

The petrology and chemical composition of a tholeiite sill on Schaapkraal 68JT, Lydenburg District, Transvaal, South Africa

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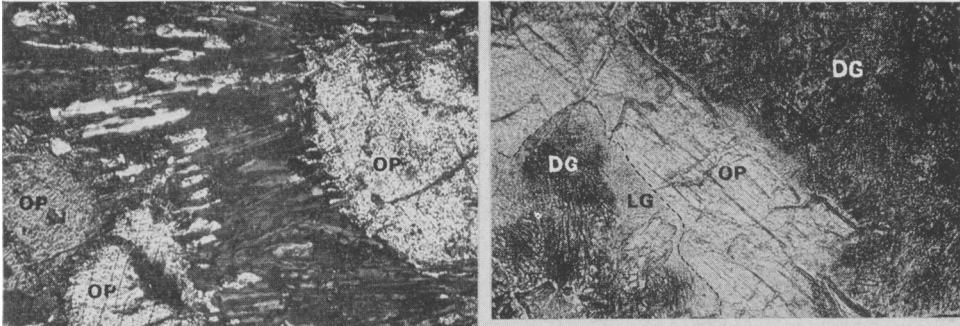
SUMMARY. A glass-bearing dolerite, which consists of orthopyroxene phenocrysts (γ 1.689, α 1.678, β 1.680, $2V_{\alpha}$ 81°, S.G. 3.35) and a glassy mesostasis (n 1.568, S.G. 3.25), is described petrologically. Three new chemical analyses are given. From the petrological and chemical data it can be concluded that the orthopyroxene formed under intratelluric conditions and probably under high pressure. According to the recalculated chemical analysis of the orthopyroxene 0.22 Al³⁺ is in the Y position and much less Al³⁺ in the Z position. The chemical analysis of the residual glass is compared with similar residual glasses, and it shows that iron enrichment characterizes the earlier stages of crystallization differentiation, whereas the later stages are marked by an increase in Si⁴⁺, K⁺, and Na⁺.

BOTH Walker (1935) and Vincent (1950) have investigated residual glasses from tholeiitic dykes, and have agreed that more analyses of similar residual glasses are much needed to establish the trends of the later stages of crystallization differentiation in small intrusions. Consequently the residual glass from the glass-bearing dolerite sill on Schaapkraal 68JT has been investigated, and the results thus obtained provide an interesting comparison with the results of the work carried out by Walker (1935) and Vincent (1950).

Field relationship. The glass-bearing dolerite, which consists of orthopyroxene phenocrysts set in a glassy mesostasis, forms the chilled contact of a differentiated dolerite sill, situated on the farm Schaapkraal 68JT, Lydenburg District, Transvaal. This dolerite sill is approximately 100 ft thick, and it has a chilled zone, which is about 10 ft thick, at both contacts. The chilled zone is succeeded by a crystalline zone, which shows differentiation. The sequence of differentiation from the bottom to the top of the sill is harzburgite, pyroxenite, and dolerite.

This dolerite sill is intrusive into the cordierite hornfels above the Magaliesberg quartzite of the Pretoria Series, and forms part of the Pre-Bushveld Complex magmatic activity. According to J. Willemse (1959, p. xlviii) the dolerite sills, which are intrusive into the Pretoria Series, can be grouped into the Maruleng type and the Lydenburg type. Both the mineralogical and chemical composition of this glass-bearing dolerite indicate that it belongs to the Maruleng type of dolerite. The $c\text{-}(al\text{-}alk) = 4.97$ also indicate that it is noritic in composition, and consequently can be considered as part of the Chill Zone of the Bushveld Complex (Frick, 1967, p. 65). It may therefore represent the composition of the primary magma of the Bushveld Complex.

