

## Pyroxenes from the gabbros of the Marangudzi ring complex, Rhodesia

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**SUMMARY.** Chemical, X-ray, and optical analyses of eight Ca-rich pyroxenes and three coexisting Ca-poor pyroxenes from the gabbros of the Marangudzi ring complex, Rhodesia, are presented. Both the series show limited Fe-enrichment. High Ca-content of the clinopyroxenes together with their restricted Fe-enrichment, having a trend from  $\text{Ca}_{44.8}\text{Mg}_{42.6}\text{Fe}_{12.6}$  to  $\text{Ca}_{42.7}\text{Mg}_{37.7}\text{Fe}_{19.6}$ , could be indicative of an alkaline nature. But the presence of a Ca-poor pyroxene phase with a compositional trend between  $\text{Ca}_{2.6}\text{Mg}_{71.2}\text{Fe}_{25.9}$  and  $\text{Ca}_{3.1}\text{Mg}_{63.0}\text{Fe}_{34.9}$  onwards in small amounts suggests tholeiitic to calc-alkaline nature. Certain characteristics in the variation in composition of the pyroxenes confirm a transitional nature of the Marangudzi parent magma, originating at a depth comparatively greater than the normal tholeiitic magma, but less deep than alkaline magma, at a fairly high pressure. The Marangudzi pyroxenes are compared with the pyroxenes of the similar world-wide igneous complexes.

THE pyroxenes described here come from the gabbro cumulates of the Marangudzi ring complex, Rhodesia (Rees, 1960; Gifford, 1961). The complex is a typical Karoo intrusive igneous body of the Nuanetsi province (Cox *et al.*, 1965), emplaced into the roughly 2000 Myr old granitic basement and characterized by an early NNW-SSE trending rectangular gabbroic sheet aged about 186 Myr, repeatedly intruded by the ring dikes of saturated syenites, cone sheets of undersaturated syenites, and radial phonolitic dikes. The gabbroic mass being basic to very basic, shows occasional banding features; petrographically the gabbros are considered as mesocumulates and orthocumulates (Hossain and Henderson, *in preparation*). The major coexisting mineral phases in the gabbros are clinopyroxenes of the augite field ( $\text{Ca}_{45}\text{Mg}_{43}\text{Fe}_{12}$  to  $\text{Ca}_{43}\text{Mg}_{37}\text{Fe}_{20}$ ), olivines ( $\text{Fo}_{72}$  to  $\text{Fo}_{48}$ ), and plagioclases ( $\text{An}_{84}$  to  $\text{An}_{77}$ ); minor phases are biotite, iron titanium oxide, alkali feldspars, apatites, and occasionally orthopyroxenes and late magmatic hornblendes.

In the present study, the pyroxenes of the Marangudzi gabbros have been chemically analysed and their X-ray and optical parameters determined. Compositional trends of the pyroxenes are discussed in the light of the findings of various authors for the pyroxenes of major igneous complexes of the world in order to establish their nature and crystallization behaviour. From the nature of the pyroxenes, some comments on the origin and physicochemical condition of the Marangudzi complex are made.

*Description and method of study:* The pyroxenes of the Marangudzi gabbros are mainly limited to the monoclinic group. Orthorhombic pyroxenes occur in small quantities as reaction rims around some olivines and also as minor discrete cumulus grains. Clinopyroxenes occur as anhedral and subhedral grains or irregular patches, often with subophitic or poikilitic habit. Ubiquitous inclusions of opaque iron oxide appear as minute particles (concentrated parallel to the {100} cleavage), as well as larger oriented plates in some grains. A little marginal zoning is seen in some pyroxenes. Some of the late stage clinopyroxenes show late stage alteration to green hornblende and biotite. Exsolution lamellae are common in the pyroxenes of coarser gabbros. In the orthopyroxenes, the exsolution lamellae are fine and parallel to {100}, typical of Bushveld type.

