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GEOCHEMISTRY OF SOME GABBROS FROM MUHAMMAD QOL AREA, NORTHERN RED SEA HILLS, SUDAN REPUBLIC

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ABSTRACT

The Muhammad Qol gabbros can be classified as 3 main rock units comprising olivine pyroxene gabbros, pyroxene gabbros and hornblende pyroxene gabbros. The modal and normative minerals together with the chemical data show that the three rock types were formed during a limited fractionation process in which a type of regular gradation in the chemical composition of the magma had taken place.

The early fractionation stage was characterized by a pronounced mafic liquidus phase from which gabbros bearing much olivine and pyroxene with little plagioclase were formed under high temperature. With progressive fractionation, the crystallized plagioclases became more abundant than the mafic minerals which comprise pyroxene and little olivine crystals. At late fractionation stage, the hydrous minerals began to crystallize under high water pressure and relatively low temperature producing hornblende pyroxene gabbros.

The strong alteration in some gabbroic rocks shows that they were affected greatly by late magmatic hydrothermal solutions. As a result, some major and trace elements in the mafic and felsic minerals had been redistributed during uralitization, chloritization and sericitization processes.

INTRODUCTION

The present study deals with the petrochemistry and geochemistry of some gabbros from the basement complex of Muhammad Qol area, northern Red Sea Hills, Sudan Republic. Broadly, the Red Sea Hills Province is dominantly covered by basement rocks of Precambrian age. However, the Red Sea Hills of the Sudan had been the goal of several investigations. A number of syntheses have been attempted of the basement geology and associated mineralization. The most important are the works of RUXTON [1956], GABERT *et al.* [1960], KABESH [1962], KABESH and LOTFI [1962], LOTFI and KABESH [1964], NEARY *et al.* [1976] and AHMED [1977]. On the other hand, the general geology and economic mineral deposits of the Sudan Republic have been outlined by WHITEMAN [1971] and VAIL [1978].

The gabbroic rocks described and discussed in this work were collected by one of us [KABESH] from Muhammad Qol area in the north-east of the Sudan Republic *(Fig. 1)*. The gabbros examined form several quantitatively insignificant masses in Muhammad Qol area. Invariably, the emplacement of the gabbro precedes that of the granitic rocks. This is confirmed by field evidence where gabbros are intruded and veined by granitic rocks [KABESH, 1962].

PETROGRAPHY

The petrographic study of Muhammad Qol gabbros shows that they can be classified as 3 main rock units: olivine pyroxene gabbros, pyroxene gabbros and hornblende pyroxene gabbros.

1. The olivine pyroxene gabbros are composed of 23% olivine. 15% hypersthene, 11% augite, 7% iron ores and 44% plagioclase. These volume mineral percentages are the average of 3 varieties comprising olivine gabbro, olivine hyperstene gabbro and olivine augite gabbro.

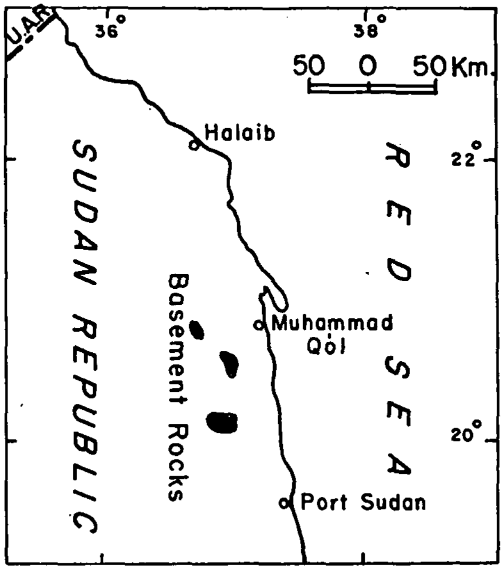

Fig. 1. Location Map

2. The pyroxene gabbros contain 10% hypersthene, 6% diopside, 14% augite, 7% olivine, 5% iron ores and 58% plagioclase. These modal mineral percentages are the average of gabbroic varieties representing hypersthene diopside gabbro and augite gabbro.

3. The hornblende pyroxene gabbros comprise 17% hornblende, 8% augite, 6% chlorite, 5% iron ores and 64% plagioclase. These modal mineral percentages represent the average of 2 gabbroic varieties (hornblende augite gabbro and hornblende gabbro).