The petrology of the glass-bearing dolerite. The chilled dolerite consists of large orthopyroxene phenocrysts (0.2–7.0 mm in diameter) set in a glassy mesostasis, which is in places devitrified to clinopyroxene, plagioclase, and magnetite (fig. 1). In many places the glass is crowded with margarites of opaque minerals (fig. 2). The latter are often arranged in typical flowlines or form globospherites. The glass is isotropic, $n \ 1.568 \pm$



FIGS. 1 and 2: Fig. 1 (left). Orthopyroxene phenocrysts (OP) in a devitrified mesostasis, which shows a trachytoidal texture (CF.17). Crossed Nicols, $\times 75$. Fig. 2 (right). A phenocryst of orthopyroxene (OP) bordered by a light-coloured glass (LG) in a dark glass (DG) that contains many margarites of opaque minerals (CF.6). Ordinary light, $\times 75$.

0.003 and S.G. 3.25 ± 0.05 ; the latter was determined by the pycnometer method. The high specific gravity of the glass can be ascribed to the many margarites present.

The clinopyroxene, plagioclase, and magnetite, which crystallized from the glassy matrix, usually display a trachytoidal texture also described by Willemse (1959,

p. xxxviii). This texture may be explained by the recrystallization of spherulites, which formed in a viscous environment (Colony and Howard, 1934, p. 517). The devitrification was probably caused by a rise in temperature during the emplacement of the main plutonic phase of the Bushveld Complex.

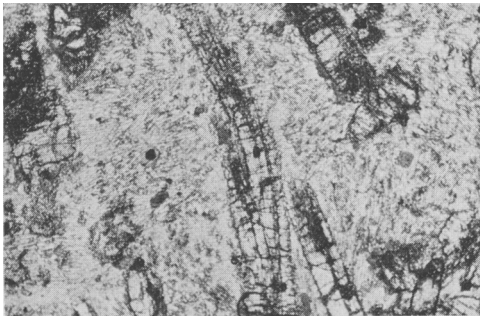


FIG. 3. A bent phenocryst of orthopyroxene in the devitrified mesostasis (CF.27). Ordinary light, $\times 44$.

The orthopyroxene phenocrysts are often bent (fig. 3), similar to those described by Strauss (1947, p. 79) from a quartz-dolerite near Potgietersrust. According to Strauss this texture can either be explained by deformation

during or after crystallization. Since this glassy dolerite consists only of orthopyroxenes in a glassy mesostasis, it is evident that the pyroxenes must have crystallized intratelluric and were deformed during emplacement. The orientation of phenocrysts parallel to flowlines also bears witness of this movement in the magma during emplacement.

Chemical analyses. In order to get a pure sample of the residual glass and the orthopyroxene phenocrysts, the rock was crushed and the —200-mesh fraction was used. Since the glass contains many microlites of opaque minerals, which are strongly magnetic, it was possible to separate the glass and the pyroxene with the aid of a hand magnet and an isodynamic separator. The purity of the concentrates were checked by means of point counting, and it was found that the glass contained 3.80 % of

TABLE I. *The recalculated chemical analysis of orthopyroxene from the glass-bearing dolerite from Schaapkraal*

A		B			C
SiO ₂	53.8	Si	1.98	} 2.00	α 1.678 ± 0.002
Al ₂ O ₃	5.7	Al ^{iv}	0.02		β 1.680 ± 0.002
Fe ₂ O ₃	1.4	Al ^{vi}	0.22	} 0.72	γ 1.689 ± 0.002
FeO	9.8	Fe ³⁺	0.04		2V 81°
MgO	21.6	Ti	0.01	} 1.49	S.G. 3.35
CaO	4.8	Cr	0.01		
Na ₂ O	0.2	Mg	1.18	} 0.23	
K ₂ O	0.6	Fe ²⁺	0.30		
H ₂ O	1.3	Mn	0.01		
TiO ₂	0.2	Ca	0.19		
Cr ₂ O ₃	0.3	Na	0.01		
MnO	0.3	K	0.03		
Sum	100.0				

A. Recalculated chemical analysis, corrected for adherent glass.

B. The formula calculated on six oxygen atoms to the unit cell according to the formula of Hess (1949, 624).

C. The physical properties of the orthopyroxene.

orthopyroxene, whereas the orthopyroxene only contained 2.4 % of glass grains. However, heavy medium separations at densities of 3.30 and 3.25 g cm³ indicated that the orthopyroxene grains also contain some glass. The percentage of glass adhering to the pyroxene was calculated by doing three separations at densities between that of the glass and the pyroxene, at 3.32, 3.30, and 3.27 g cm³ in Clerici solution and calculating the impurity according to the formula:

$$3.25x + 3.35(100 - x) = 100y$$

where x = the percentage impurity of the percentage of floats at each separation and y = the density at which the separation was carried out.