Eight clinopyroxenes and three co-existing orthopyroxenes were separated from eight representative gabbros (Table I), showing chemical variation. Complete chemical analyses of the pyroxenes were made using combined gravimetric and spectrographic methods including atomic absorption spectroscopy. Trace-element determinations were conducted by X-ray fluorescence spectrography. A Zeiss four-axis universal stage using orthoscopic method was used to measure the optic axial angles. The  $\beta$ -refractive index measurements were made from the grains of {100} partings in monochromatic light under controlled temperature of the refractive index liquids. The unit-cell dimensions of the pyroxenes were determined with a Phillips high-angle X-ray powder diffractometer using Co- $K\alpha$  Fe-filtered radiation. The optical and X-ray data of the pyroxenes are presented in Table II along with the chemical data.

### Composition

*Major element variations:* The major variables Ca, Mg, and Fe( $\text{Fe}^{2+} + \text{Fe}^{3+} + \text{Mn}^{2+}$ ) show a limited range of compositions for the Marangudzi pyroxenes. In the standard pyroxene quadrilateral (Poldervaart and Hess, 1951), the clinopyroxenes plot in the angite field close to sahlite and diopside, and the orthopyroxenes in the hypersthene and bronzite fields (fig. 1).

The pyroxenes are remarkably high in Al and Ca, relative to their Si content. Thus, the %  $\text{Al}^{\text{IV}}$  of the clinopyroxenes is rather high compared to similar clinopyroxenes of tholeiitic affinity. But the %  $\text{Al}^{\text{IV}}$  is not too high for the clinopyroxenes to be considered for alkaline affinity. None of the major elements other than Fe and Mg show any notable range of variation in the pyroxene series.

The  $\text{Fe}^{2+}/\text{Mg}^{2+}$  ratios in both series of pyroxenes show considerable ranges. The range of Fe/Mg ratio of the Marangudzi pyroxenes is similar to those from the early and middle stage pyroxenes of Inch (Clarke, 1965; Clarke and Wadsworth, 1970), Stillwater (Hess, 1960), Kap Edvard Holm (Deer and Abbott, 1965), Bushveld (Atkins, 1969), Guadalupe (Best and Mercy, 1967), Garbh Eilean (Murray, 1954), and Skaergaard (Brown, 1957) intrusions. The Marangudzi clinopyroxenes are comparatively high in Ca content, similar to the clinopyroxenes of Guadalupe, Inch, Kap Edvard, Garbh Eilean, etc., while the early and middle stage pyroxenes of the other intrusions, such as Stillwater, Bushveld, and Skaergaard, have lower Ca contents. On the other hand, Marangudzi clinopyroxenes are less Ca-rich than the clinopyroxenes of Black Jack (Wilkinson, 1957) and Somma-Vesuvius (Rahman, 1975). In general the Marangudzi pyroxenes have much similarity with the pyroxene assemblages of Kap Edvard Holm complex.

*Trace element variation:* The clinopyroxenes carry a large part of the Sr, Zr, Cr, V, and Ni content of the Marangudzi gabbros. With Fe enrichment in the series, the clinopyroxenes show marked depletion in Cr and Ni, fluctuating increase of Zr, and an approximately uniform concentration of V, Sr, etc. (Table III).

### Compositional trend of the pyroxenes and their relationship with the primary magma type

Compositional trends of the pyroxenes relative to the physicochemical conditions and type of magma have been studied by many authors. Compositional trends of Marangudzi pyroxenes in the light of this work also provide much valuable information about the genesis of the pyroxenes themselves and the origin of the associated igneous complex.

*Relative variations in chemistry:* Both series of Marangudzi pyroxenes show limited Fe-enrichment. The high Ca-content of the clinopyroxenes together with their restricted Fe-enrichment ( $\text{Ca}_{44.8}\text{Mg}_{42.6}\text{Fe}_{12.6}$  to  $\text{Ca}_{42.7}\text{Mg}_{37.7}\text{Fe}_{19.6}$ ) could be indicative of an alkaline nature. However, the presence of a Ca-poor pyroxene phase with compositions between  $\text{Ca}_{2.9}\text{Mg}_{71.2}\text{Fe}_{25.9}$  and

TABLE I. *Analyses, C.I.P.W. norms, and modes of the representative Marangudzi gabbro cumulates*