Both olivine pyroxene gabbros and pyroxene gabbros are nearly identical in their mineralogical constituents and textural features. Olivine mineral is considered the sole ferromagnesian mineral in rare gabbroic samples, while, the olivine and iron tend to occur as aggregates with hypersthene or augite in most gabbros. The olivine augite gabbro is characterized by subophitic intergrowth between normal zoned plagioclase and augite. The augite is light pink in colour and slightly pleochroic.

Some samples of gabbro contain pyroxene as dominant mafic minerals in which hypersthene and diopside or augite are associated with little amounts of olivine. Some gabbroic samples comprise strongly pleochroic hypersthenes which sometimes have occasional diopside along their lamellae planes. Most of the pyroxene crystals are generally interstitial to the plagioclases.

In both olivine pyroxene gabbros and pyroxene gabbros, the plagicclases (labradorite) form euhedral crystals ranging in composition from An_{55} to An_{67}. The presence of high volume percentage of mafic minerals in the olivine pyroxene gabbros shows that they were crystallized early from a high basic magma compared to gabbros bearing pyroxenes as dominant mafic minerals.

On the other hand, the mcdal feldspar in the hornblende pyroxene gabbros indicates that this rock unite was crystallized from a declared plagioclase liquidus phase. The plagioclases form euhedral crystals ranging in composition from labradorite (An_{52-60}) to andesine (An_{42-48}). Hornblendes constitute subhedral crystals, pleochroic from pale yellowish green to dark or even dark brown. Some of the hornblendes enclose the early formed plagioclase crystals. Augite is present in minor amounts and has a typical sieve texture with the enclosing hornblende.

Some samples of the hornblende pyroxene gabbros in which the augite is of ferriferous type are strongly altered showing uralitization at the margins of the pyroxenes. Many augite crystals are altered to greenish hornblende preserving a distinct type of exsolution along their lamellae.

Uralitization, chloritization and sericitization are the common develcped processes at late magmatic hydrothermal stage. As the hydrous mineral become more abundant, the hornblende largely replaces the pyroxene crystals. The pyroxene is rimmed by fine fibrous bluish green amphibole showing that a type of reaction relationship between both minerals had taken place due to the effect of hydrothermal solutions which attacked some gabbros at late magmatic stage.

GEOCHEMISTRY OF GABBROS

Eight new chemical analyses representing the different petrographic varieties of Muhammad Qol gabbroic rocks are discussed in this study. The major elements (Table 1) of these gabbros were determined by using volumetric and gravimetric methods of BENNETT and REED [1971]. The average analysis of 4 gabbroic samples from the north of Muhammad Qol area [NEARY *et al.* 1976] is given in Table 1 for comparison. The average analysis (analysis no. 9. Table 1) of NEARY *et al.* [1976] agrees to a certain extent with the analysis of augite gabbro (sample no 5, Table 1) in the present study. The normative minerals (Table 2) of the gabbros are calculated from their chemical analyses (Table 1).

Table 3 shows the trace elements (Rb, Sr, Ba, Co, Ni and Cr) for the examined gabbros. These trace elements were detected by spectrographic methods.

Major and trace elements

Fig. 2 shows a ternary relation between the FeO*, MgO and Na_2O+K_2O (Table 1). The diagram is subdivided into 3 fields in which field A comprises the gabbros of Mid-Oceanic Ridge [MIYASHIRO *et al.*, 1970], field B represents the serpentinites of Mid-Atlantic Ridge [MIYASHIRO *et al.*, 1969] and field C is the ultramafic and gabbroic rocks of Alpine Intrusive Complexes [THAYER, 1967].