This calculation revealed an impurity of 28.3 % of residual glass in the pyroxene. In table I the recalculated chemical analysis and the physical properties of the orthopyroxene are given. The orthopyroxene appears to have a high content of Al³⁺ in the Y position, and a low Al³⁺ content in the Z position. A high Ca²⁺ content in the W position is also present, and since no exsolution lamellae of clinopyroxene are present, it may be ascribed to Ca²⁺ in solid solution in the orthopyroxene. The high content of Al³⁺ in the Y position of the orthopyroxene is probably an indication of a high-pressure phase in contrast to minerals like fassaite, which has a high Al³⁺ content in the

TABLE II. *Chemical analysis, katamolecular norms, volumetric compositions, and Niggli values of the tholeiites from Kap Daussy, Kinkell, and Schaapkraal*

	A	B	C		Katamolecular norms		
					A	B	C
SiO ₂	47.42	49.10	56.91	qu	1.82	7.6	13.3
Al ₂ O ₃	11.75	12.13	12.68	or	3.22	12.2	3.5
Fe ₂ O ₃	3.39	4.61	2.51	alb	19.96	17.8	13.1
FeO	12.79	8.92	6.71	an	19.79	17.5	25.7
MgO	5.35	4.50	9.77	diop	25.19	15.8	6.04
CaO	10.83	8.20	7.14	hyp	15.09	9.7	32.70
MnO	0.10	0.15	0.19	mt	4.92	6.7	3.5
Na ₂ O	2.36	2.14	1.46	ilm	7.55	7.6	0.2
K ₂ O	0.55	2.10	0.62	ap	1.28	1.3	0.1
TiO ₂	3.98	4.02	0.38	water	1.25	3.6	2.0
P ₂ O ₅	0.54	0.51	0.09	Sum	100.04	99.8	100.14
H ₂ O ⁺	0.95	2.50	0.98				
H ₂ O ⁻	0.30	1.02	0.04				
Others	—	0.03	0.36				
Sum	100.31	99.93	99.84				

	Volumetric composition				Niggli values		
	A	B	C		A	B	C
Plagioclase	38.2	28.3	—	si	110.16	132.36	145.36
Augite	31.7	22.4	—	al	16.12	19.30	19.15
Hypersthene	—	7.0	44.8	fm	50.82	47.94	56.72
Olivine	3.3	—	—	c	26.97	23.62	19.55
Magnetite	6.5	10.8	—	alk	6.10	99.13	4.57
Glass	20.3	31.5	55.2	k	0.13	0.04	0.21
Sum	100.0	100.0	100.0	mg	0.36	0.38	0.66
				ti	6.95	8.12	0.74
				p	0.56	0.65	0.14

- A. Tholeiite from Kap Daussy, East Greenland. Vincent (1950, p. 56). Magma type is hawaiitic.
 B. Tholeiite from Kinkell, North Scotland. Walker (1935, p. 150). Magma type is melagabbrodioritic.
 C. Tholeiite from Schaapkraal 68JT, Lydenburg District. Analyst: National Institute for Metallurgy. Magma type is melagabbrodioritic.

Z position, and forms under high temperatures. Hess (1952, p. 177) has also mentioned that pressure would favour the reaction of enstatite + Al₂O₃ to give a Mg Tschermak's molecule, but this effect can also be achieved by an increase in temperature, which generally increases the extent of solid solution. However, it seems likely that the orthopyroxene phenocrysts crystallized intratellurically under high temperature and pressure conditions.