	G265	100A	T203	A12	A4	G205	T398	T168
SiO <sub>2</sub>	47.04	48.16	47.06	47.72	46.40	46.72	45.92	48.19
Al <sub>2</sub> O <sub>3</sub>	15.28	13.35	19.92	16.87	24.10	19.37	12.89	18.33
Fe <sub>2</sub> O <sub>3</sub>	3.45	1.37	5.17	1.67	1.75	1.74	2.38	2.62
FeO	5.18	6.42	4.11	9.19	3.47	6.40	11.49	7.72
MgO	10.52	13.47	6.45	9.61	4.55	7.56	12.99	5.83
CaO	16.45	15.38	13.80	9.34	15.85	15.24	12.54	12.00
Na <sub>2</sub> O	1.06	0.86	2.25	2.47	1.51	1.33	1.07	2.55
K <sub>2</sub> O	0.20	0.17	0.30	1.16	0.43	0.36	0.31	0.84
TiO <sub>2</sub>	0.16	0.21	0.59	0.51	0.18	0.27	0.41	0.71
MnO	0.12	0.17	0.14	0.19	0.09	0.15	0.22	0.19
P <sub>2</sub> O <sub>5</sub>	0.35	0.22	0.09	0.29	0.22	0.11	0.11	0.31
H <sub>2</sub> O <sup>+</sup>	0.64	0.40	0.63	0.81	0.78	0.43	0.29	0.56
H <sub>2</sub> O <sup>-</sup>	0.03	0.02	—	0.03	0.06	0.02	—	0.01
CO <sub>2</sub>	0.11	0.06	0.17	0.10	0.19	0.01	0.06	0.05
	100.59	100.26	100.68	99.96	99.58	99.71	99.80	99.91
C.I.P.W. norms								
Or	1.18	1.01	1.77	6.86	2.54	2.13	0.77	4.96
Ab	8.97	7.28	19.04	20.90	12.78	11.25	9.05	21.58
An	36.34	32.06	43.37	31.52	57.71	45.82	29.99	36.09
Di	Wo	17.66	17.71	9.78	5.13	7.63	12.11	8.81
	En	12.80	12.33	7.54	3.00	4.99	7.42	4.80
Hy	Fs	3.23	3.91	1.20	1.88	2.11	4.00	3.70
	En	3.82	6.62	3.31	1.67	1.61	1.12	1.74
Ol	Fs	0.97	2.09	0.53	1.05	0.68	0.61	1.34
	Fo	6.71	10.23	3.65	13.50	3.31	7.21	5.59
Mt	Fa	1.87	3.57	0.64	9.32	1.55	4.28	4.75
	En	5.00	1.99	7.50	2.42	2.54	2.52	3.80
Ilm	0.30	0.40	1.12	0.97	0.34	0.51	0.78	1.35
Ap	0.77	0.48	0.20	0.63	0.48	0.24	0.24	0.68
cc	0.25	0.14	0.39	0.23	0.43	0.02	0.14	0.11
Water	0.67	0.42	0.69	0.84	0.84	0.45	0.29	0.57
	100.54	100.31	100.67	99.92	99.54	99.69	99.80	99.60
D.I.	-0.29	-0.34	-0.14	-0.12	-0.13	-0.19	-0.27	-0.07
Fe <sub>2</sub> O <sub>3</sub>	0.67	0.21	1.26	0.18	0.50	0.27	0.21	0.34
FeO	—	—	—	—	—	—	—	—
Mode								
Orth.	—	0.1	—	0.2	tr.	—	—	0.2
Plag.	44.1	42.5	63.5	53.8	82.6	63.0	38.6	64.3
Oliv.	8.2	10.8	8.4	15.7	1.9	6.1	21.9	8.3
Pyr.	47.1	46.2	23.6	19.2	9.9	27.7	38.3	21.3
Biot.	0.5	0.3	1.3	9.5	4.1	1.7	0.2	3.0
Fe ox.	tr.	0.1	3.2	0.5	0.7	1.4	0.9	2.3
Apat.	0.1	tr.	tr.	1.1	0.8	0.1	0.1	0.6
Colour index	55.9	57.4	36.5	46.0	17.4	37.0	61.4	35.5