It is evident that most samples (numbers 1 and 2) which are characterized by high mafic minerals particularly olivine and orthopyroxene fall within the field of ultramafic and gabbroic rocks. Whereas, the less mafic gabbros (samples numbers 3, 4, 5, 6, and 7) which comprise pyroxene and/or hornblende plot within the field of gabbro. The plotting of sample no. 8 out the 3 discriminated fields of gabbros

Major elements analyses (%) and some elemental ratios of the Muhammad Qol gabbroic rocks

	1	2	3	4	5	6	7	8	9
SiO_2	45.81	46.89	46.31	46.33	45.87	47.91	50.01	48.21	45.58
TiO_2	1.23	1.82	1.02	2.98	1.63	1.59	0.61	0.71	1.01
Al_2O_3	13.01	14.63	13.59	14.83	15.93	15.59	16.69	17.21	18.28
Fe_2O_3	1.72	1.95	2.61	2.60	1.51	2.34	2.53	3.05	3.44
FeO	11.99	9.98	11.43	9.32	9.78	8.87	7.85	8.00	6.2
MnO	0.27	0.21	0.59	0.37	0.40	0.35	0.32	0.46	0.13
MgO	14.33	11.67	11.63	8.91	8.90	7.71	6.66	6.82	9.79
CaO	8.19	7.99	7.48	10.02	10.53	9.89	8.78	7.35	11.29
Na_2O	1.34	1.62	2.06	1.61	2.12	2.63	2.91	3.42	1.98
K_2O	0.20	0.25	1.11	0.35	0.36	0.30	0.45	0.91	0.18
P_2O_5	0.09	0.28	0.20	0.17	0.17	0.26	0.14	0.08	0.06
H_2O	1.56	1.93	1.78	2.32	1.92	2.18	2.32	3.11	2.09
Total	99.81	99.22	99.81	99.29	99.12	99.59	99.27	99.33	100.08
FeO*%	46.16	46.41	48.19	51.75	49.44	50.76	50.24	49.06	
MgO%	48.89	46.18	40.70	39.54	39.53	35.67	33.06	31.15	
Na_2O+K_2O%	4.95	7.41	11.11	8.71	11.03	13.57	16.71	19.79	
Felsic index $=(Na_2O+$ $+K_2O)\cdot 100/Na_2O+$ $+K_2O+CaO$	15.82	18.96	29.76	16.73	19.06	22.85	27.67	37.07	
Mafic index $=(Fe_2O_3+$ $+FeO+MnO)\cdot 100/Fe_2O_3+$ $+FeO+MnO+MgO$	49.38	50.98	55.71	57.99	56.77	59.98	61.63	62.79	
100 MgO/(MgO+FeO)	54.30	53.90	50.43	48.87	47.64	46.50	45.89	46.01	
FeO*/MgO	0.94	1.00	1.18	1.30	1.25	1.42	1.52	1.57	

$FeO^* = FeO + 0.899\ Fe_2O_3$

and ultramafic rocks *(Fig. 2)* is attributed to the presence of high alkali elements (Na_2O+K_2O) in this rock variety as result of sericitization process.

The relation between mafic index and felsic index (Table 1) is shown in *Fig. 3*. The diagrame is divided by DREVER and JOHNSTON [1966] into 2 fields comprising basic (upper field) and ultrabasic (lower field) rocks. All Muhammad Qol gabbros fall in the field of basic rocks but samples number 1, 2 and 4 are considered the nearest gabbroic rocks to the ultramafic field.

It is noted that the felsic index varies from 15.82 (olivine gabbro, Table 1) to 37.07 (altered gabbro) whereas, the mafic index ranges from 49.30 (olivine gabbro) to 62.79 (altered gabbro). The low value of mafic index in the olivine gabbro reflects its high content of MgO (14.33, Table 1) compared to MgO (6.82) in the altered gabbro. The great variations in the values of both felsic and mafic indices show that these gabbros were crystallized from a highly changeable magma in its chemical composition during a fractionation process.

Some major and trace elements are plotted against the MgO/(MgO+FeO) ratio in *Fig. 4*. MgO, FeO, Cr, Ni and Co increase gradually with increasing the MgO/(MgO+FeO) ratio whereas, Al_2O_3, Na_2O, Ba and Rb deplete in the same direction. The contents of TiO_2 in the gabbroic varieties are scattered against the same ratio reflecting that the crystal structure of augite received Ti more rapidly

