (1971; Fig. 6).

Plot of major oxides versus S.I. indicates evolved composition of these rocks. The general scatter of the data points is probably due to polybaric fractional crystallization, source hetrogenity, variable degree of partial melting and crustal contamination.

Variation trend mostly to the CAS2 - CMS2 join in a projection from S into CAS2 MS2 - CMS2 (i.e., from quartz into plagioclase-olivine and diopside) in Figure 7 indicates the fractionation control of plagioclase and clinopyroxene. The greater proximity of the data points towards the CAS2 position rather than to CMS2 position reflects that the role of plagioclase fractionation was dominant over clinopyroxene. Such interpretations are consistant with the petrographic data (Tables 1 & 2).

MAGMATIC AFFINITY AND TECTONIC SETTING

The transitional basalts are generally associated with continental rifting like the basalts associated with Afar Rift Ethopia and Kenya Rift (Wilson, 1989). Igneous activity within the PPAIP which includes the Malka dolerites, has already been related to extensional tectonics within the NW Indo-Pakistan plate margin (Kemp and Jan, 1970; Rafiq, 1986).The Rb/Sr isochron for Koga nephiline syenite within the PPAIP fixes the date of rifting event around 297 - 315 Ma. (Le Bas et al., 1987).

It has been pointed out that continental rift zones, being the areas of localized extension, exhibit a broad spectrum of magma composition, e.g. from alkaline in major continental rift zones to transitional basalts in zones of greatest crustal extension (Wilson, 1989; Baily, 1983). Close correspondence of average dolerite composition from the studied area with compositions 2 and 3 in Table 7 (transitional basalts from Afar Rift Ethopia and Kenya rift) further signifies their transitional character and support their assumed production in an extensional type environment. The composition of clinopyroxene from the Malka dolerites in Table 3 further supports this view.

TABLE 5. MAJOR ELEMENTS DATA AND C.I.P.W. NORMS OF MALKA DOLERITES

	Fresh					Slightly altered		
	M5	M6A1	M11B	M12	Y	M2	M10	M11
SiO_2	49.66	47.92	48.69	46.99	48.99	44.25	46.85	46.22
TiO_2	1.82	3.50	3.03	2.90	3.23	4.94	3.67	3.47
Al_2O_3	12.19	12.70	12.97	13.86	13.46	10.79	15.23	11.80
Fe_2O_3	1.77	2.84	3.65	4.39	1.76	6.52	4.18	0.00
FeO	8.76	7.30	8.50	7.61	8.76	4.80	6.05	10.42
MnO	0.21	0.19	0.22	0.22	0.19	0.21	0.14	0.18
MgO	7.30	10.25	5.90	6.40	9.25	8.10	9.50	8.55
CaO	10.30	12.25	11.45	11.40	10.50	11.00	12.60	13.60
Na_2O	2.24	1.58	4.40	4.44	2.10	4.20	1.48	1.88
K_2O	0.40	0.40	1.10	1.20	0.82	0.62	0.32	0.76
P_2O_5	0.08	0.12	0.07	0.08	0.10	0.14	0.14	0.14
H_2O^+	1.80	1.41	1.05	1.15	1.19	1.03	1.50	1.96
H_2O^-	0.59	0.14	0.20	0.29	1.45	0.83	0.12	1.36
Total	97.12	100.60	101.23	100.92	101.80	97.43	101.78	100.34

C.I.P.W. NORMS.

	M5	M6A1	M11B	M12	Y	M2	M10	M11
Q	3.07	0.70	0.00	0.00	0.00	1.38	0.00	2.68
Or	2.36	2.36	6.5	7.09	4.85	3.66	1.89	4.49
Ab	18.80	13.37	22.12	17.34	17.77	20.44	12.52	15.91
An	22.03	26.38	12.39	14.35	24.88	8.76	33.97	21.52
Ne	0.00	0.00	8.19	10.96	0.00	8.18	0.00	0.00
Di	23.31	26.71	35.68	33.53	21.40	34.95	21.67	35.31
Hy	18.80	18.48	0.00	0.00	18.68	0.00	15.37	6.09
Mt	2.57	4.12	5.29	6.37	2.55	2.07	6.06	7.21
Il	3.46	6.65	5.75	5.51	6.13	9.38	6.97	6.59
Hem	0.00	0.00	0.00	0.00	0.00	5.01	0.00	0.00
Ap	0.19	0.28	0.16	0.17	0.23	0.32	0.33	0.32
FeO*	10.35	9.86	11.79	11.56	10.34	10.67	9.81	10.42
Mg#	0.44	0.54	0.36	0.39	0.50	0.46	0.52	0.48

Table 5 (continued).