D.I., Differentiation index, = (1/3 Si+K)-(Ca+Mg).  
 100A: Coarse plagioclase-pyroxene-olivine mesocumulate; southeastern part of the Complex near Madwala Hill.  
 T398: Coarse plagioclase-pyroxene-olivine mesocumulate; from top of Madwala Hill.  
 G205: Coarse plagioclase-pyroxene-olivine mesocumulate; southern part of the Complex, immediately outside the saturated ring.  
 G265: Medium to fine plagioclase-pyroxene-olivine mesocumulate; southwestern part of the Complex, immediately inside the saturated ring.  
 A4: Coarse plagioclase mesocumulate with pyroxene and olivine; north central part of the Complex, in between the saturated and undersaturated rings.  
 T203: Plagioclase-pyroxene-olivine orthocumulate; central part of the Complex inside the saturated ring.  
 A12: Plagioclase-pyroxene-olivine orthocumulate; southern part of the Complex, immediately inside the saturated ring.  
 T168: Plagioclase-pyroxene-olivine orthocumulate; central part of the Complex south of A4.

TABLE II (left). *Analyses and optical and X-ray data of the pyroxenes.* TABLE III (right). *Trace element concentrations (p.p.m.) in the clinopyroxenes*

TABLE II

	G265			T203		A12		A4	G205	T398	T168
	Cpx. 1	Cpx. 2	Opx. 3	Cpx. 4	Opx. 5	Cpx. 6	Cpx. 7	Cpx. 8	Cpx. 9	Cpx. 10	Cpx. 11
SiO <sub>2</sub>	51.48	51.63	51.74	49.81	51.12	52.28	50.54	49.09	51.33	50.47	
TiO <sub>2</sub>	0.39	0.57	0.43	0.51	0.39	0.44	0.50	0.42	0.48	0.44	
Al <sub>2</sub> O <sub>3</sub>	3.79	3.75	1.21	4.10	2.80	0.44	4.56	4.58	2.73	3.21	
Fe <sub>2</sub> O <sub>3</sub>	2.16	11.34	1.36	2.15	1.50	0.55	2.21	2.67	1.04	2.29	
FeO	5.64	6.83	16.15	6.67	8.08	21.76	7.37	7.50	9.82	9.59	
MnO	0.21	0.17	0.53	0.30	0.25	0.47	0.23	0.20	0.26	0.36	
MgO	14.91	14.72	26.67	14.47	14.46	22.41	13.26	13.39	14.19	12.98	
CaO	21.84	20.50	1.50	20.86	20.78	1.57	21.20	20.60	20.36	20.42	
Na <sub>2</sub> O	0.46	0.46	0.10	0.45	0.40	0.14	0.45	0.47	0.40	0.42	
K <sub>2</sub> O	0.02	0.01	—	0.02	0.02	—	0.03	0.03	0.02	0.03	
	100.90	99.98	99.69	99.34	99.88	100.06	100.35	99.75	100.63	100.21	
Cations, atoms %											
Ca	44.84	43.70	2.87	43.51	43.36	3.12	44.95	43.70	42.13	42.68	
Mg	42.61	43.64	71.21	41.98	41.87	61.98	39.11	39.52	40.83	37.74	
Fe†	12.55	12.66	—	14.50	14.67	34.90	15.94	16.78	17.04	17.04	
En mol %	—	—	72.64	—	—	63.68	—	—	—	—	
Ionic ratios to 6 oxygen											
Si	1.880	1.507	1.902	1.861	1.988	1.955	1.876	1.866	1.911	1.895	
Al <sup>IV</sup>	0.120	0.093	0.053	0.139	0.092	0.019	0.124	0.134	0.089	0.105	
Ti	—	—	0.012	—	—	0.011	—	—	—	—	
Fe <sup>3+</sup>	—	—	0.033	—	—	0.015	—	—	—	—	
Al <sup>VI</sup>	0.058	0.070	—	0.50	0.032	—	0.075	0.067	0.031	0.037	
Fe <sup>2+</sup>	0.059	0.037	0.009	0.061	0.042	—	0.062	0.075	0.029	0.064	
Fe <sup>2+</sup>	0.172	0.211	0.497	0.288	0.252	0.681	0.229	0.235	0.306	0.381	
Mn	0.006	0.005	0.017	0.009	0.008	0.015	0.007	0.006	0.008	0.012	
Mg	0.812	0.810	1.461	0.806	0.804	1.249	0.733	0.746	0.787	0.726	
Ca	0.855	0.811	0.059	0.835	0.831	0.063	0.843	0.825	0.812	0.821	
Na	0.033	0.033	0.007	0.033	0.035	0.010	0.033	0.034	0.029	0.031	
K	0.001	0.001	—	0.001	0.001	—	0.001	0.002	0.001	0.001	
Ti	0.011	0.016	—	0.014	0.011	0.002	0.014	0.012	0.013	0.012	
WXY	2.007	1.994	2.050	2.017	2.016	2.020	1.997	2.002	2.016	2.005	
Ca-Ti‡	3.46	3.42	n.d.	3.54	2.43	n.d.	3.84	3.74	2.42	2.22	
C.I.P.W. norm (recalculated to 100%)											
Di	93.23	88.11	—	90.48	89.82	—	92.88	91.34	86.57	89.37	
Ol	6.41	4.98	—	8.84	8.39	—	6.41	7.40	8.61	5.87	
Hy	—	6.91	—	—	1.79	—	0.71	1.25	7.82	4.76	
Ne	0.36	—	—	0.68	—	—	—	—	—	—	
Optical data											
β	1.700	1.699	1.697	1.708	1.704	1.700	1.708	1.703	1.703	1.710	
2V	49.4°	46.8	67.4	48.3	49.3	60.3	49.0	50.6	46.4	49.0	
Exsol. §	None	(100)	(100)	—	—	(100)	—	—	Present	—	
X-ray data											
a	9.751 Å	9.749	—	9.753	9.747	18.313	9.761	9.755	9.749	9.759	
b	8.917	8.915	—	8.922	8.920	8.880	8.918	8.922	8.921	8.937	
c	5.245	5.257	—	5.261	5.246	5.208	5.258	5.261	5.259	5.254	
β	73.96°	74.02	—	74.05	73.93	—	74.02	73.98	73.98	73.95	