According to the chemical and volumetric compositions (table II), the glass-bearing dolerite from Schaapkraal can be considered as a tholeiitic sill. It is both quartz and hypersthene normative, and augite and nepheline are absent from the volumetric

composition and consequently it falls into the tholeiite field (Yoder and Tilley, 1962, p. 352). According to the diagram constructed by Tilley (1964, p. 258) for the rocks from Hawaii, the dolerite from Schaapkraal falls in the field of the rocks in which orthopyroxene would occur in the mode. Since the tholeiite from Schaapkraal is quartz normative, it substantiates the idea of Yoder and Tilley (1962, p. 410) that rocks containing orthopyroxene should be quartz normative.

Since orthopyroxene has an incongruent melting point, it does not seem likely that orthopyroxene should crystallize first, unless the magma has a special composition. Although the tholeiite from Schaapkraal falls in this area in Tilley's diagram, Verhoogen (1954, p. 87) also explained this phenomenon by suggesting that the incongruent melting point of orthopyroxene will vanish at high pressure. This has in fact

TABLE III. *Chemical analyses, katamolecular norms, and Niggli values of the residual glasses from Kap Daussy, Kinkell, and Schaapkraal*

	3	3'		Katamolecular norms			Niggli values			
				1	2	3'	1	2	3'	
SiO ₂	58.52	58.39	qu	36.3	30.7	17.32	si	249.48	384.64	164.62
Al ₂ O ₃	15.07	14.82	or	9.2	25.0	3.73	al	30.58	41.16	24.59
Fe ₂ O ₃	2.48	2.45	alb	15.4	20.4	15.33	fm	29.48	13.73	46.26
FeO	5.74	5.84	an	17.9	10.0	28.87	c	27.49	16.05	22.97
MgO	5.99	6.40	diop	2.7	0.3	4.06	alk	12.71	29.06	22.97
MnO	0.14	0.14	hyp	3.1	2.5	20.10	k	0.36	0.54	0.18
CaO	7.65	7.58	mt	4.3	1.4	3.25	mg	0.26	0.30	0.58
Na ₂ O	1.89	1.85	ilm	1.5	0.5	0.53	ti	2.73	0.90	0.07
K ₂ O	0.66	0.65	ap	2.3	1.0	0.26	p	1.88	1.00	0.02
TiO ₂	0.41	0.40	calcite	—	—	0.60				
P ₂ O ₅	0.11	0.11	chromite	—	—	0.04				
H ₂ O ⁺	0.99	0.99	water	7.0	8.7	5.92				
H ₂ O ⁻	0.02	0.02	Sum	99.7	100.5	100.01				
Others	0.27	0.27								
Sum	99.84	99.91								

1. Residual glass from the tholeiite from Kap Daussy, East Greenland. Vincent (1950, p. 56). Magma type is granitic.
2. Residual glass from the tholeiite from Kinkell, North Scotland. Walker (1935, p. 150). Magma type is trondhjemitic.
3. Residual glass from the tholeiite from Schaapkraal 68JT. Analyst: National Institute for Metallurgy.
- 3'. Corrected analysis of the residual glass from Schaapkraal. Magma type is Si-gabbrodioritic.

been verified experimentally by Boyd and England (1961, p. 115) at 6 kb for an anhydrous system. According to Yoder and Tilley (1962, p. 411) it is to be expected that orthopyroxene would continue to melt incongruently at high p_{H_2O} . Since the orthopyroxene from Schaapkraal contains much Al³⁺ in the Y position, and the residual glass (table III) has a low percentage of H₂O, the ideas of Boyd and England may be applicable to this system.

Both petrological and chemical data indicate that the orthopyroxene crystallized

intratellurically and was emplaced with the magma. During ascent of the magma through the upper layers of the crust resorption and partial melting occurred and this was probably caused by the lowering of the solidus temperature with decrease in pressure (Winkler, 1962, p. 225). During emplacement the magma must have moved a great deal, causing flowlines, bent phenocrysts, and radially orientated pyroxene crystals. The rapid chilling close to the surface produced the glass, which is in places devitrified due to a rise in temperature during emplacement of the Bushveld Complex.