Table 2

CIPW-norms of the Muhammad Qol gabbroic rocks

		1	2	3	4	5	6	7	8
or		1.16	1.47	6.56	2.05	2.12	1.77	2.65	5.38
ab		11.31	13.73	17.39	13.50	17.91	22.20	24.51	28.90
an		28.80	31.84	24.51	32.18	32.84	29.80	31.15	28.87
di	*wo*	4.57	2.50	4.71	6.86	7.64	7.34	4.81	2.96
	fs	1.49	0.76	1.72	2.08	2.90	2.73	1.92	1.55
	en	2.83	1.57	2.75	4.33	4.38	4.25	2.68	1.31
hy	*fs*	7.84	10.45	4.25	8.60	3.02	6.17	9.96	3.41
	en	14.63	21.62	6.77	17.94	4.55	9.58	13.96	5.04
ol	*fa*	7.58	2.22	9.47	—	6.81	2.72	—	5.48
	fo	12.83	4.16	13.65	—	9.30	3.80	—	7.30
mt		2.48	2.82	3.78	3.78	2.18	3.39	3.66	4.42
il		2.32	3.45	1.93	5.66	3.09	2.96	1.15	1.34
ap		0.21	0.66	0.47	0.39	0.39	0.61	0.32	0.18
or%		2.81	3.12	13.50	4.29	4.00	3.29	4.54	8.51
ab%		27.40	29.18	35.88	28.28	33.00	55.42	42.03	45.76
an%		69.79	76.70	50.62	67.43	62.13	41.29	53.43	45.73
ab+*an*		40.11	45.57	41.90	45.68	50.78	52.00	55.66	57.77
Di		12.47	15.20	23.95	15.55	20.03	23.97	27.16	34.28
CI		56.78	50.21	49.50	49.64	44.26	43.53	38.46	32.99
An		71.80	69.80	58.50	70.40	64.70	57.30	55.90	49.90

Di (Differentiation index) $= q + ab + or$. Normative quartz *(q)* in all samples = 0
CI (Colour index) $= di + hy + ol + mt + il + ap$
An (Anorthite content of plagioclase) $= an \times 100/an + ab$

Table 3

Trace element concentrations (ppm) of the Muhammad Qol gabbroic rocks

	1	2	3	4	5	6	7	8
Rb	12	15	12	15	14	20	25	35
Sr	180	270	155	175	160	305	390	290
Ba	100	145	110	112	140	150	200	185
Co	95	75	90	63	55	50	45	40
Ni	355	295	380	250	150	180	110	85
Cr	795	580	455	285	185	250	205	130

rather than the other ferromagnesian minerals during the magmatic fractionation process. The behaviour of CaO *(Fig. 4)* shows a vibrated trend against the mafic ratio, *i. e.* the amounts and types of crystallized calcic minerals particularly plagioclases were controlled by 2 factors: the chemical changes in the pronounced mafic liquidus phase of the gabbroic melt at early stage in addition to the remarkable decreasing in the An contents of the plagioclases with progressive fractionation.

Generally, the MgO/(MgO+FeO) ratios vary from 45.89 in the hornblende gabbro to 54.30 in the olivine gabbro indicating that the chemical composition of the mafic constituents in these gabbros was graduated from a high mafic magma to less basic melt through a limited fractional crystallization process.

Normative minerals

An, Ab and Or normative minerals (recalculated to 100% total, Table 2) are plotted in *Fig. 5* [HIETANEN, 1963]. The examined rock types which are identified by petrographic criteria as gabbroic rocks fall in the fields of mafic gabbro (samples number 1, 2, 3, 4 and 5), gabbro (samples number 7 and 8) and quartz diorite (sample number 6).