TABLE III

	G265	A4	G205	T168
Cr	373	236	361	214
V	357	378	396	244
Ni	112	86	93	45
Zr	28	37	65	103
Sr	45	61	48	38
Cr				
V	1.07	0.62	0.91	0.88
Ni				
Cr	0.30	0.36	0.26	0.21

\* Orthopyroxene from T398 had β 1.701, abundant exsolution lamellae || (100), 62.5 mol % En (from X-ray data, after Howie, 1963 and a 18.299, b 8.878, c 5.201 Å.

† Fe<sup>2+</sup> + Fe<sup>3+</sup> + Mn.

‡ Ca-Tschermak Molecule (Kushiro, 1962)

§ Exsolution lamellae.

$$|| \text{ En mol. \%} = \frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}^{2+} + \text{Fe}^{3+} + \text{Mn}}$$

Ca<sub>3-1</sub>Mg<sub>6-2</sub>Fe<sub>34-9</sub> in small amounts in a few of the rocks suggests tholeiitic to calc-alkaline nature. The trend of crystallization of the pyroxenes of typical tholeiitic magmas, such as Skaergaard, commences with the enrichment of Fe, principally at the expense of Mg, but also replacing Ca. At the late stage of fractionation, the augites become enriched in Ca (Brown,

1957). Carmichael (1960) related the variation in Ca content of augite with fractionation to the complex shape of the solvus surface.

Marangudzi clinopyroxenes are fairly rich in Al; the  $A^{IV}$  is a little higher than in the clinopyroxenes of typical tholeiitic affinity rocks, such as Bushveld and Skaergaard, but much lower than in those of typical alkaline complexes. With increasing Al substitution in the pyroxene structure during fractionation, Fe tends to replace Ca rather than Mg to compensate for