Chemical composition of the residual glass. The chemical analyses, norms, and Niggli values of the residual glasses from Schaapkraal, Kap Daussy, and Kinkell are listed in table III. The norm and the Niggli values of the residual glass from Schaapkraal have been calculated for the corrected chemical analysis. When the analyses of the residual glasses are compared with the analyses of the rocks from which they were separated, the trends of differentiation can be determined.

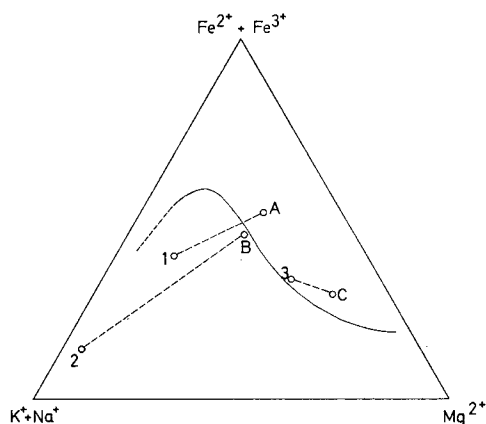


FIG. 4. The composition of the glasses from Kinkell, Kap Daussy, and Schaapkraal compared to the differentiation trend of the Bushveld Complex. A, B, and C chemical composition of the rocks (table II), and 1, 2, 3 composition of the residual glasses (table III). Tie line between rocks and their residual glasses. Trend of differentiation of the Bushveld Complex, after J. Willemse (1967).

According to fig. 4 it is obvious that the trend of differentiation of the Schaapkraal tholeiite differs significantly from that of the Kap Daussy and Kinkell tholeiites. This difference can be explained by the differences in the composition of the magma during emplacement, and by the duration of the crystallization differentiation process. It is obvious that the Schaapkraal tholeiite contains less Fe^{2+} , Fe^{3+} , Na^+ , Ca^{2+} , and Ti^{4+} and more Mg^{2+} than the Kap Daussy and Kinkell tholeiites,

thus indicating that the rocks from the latter two localities already represent iron-enriched phases, whereas the Schaapkraal tholeiite has not yet differentiated that far.

The volumetric compositions (table II) indicate that the Schaapkraal tholeiite contains 55 % of glass, whereas the Kinkell and the Kap Daussy tholeiites contain much less (31.5 and 20.3 respectively). This means that 55 % of the Schaapkraal tholeiite has not yet differentiated, whereas the Kinkell and Kap Daussy tholeiites are more completely differentiated. Consequently the residual glass from the latter localities represent a more extreme case of crystallization differentiation. This also explains the enrichment in H_2O in the tholeiites from Kap Daussy and from Kinkell.

The crystallization differentiation in the Schaapkraal tholeiite involved enrichment in Fe^{2+} , Fe^{3+} , K^+ , Na^+ , Ca^{2+} , and Si^{4+} , and a decrease in Mg^{2+} . The crystallization of orthopyroxene thus caused the magma to become enriched in feldspar and quartz.

The $\Delta\text{Al}_2\text{O}_3/\Delta\text{SiO}_2$ value for the Schaapkraal tholeiite and its residual glass is 1.45, which is very high, but it does not cause such a tremendous increase in quartz as was suggested by Yoder and Tilley (1962, p. 413); it is evident from the chemical composition of the orthopyroxene that quartz enrichment could not be very high, because Al^{3+} does not replace Si^{4+} , but enters the Y position.

The Niggli values show much the same trends of differentiation in all three residual glasses, except that the degree of enrichment or decrease varies considerably. It is further clear from the data presented that iron enrichment characterizes the earlier stages of crystallization differentiation as seen from the analyses of the Schaapkraal tholeiite, and that the later stages of differentiation are marked by an increase in Si^{4+} , K^+ , and Na^+ .

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