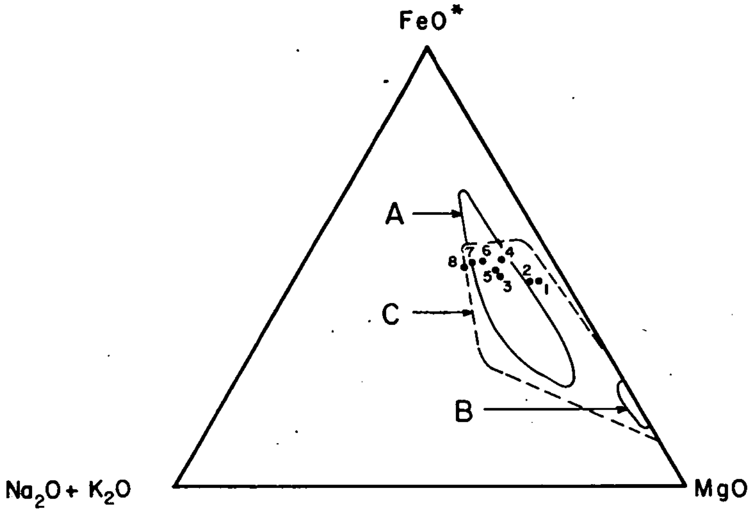

Fig. 2. FeO*—Na_2+K_2O—MgO diagram (THORPE, 1974).
A is the field of gabbro [MIYASHIRO *et al.* 1970],
B is the field of serpentinite [MIYASHIRO *et al.* 1969] and
C is the field of ultramafic and gabbroic rocks [THAYER, 1967.
$FeO^* = FeO + 0.899\ Fe_2O_3$

Explanation:

Sample No.	*Rock variety*
1	Olivine gabbro
2	Olivine hypersthene gabbro
3	Olivine augite gabbro
4	Hypersthene diopside gabbro
5	Augite gabbro
6	Hornblende augite gabbro
7	Hornblende gabbro
8	Altered gabbro

It is interesting to mention that the gabbros which have high modal olivine and pyroxene are rich in their normative mafic minerals (C. I. = 49.50 to 56.78, Table 2) whereas, gabbros bearing pyroxene as dominant mafics are characterized by normal amounts of mafic minerals (C. I. = 44,26 to 49.64, Table 2). On the other hand, the low normative mafic minerals (C. I. = 32.99 to 43.53, Table 2) are recognized in gabbros containing hornblende and little pyroxene. Both modal and normative plagioclases increase gradually with the decrease of mafic minerals during the progressive fractionation of a highly basic magma. The little crystallized plagioclases in the mafic gabbros have high normative An contents (58.50—71.80, Table 2) compared to those present in fair amounts in the hornblende pyroxene gabbros in which the

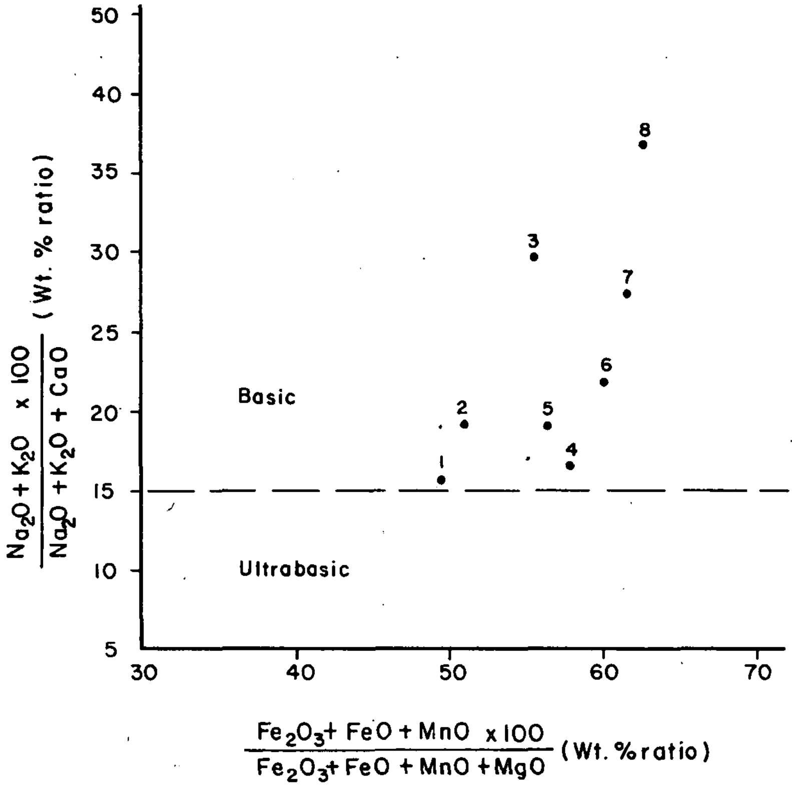

Fig. 3. The relationship between felsic and mafic index [DONALDSON, 1977]
Dashed line represents the basic ultrabasic felsic index of DREVER and JOHNSTON [1966]. Index of numbers as in *Fig. 2*.

An contents range from 49.90 to 57.30 (Table 2). These An contents are calculated according to the following equation:

$$\text{An in plagioclases} = \frac{\text{Rock normative An} \times 100}{\text{Rock normative (An + Ab)}}$$ [CARACAS and LEXINGTON, 1974].