	Altered dolerites					
	X	AS1	M3B1	M3B2	M6B2	AS2
SiO_2	48.56	52.40	47.29	47.50	48.78	51.11
TiO_2	3.05	1.73	3.14	3.27	1.48	2.02
Al_2O_3	15.49	14.35	12.50	12.06	14.09	13.96
Fe_2O_3	6.79	6.09	2.83	1.03	3.49	5.52
FeO	5.58	5.22	8.34	9.69	7.20	6.73
MnO	0.23	0.22	0.18	0.20	0.21	0.23
MgO	6.40	6.95	8.25	10.10	7.50	6.40
CaO	10.90	10.15	9.55	10.90	10.35	10.50
Na_2O	2.18	2.52	4.04	3.82	3.94	2.66
K_2O	0.80	0.66	0.56	0.60	0.50	0.64
P_2O_5	0.09	0.04	0.14	0.16	0.04	0.07
H_2O^+	0.62	0.98	1.33	1.67	1.60	1.15
H_2O^-	0.03	0.26	0.67	0.67	0.18	0.17
Total	100.72	101.57	98.82	101.67	99.36	101.15
	C.I.P.W NORMS					
Q	2.68	4.26	0.00	0.00	0.00	2.77
Or	4.73	3.90	3.31	3.55	2.95	3.78
Ab	18.45	21.32	27.75	19.36	28.00	22.51
An	30.12	25.90	14.32	13.99	19.29	24.26
Ne	0.00	0.00	3.49	7.03	2.89	0.00
Di	18.75	19.63	25.86	31.55	25.76	22.33
Hy	12.53	16.98	0.00	0.00	0.00	14.90
Ol	0.00	0.00	11.70	15.79	11.41	0.00
Mt	6.60	4.68	4.10	1.49	4.32	5.10
Il	5.79	3.29	5.96	6.21	2.81	3.84
Hem	0.00	0.00	0.00	0.00	0.00	0.00
Ap	0.21	0.09	0.32	0.38	0.09	0.15
FeO*	11.69	10.70	10.89	10.62	10.34	11.70
Mg#	0.38	0.42	0.46	0.52	0.45	0.38

FeO* = Total iron

Mg# = MgO / MgO + FeO

TABLE 6. AVERAGES OF MAJOR ELEMENTS DATA OF MALKA DOLERITES

	1	2	3	4
SiO_2	48.25	48.45	48.67	47.66
TiO_2	2.95	2.90	2.48	3.37
Al_2O_3	13.25	13.04	13.15	13.53
Fe_2O_3	3.60	2.88	3.22	4.72
FeO	7.50	8.19	7.99	5.37
MnO	0.20	0.21	0.20	0.20
MgO	7.90	7.82	8.06	7.90
CaO	11.10	11.18	10.32	11.65
Na_2O	2.96	2.95	3.61	2.45
K_2O	0.67	0.78	0.57	0.63
P_2O_5	0.10	0.09	0.10	0.11
H_2O^+	1.32	1.32	1.44	1.22
H_2O^-	0.50	0.53	0.42	0.52
Total	100.32	100.33	100.25	99.33

KEY:
1 = Average dolerite (average of 14 samples).
2 = Dolerites [fresh] (average of 5 samples).
3 = Dolerites [slightly altered] (average of 5 samples).
4 = Altered dolerites (average of 4 samples).

Figure 8c is a plot of Alz verses TiO_2 of the clinopyroxene analyses (boundaries after Le Bas, 1962). This plot indicates that most of clinopyroxene plot in non-alkaline and normal alkaline fields, with only one sample in peralkaline field. A similar spread is repeated in the Al_2O_3 verses SiO_2 and Ca+Na versus Ti plot (Fig. 8, b and c) which further supports the transitional nature of the dolerites from the studied area. Positions of the data points in Fig. 9 further confirm the conclusion that the Malka dolerites are chemically variable from non-alkaline to normal alkaline basalts.