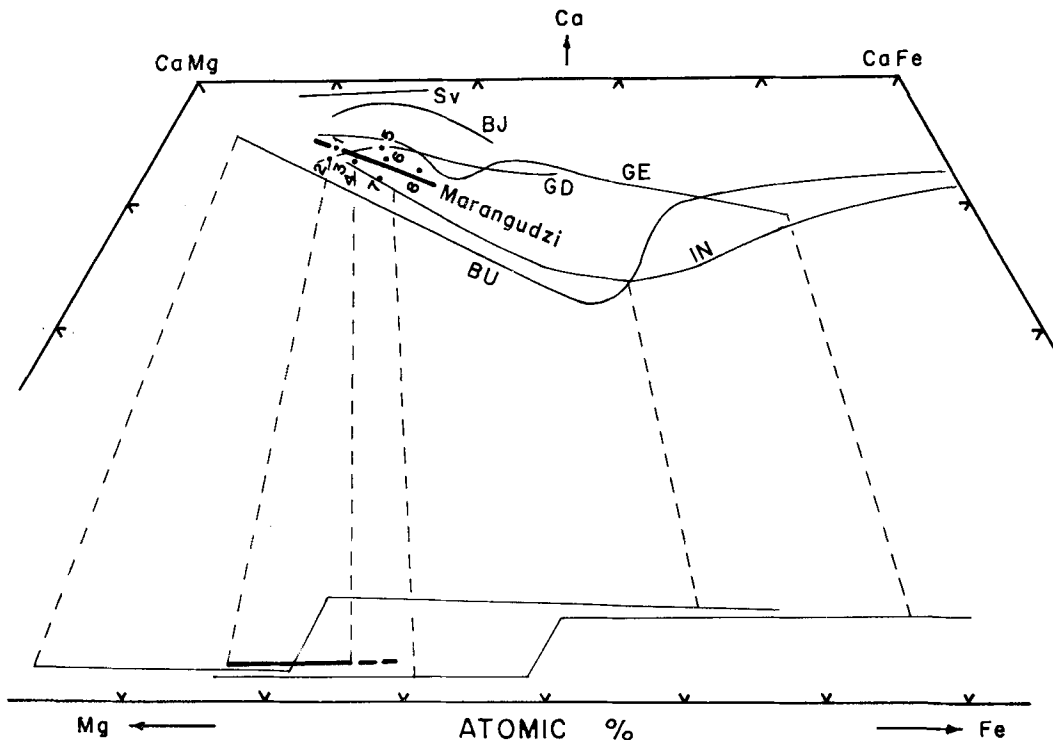


FIG. 1. Composition of the pyroxenes of Marangudzi gabbros in solid circle (see Table II for sample numbers) and their compositional variation showing trend of crystallization in thick line. For comparison, crystallization trend of the pyroxenes of other igneous complexes are shown as BU for Bushveld (Atkins, 1969), IN for Insch (Clarke, 1965), GD for Guadalupe (Best and Mercy, 1967), GE for Garbh Eilean (Murray, 1954), BJ for Black Jack (Wilkinson, 1957) and SV for Somma Vesuvius (Rahman, 1975).

distortions in structure, caused by substitution of  $Al^{3+}$  for  $Si^{4+}$ . The relationship of Si, Al, and Ti in the clinopyroxenes of various rock types were studied by Kushiro (1960) and Le Bas (1962) in order to determine the physicochemical condition of the magma. Comparison of the present analytical data for the Marangudzi clinopyroxenes with the data quoted by these authors shows:

In the diagram  $TiO_2$  vs.  $Al^{IV}$  (Le Bas, 1962, fig. 5) the Marangudzi clinopyroxenes plot inside the tholeiitic field close to the alkaline boundary, showing a haphazard trend with comparatively high  $Al^{IV}$ .

Plots of atomic proportion of Al against Ti in Kushiro's diagram (1960, fig. 2) for the clinopyroxenes show similar relations but lie much closer to the field of the pyroxenes of alkaline affinity.

Comparatively high amounts of Al in the tetrahedral site and the nature of variations of

Al and Si in the tetrahedral site are shown in the plot of atomic proportions of Si against Al in Kushiro's diagram (Kushiro, 1960, fig. 1) in fig. 2. In this diagram, the Marangudzi clinopyroxenes plot in the field transitional between pyroxenes of tholeiitic and alkaline affinities.