The differentiation index [THORNTON and TUTTLE, 1960] of the gabbroic varieties (Table 2) ranges from 12.74 in the olivine gabbro to 27.16 in the hornblende gabbro showing a certain changes in the chemical composition of the gabbroic melt with progressive fractionation.

PETROGENESIS

The Muhammad Qol gabbroic rocks generally form an early crystallized pluton in which a highly basic magma was differentiated through a wide range producing a series of basic (gabbros), intermediate (diorites) and acidic (granitic rocks) intrusions respectively.

The gabbroic rocks which are characterized by high values of heavy elements (Fe^{2+}, Mg, Ni, Co and Cr) are considered the chief hosts for the early crystallized olivine and pyroxene. Whereas, Al, Na, Ba, Rb and Sr are concentrated in the gabbbros bearing hornblende and little pyroxene which had been crystallized at late stage. The modal and normative mafic minerals specially olivine and pyroxene decrease systematically from olivine gabbro to hornblende gabbro. Furthermore, a remarked

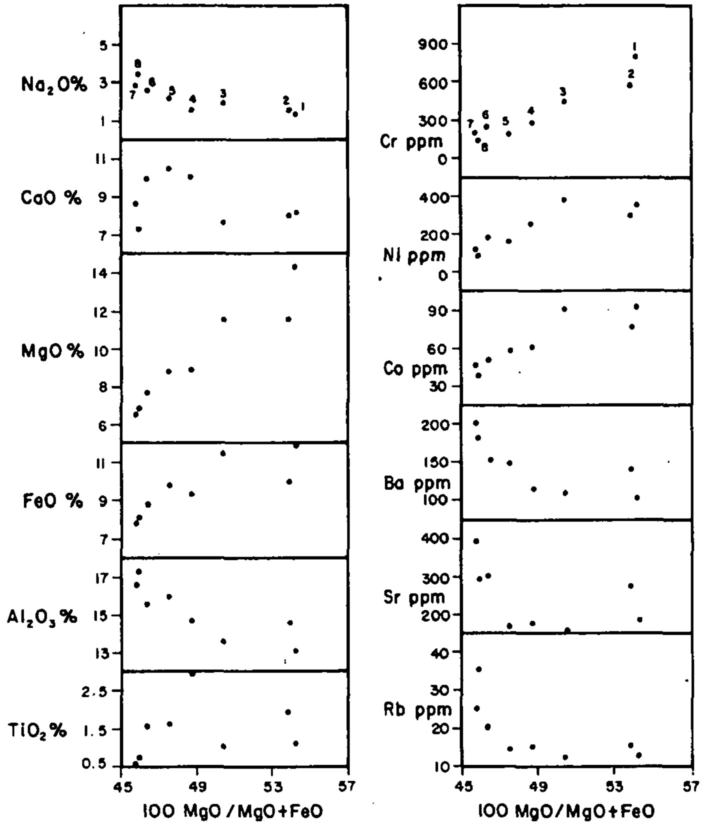

Fig. 4. Some major and trace element *versus* 100 MgO/MgO + FeO ratio. Index of numbers as in *Fig. 2.*

decrease in both measured and normative An contents (Table 2) of the plagioclases take place toward the hydrous end minerals. The FeO*/MgO ratio (Table 1) increases from the olivine gabbro to the hornblende gabbro, i. e both Fe^{2+} and Mg contents had been fractionated during the formation of the gabbroic sequence. All the above variations in the elements and their ratios together with the modal and normative minerals conform the existence of gradual chemical changes in the gabbroic magma during a short limited fractionation process [McSween and Nystrom, 1979]

The CaO shows an unusual behaviour through the fractionation of the gabbroic melt. At the beginning of crystallization, the mafic minerals (olivine and hypersthene) represented the main liquidus phase in the magma. Therefore, the crystallized plagioclases are not enough as it might be expected. As a result, low amounts of CaO (7.48—8.19%, Table 1) are recognized in the olivine pyroxene gabbros. With progressive