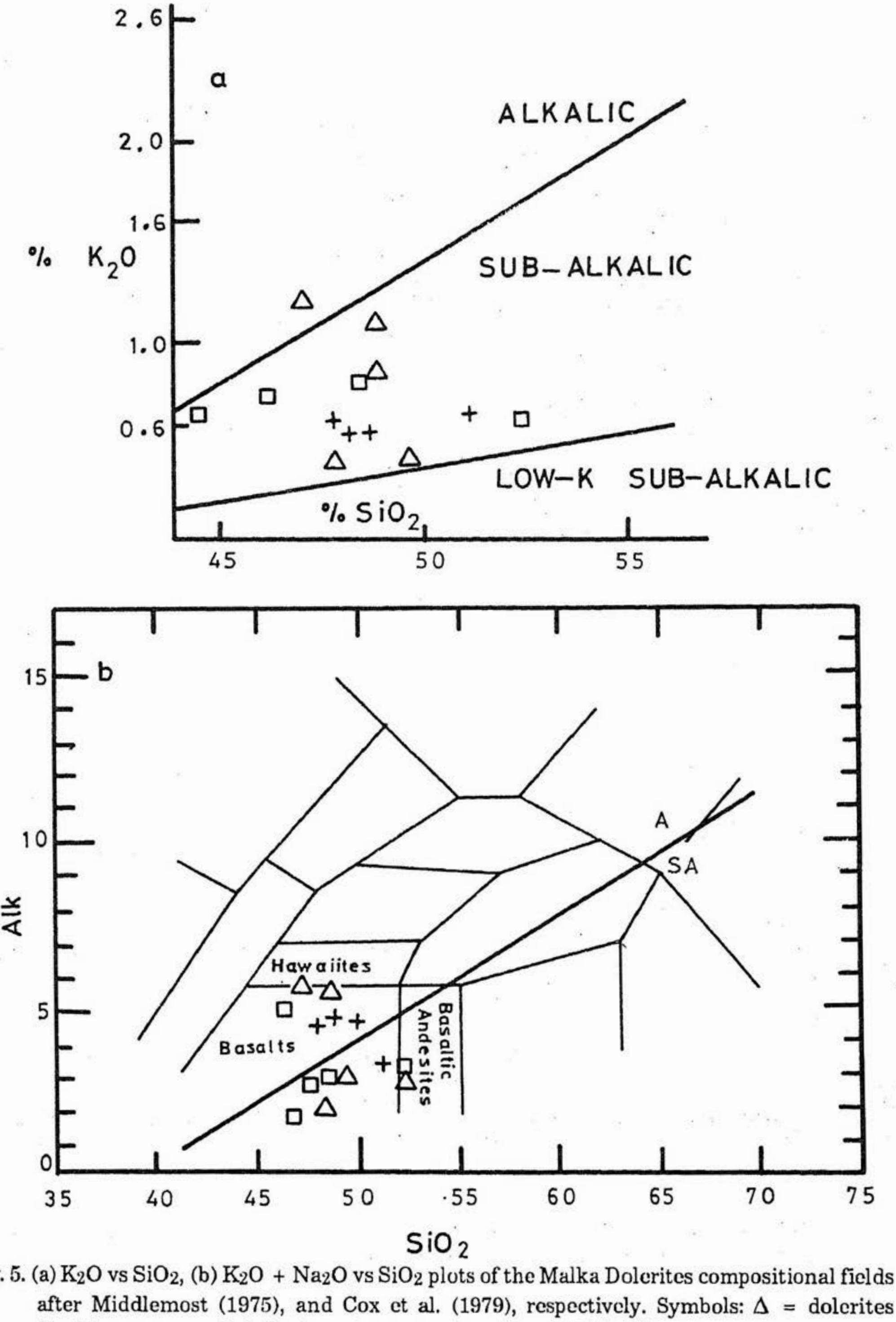

Fig. 5. (a) K_2O vs SiO_2, (b) K_2O + Na_2O vs SiO_2 plots of the Malka Dolerites compositional fields after Middlemost (1975), and Cox et al. (1979), respectively. Symbols: Δ = dolerites (fresh), square□= slightly altered dolerites, + = altered dolerites.

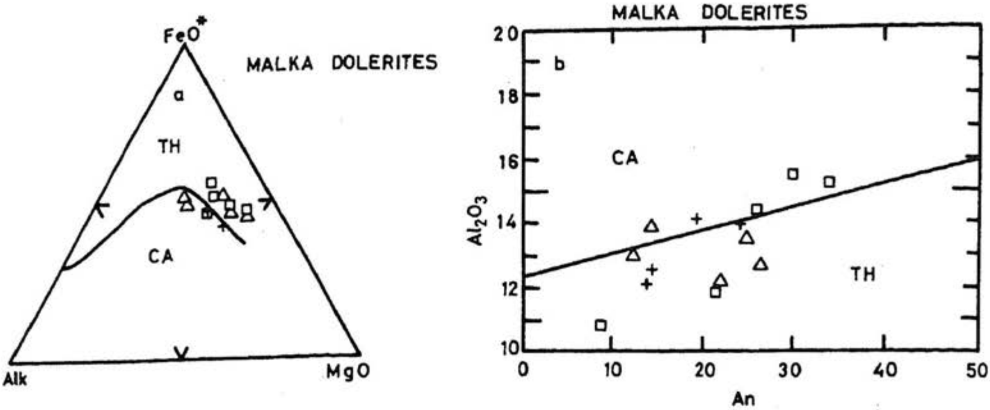

Fig. 6. a) AFM plot, b) Al_2O_3 VS An plots of Malka Dolerites (bounderies after Irvine and Baragar, 1971). Samples represented by symbols as in Fig. 5.