In the triangular diagram  $(Ca+Na+K):(Fe^{2+}+Fe^{3+}+Mn):Mg$  (atomic %) Marangudzi clinopyroxenes plot almost entirely in the field of clinopyroxenes of alkaline rock series, but close to the field of tholeiitic affinity (Le Bas, 1962, fig. 1). Comparison of these plots with respect to Le Bas's plot of %  $(Al_Z)$  ( $= 50 Al^{IV}$ ) in the same triangular diagram (Le Bas, 1962, fig. 3) shows the Marangudzi clinopyroxenes are tholeiitic to transitional between

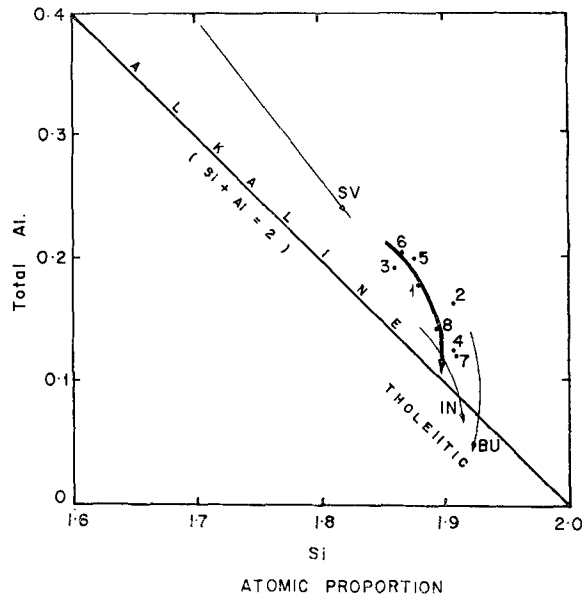


FIG. 2. Relation between the atomic proportions of Si and Al (after Kushiro, 1960) in the Marangudzi clinopyroxenes (solid circles and thick line), and comparison with the clinopyroxenes of Bushveld (BU), Inch (IN), and Somma Vesuvius (SV).

tholeiitic and alkaline nature. This is because of their comparatively low %  $Al^{IV}$  values with respect to the clinopyroxenes of typical alkaline affinity (Rahman, 1975).

In the wt. %  $SiO_2$  vs.  $Al_2O_3$  diagram (Le Bas, 1962, fig. 2), Marangudzi clinopyroxenes plot along the boundary between the fields of pyroxenes of both tholeiitic and alkaline series, although most of them lie close to the tholeiitic field.

From the above comparisons it appears that the clinopyroxenes of the Marangudzi gabbros are transitional in nature and they have probably been associated with a magma having physicochemical properties between the tholeiitic and alkaline series.

*Alumina contents and % Ca-Tschermak's molecule in the pyroxenes:* High amounts of  $Al^{IV}$  have been related to high temperatures of formation (Thompson, 1947; Buerger, 1948; Kushiro, 1962; Wilkinson, 1957 and 1966). However, Hytönen and Schairer (1961) have shown that the pyroxenes in the system Di-En-An are not strictly binary Di-En solid solutions, but aluminous ones, containing Tschermak's molecule ( $CaAl_2SiO_6$ ). With falling temperature, diopside crystallized from mixtures of diopside-Ca-Tschermak's molecule and the system Di-En-An are enriched in alumina. Bushveld and Stillwater magmas are very similar in nature, but the clinopyroxenes from the Stillwater intrusion are more Al-rich. Hess (1960)

suggested that this may be due to higher load pressure for Stillwater. Kushiro (1960) and Le Bas (1962) in course of their statistical analysis of the pyroxenes of various origin, also suggested this.

It has been suggested that progressive lowering of silica content in the magma favours the concentration of increasing amounts of Ca-Tschermak's molecule ( $\text{CaAl}_2\text{SiO}_6$ ) into pyroxenes (Hytönen and Schairer, 1961; Sakata, 1957). Muir and Tilley (1964) have described augite phenocrysts from apparently tholeiitic basalts containing up to 6.6%  $\text{Al}_2\text{O}_3$  and noted that the pressure effect must be taken into account and that these phenocrysts crystallized at appreciable depths. Kushiro (1962) and Aoki (1964) suggested that Ca-Tschermak's molecule of the clinopyroxenes may be used as a measure of pressure.

The average  $\text{CaAl}_2\text{SiO}_6$  content of Marangudzi clinopyroxenes is 3.01% (Table II). This value is higher than the value of 1.7% quoted by Kushiro (1962) for the clinopyroxenes of basaltic rocks throughout the world. Thus, comparatively higher values for  $\text{Al}_2\text{O}_3$  and  $\text{CaAl}_2\text{SiO}_6$  for the Marangudzi clinopyroxenes may be related to their formation at higher pressures than the average tholeiitic plutonic complex.