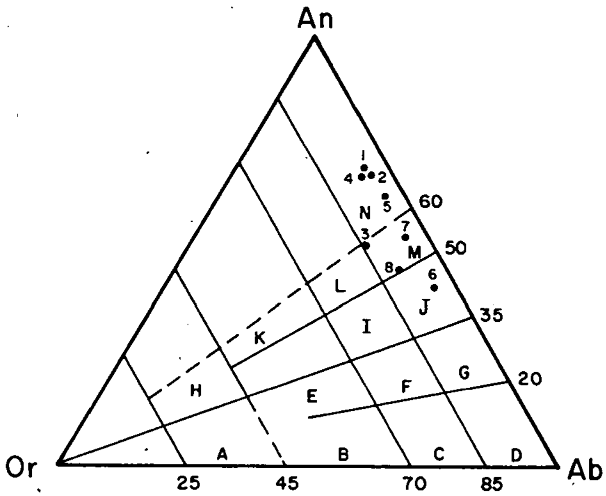

Fig. 5. Triangular diagram for An, Ab and Or normative ratio in the investigated gabbroic rocks [Hietanen, 1963]. Index of numbers as in *Fig. 2.*

(A) Potassium granite
(B) Granite
(C) Granit: trondhjemite
(D) Trondhjemite
(E) Quartz monzonite
(F) Monzonite
(G) Tonalite
(H) Calci-granite
(I) Granodiorite
(J) Quartz diorite
(K) Calci-monzonite
(L) Granogabbro
(M) Gabbro
(N) Mafic gabbro

fractionation, the crystallized olivine and hypersthene decreased with the increase of Ca-pyroxene and plagioclase, i. e. the main liquidus phase in the magma was represented by plagioclases in this stage in which the formed pyroxene gabbros are characterized by the highest values of CaO (10.02—10.53%, Table 1). At the end of fractionation, the hydrous minerals began to crystallize forming hornblende gabbros with little pyroxene. The composition of plagioclases in these gabbros vary from labradorite to andesine in state of labradorite only in the olivine pyroxene gabbros and pyroxene gabbros. This decrease in the An contents of plagioclases reflects the repeated depletion in the values of CaO (7.35—9.89%, Table 1) at the late fractionation stage.

The alteration processes which had taken place in some gabbros are not related to the granitic magma due to the absence of any hybridization effects in the examined gabbros in addition to the completely disappearance of any relics from the granitic materials within the gabbroic constituents. Petrographical and chemical evidences show that some gabbros were attacked by late magmatic hydrothermal solutions producing the altered gabbros through uralitization, chloritization and sericitization processes.

CONCLUSION

The system of fractionation in the Muhammad Qol gabbroic sequence can be concluded according to the petrographical and chemical evidences. Firstly, fair amounts of olivine and pyroxene particularly hypersthene had been fractionated from a basic magma of significant mafic character. As a result, the formed mafic

EXPLANATION TO TABLE 1—3

Sample no.	Rock variety
	Olivine pyroxene gabbros
1	Olivine gabbro
2	Olivine hypersthene gabbro
3	Olivine augite gabbro
	Pyroxene gabbros
4	Hypersthene diopside gabbro
5	Augite gabbro
	Hornblende pyroxene gabbros
6	Hornblende augite gabbro
7	Hornblende gabbro
8	Altered gabbro
9	Average analysis of 4 gabbroic samples from north of Muhammad Qol area (NEARY *et al.* 1976).

N. B. Sample numbers referring to various gabbroic rocks are the same throughout the present paper.

gabbros are characterized by low values of Ca contents due to the depletion of crystallized plagioclases in this stage.

The rate of crystallized pyroxene, specially Ca-pyroxene, increased with progressive fractionation in which pyroxene gabbros comprising largely of plagioclases and lesser of olivines are formed. In this stage, the pronounced plagioclase phase reflecting an enrichment in the Ca contents as compared to those in the early stage.

At the end of fractionation, the hydrous minerals began to crystallize under high water pressure and relatively low temperature producing hornblende gabbros which bear little augite and completely free from olivine. Although the plagioclases are greatly abundant in this late stage, the Ca contents fall again due to the remarkable decreasing in the An content of plagioclases from the olivine pyroxene gabbros to hornblende pyroxene gabbros passing through pyroxene gabbros.

In the altered gabbroic rocks, the uralitization, chloritizaticn and sericitization processes are readily accepted as resulting from the action of late magmatic hydrothermal solutions rather than the effects of granitic magma on the gabbros.

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