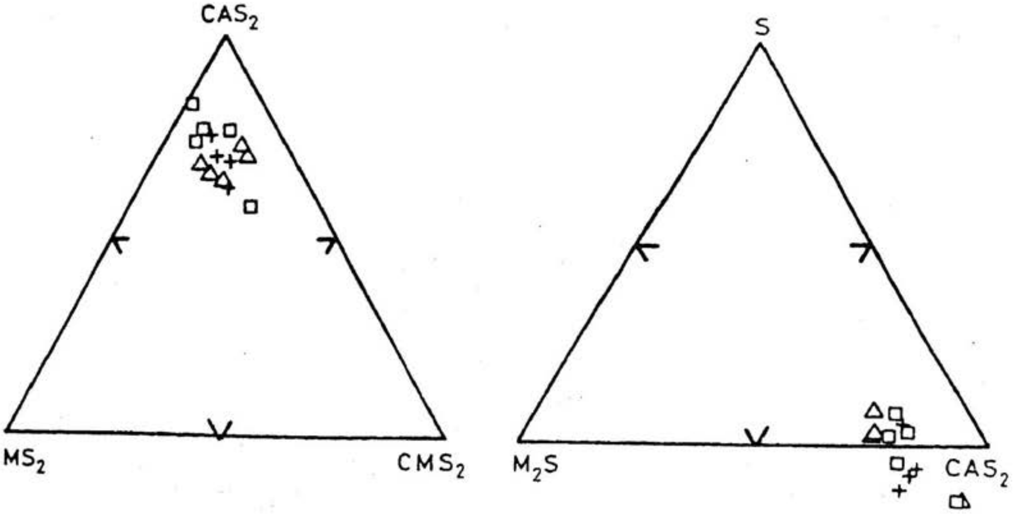

Fig. 7. CMAS plots calculated from oxide wt. % (after O'Hara, 1968), showing fractionation trends of the Malka Dolerites. Symboles are same as in Fig. 5.

TABLE 7. MAJOR ELEMENT DATA OF MALKA DOLERITES COMPARED WITH TRANSITIONAL, ALKALIC, CONTINENTAL FLOOD, OCEANIC ISLAND ARC BASALTS & NORMAL MORB BASALTS.

	1	2	3	4	5	6	7	8	9
SiO_2	48.25	46.75	47.20	45.89	50.56	50.75	50.36	50.40	47.93
TiO_2	2.95	2.30	1.95	‘3.33	2.57	3.95	3.62	1.36	2.11
Al_2O_3	13.25	13.93	15.83	14.63	13.83	13.51	13.41	15.19	15.01
Fe_2O_3	3.60	3.20	1.60	16.46*	13.79*	14.24*	13.63*	10.01*	2.99
FeO	7.50	8.08	9.61	-	-	-	-	-	8.96
MnO	0.20	0.19	0.20	0.21	0.17	0.19	0.18	0.18	0.20
MgO	7.90	9.75	7.34	6.46	5.19	4.21	5.57	8.96	6.94
CaO	11.10	10.08	12.27	9.46	9.62	8.45	9.60	11.43	12.05
Na_2O	2.96	2.70	2.62	2.84	2.65	2.80	2.80	2.30	2.69
K_2O	0.67	0.80	0.48	0.65	0.93	1.58	0.77	0.09	0.80
P_2O_5	0.10	0.35	0.24	0.69	0.22	0.66	0.42	0.14	0.32
H_2O^+	1.32	-	0.12	-	-	-	-	-	-
H_2O^-	0.50	-	-	-	-	-	-	-	-
Total	100.32	98.13	99.46	100.62	99.53	100.31	100.36	100.06	100.00

KEY: 1 = Malka dolerites (Average of 14 samples), 2 = Transitional basalt (Afar Rift Athiopia),Barberi et al.(1975), 3 = Transitional basalt (Kenya Rift), Macdonald et al. (1987), 4 = Continental flood basalt (Snake River Plain) , Thomson et al. (1983), 5 = Continental flood basalt (Deccan), Thomson et al. (1983), 6 = Continental flood basalt (Parana), Thomson et al. (1983), 7 = Oceanic island arc basalt (Average), Thomson et al. (1984), 8 = Normal M.O.R.B , Humphris et al. (1985), 9 = Alkali basalt (Kenya Rift), Baker et al. (1977).