*Nepheline in the pyroxene norm.* Normative calculations for the clinopyroxenes show minor amounts of nepheline in two of the samples cp. G265 and cp. T203 with values of 0.31 and 0.52 wt % norm respectively (Table II). These values are quite negligible and well within the probable analytical error. However, plots on (Di-Ol-Hy) and (Di-Ol-Ne) diagram (Muir and Tilley, 1964, Fig. 4) show that most of the clinopyroxenes lie close to Di-Ol join. Those with Ne in the norm or minor amounts of Hy in the norm plot very close to the join either on the Ne side or on the Hy side of the diagram; this may be an indicator of transitional nature of the pyroxenes.

*Partition of elements between coexisting pyroxenes:* Ramberg and DeVore (1951), Kretz (1961), and Bartholome (1961) observed that the distribution coefficient ( $K_D$ ) relating  $\text{Mg}^{2+}$  and  $\text{Fe}^{2+}$  distribution between coexisting clinopyroxene and orthopyroxene phases shows a striking difference for igneous ( $K_D = 0.73$ ) and metamorphic ( $K_D = 0.54$ ) pyroxene assemblages. Atkins (1969) pointed out that as the distribution coefficient  $K_D$  is dependent on the temperature, pressure, and, in some cases, concentration of other elements (Ramberg and DeVore, 1951; Kretz, 1961, 1963); it should be used as a general indicator of the physico-chemical conditions of pyroxene formation, rather than strictly as a distinction between igneous and metamorphic assemblages.

The ( $K_D$ ) values of the two Marangudzi pairs are low compared to the normal values quoted for igneous pyroxenes (0.73), pyroxene pair A12 being especially low with  $K_D = 0.57$ .  $K_D$  for the pyroxene pair 100A is 0.63, which is quite close to the  $K_D$  values for Bushveld. The values for Bushveld are lower than for Skaergaard, although both complexes are very similar in chemistry and mineralogy (Atkins, 1969). Ramberg and DeVore (1951) and Kretz (1961) attributed the variation to differences of temperature and pressure between these two intrusions and suggested that crystallization at Bushveld occurred at lower temperatures or higher pressures (or both) than at Skaergaard. Thus, the lower  $K_D$  values for the Marangudzi pyroxene pairs may indicate their crystallization at even higher pressures than Bushveld.

#### *Discussion and conclusion*

From the trend of composition and certain mineralogical characteristics, it appears that the pyroxenes of the Marangudzi gabbro cumulates have been crystallized in a magma transitional between tholeiitic and alkaline. These pyroxenes are not typical aluminous pyroxenes (Lewis, 1967; Rahman, 1975) but do contain some amount of Al in tetrahedral and octahedral

coordination. A comparatively high percentage of Ca-Tschermak's molecule in most of the clinopyroxenes and lower  $K_D$  values of some pyroxene pairs indicate a high-pressure environment of crystallization, probably between 2 and 10 kb, equivalent to a depth of crystallization between 7 and 35 km (Kushiro, 1962; Green and Ringwood, 1964; Ringwood and Green, 1964; Green, 1968). The pyroxenes show a limited range of composition. Like the pyroxenes, all other coexisting mafic and felsic mineral phases of the gabbros show restricted Fe and Na enrichment, which may be related to their crystallization at high and increasing  $P_{H_2O}$ . Presence of biotite as a coexisting hydrous mineral phase in the gabbros may be considered as principal source of high  $P_{H_2O}$ . A portion of this water dissociated to give rise to a relatively high  $P_{O_2}$ , which is reflected in the high  $Fe_2O_3/FeO$  ratio (0.18 to 0.75 and as high as 1.26) for the Marangudzi magma (Table I), where the pyroxenes and other coexisting cumulus mineral phases have been crystallized. So, in the light of the compositional trend of pyroxenes and some other related factors, it may be concluded that the pyroxenes of the Marangudzi gabbros have been crystallized from a basic magma, transitional between tholeiitic and alkaline, which was emplaced at a fairly great depth, and in course of differentiation was influenced by high and increasing  $P_{H_2O}$ . This environment of crystallization has possibly caused the final trend more towards a state of undersaturation.

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