* Total iron experessed as Fe_2O_3

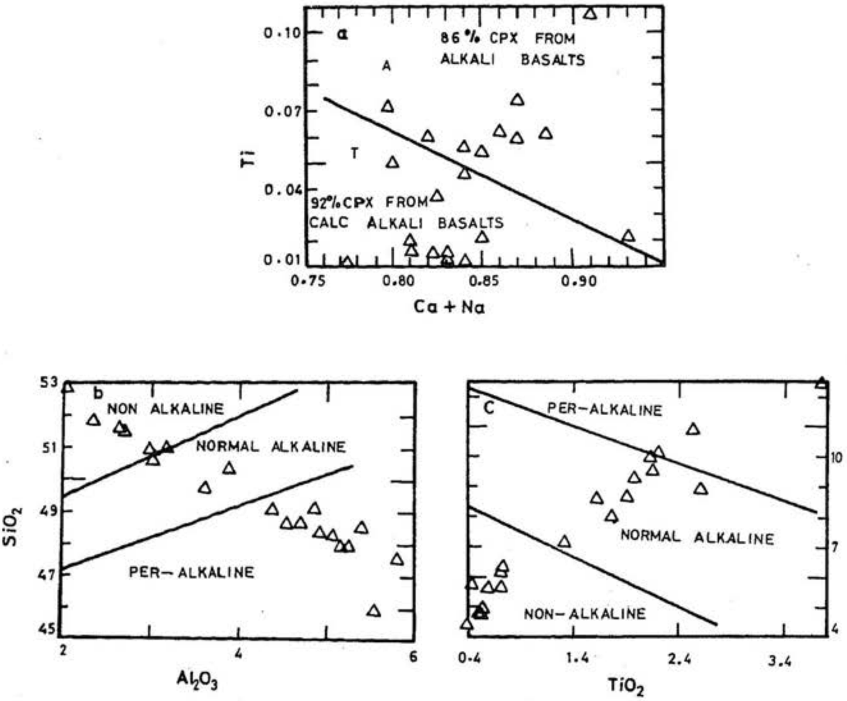

Fig. 8. Discrimation diagram on the basis of clinopyroxene composition. (a) Na VS Ti (Leterrier et al., 1982), (b) Al_2O_3 vs SiO_2 (Kushiro, 1960), (c) TiO_2 vs Alz (Le Bas et al., 1962).

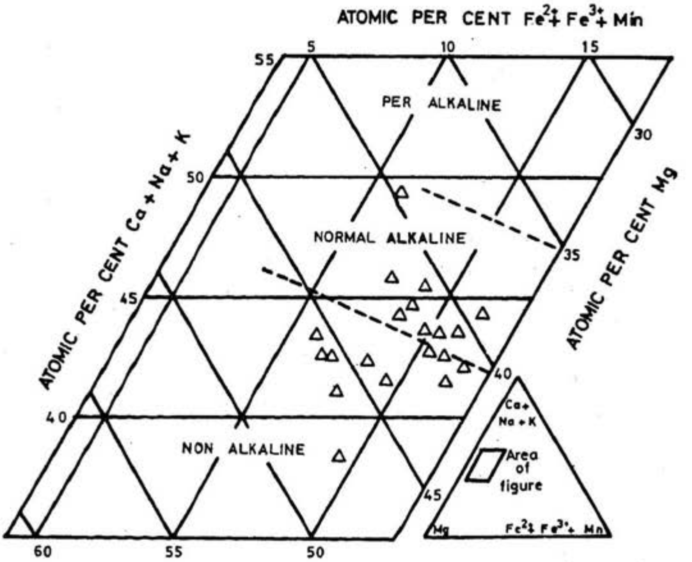

Fig.9. Analyses of cpx from the Malka Dolerites Mg - Ca+Na+K - Fe^{2+} +Fe^{3+} +Mn (bounderies after Le Bas, 1962).

CONCLUSIONS

1. The Malka dolerites have evolved from a basic magma of transitional characters between alkaline and calcalkaline, possibly in rift related environment.
2. Plagioclase and clinopyroxene played a major role in the fractionation history of these dykes.
3. Secondary alteration/low grade metamorphism resulted in the development of epidote after plagioclase and clinopyroxene, and amphibole after clinopyroxene

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