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Mineralogical data on a multiple intrusion in the Rustenburg Layered Suite of the Bushveld Complex

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ABSTRACT. Mineralogical and chemical data are presented on an intrusion of a hypersthene gabbro body into coarse-grained noritic cumulates of the critical zone, which occurs at the margin of the Rustenburg Layered Suite of the Bushveld Complex. Two types of contact relations are found between the above two rock suites: (1) a clearly cross-cutting contact is observed on the southern margin of the hypersthene gabbro body close to the interface between the layered suite and the floor rocks; (2) a diffuse heterogeneous contact is found on the north-western limb of the body which is further into the complex. Field observations and chemical data suggest that, at the time of the hypersthene gabbro injection, the surrounding cumulates were above ambient temperatures. The difference in the contacts described above is probably related to the prevailing temperature gradient at the time of emplacement. The cumulate rocks further into the complex were at a higher temperature than those closer to the margin.

Trace element chemistry and phase relations in the basalt tetrahedron indicate that the hypersthene gabbro is genetically unrelated to the cumulate rocks which it intrudes. The body probably represents an offshoot of the magma from which the upper zone of the Rustenburg Layered Suite crystallized.

THE Rustenburg Layered Suite of the Bushveld Complex has been studied since the turn of the century and many ideas have been forwarded on the nature and number of magma injections involved in the formation of this body. On the one extreme are proponents of the single magma hypothesis, for example Hall (1932), Willemse (1959), Hess (1960), and Cameron (1978). These workers believed the Bushveld Complex resulted from a single magma injection which subsequently crystallized to form the various cumulate assemblages. They stressed the overall similarity in the layering between the various lobes of the complex and the fact that individual horizons persist over hundreds of kilometres.

On the other extreme, Cousins (1959) believed the complex to have been formed from a large number of lava sheets. Irvine (1977) postulated a new magma injection to explain each chromitite layer. Multiple injection on a smaller scale was also favoured by Reuning (1928), Lombaard (1934), Truter (1955), Schwellnus (1956), and Coertze (1958 and 1974). They believed most of the major mineralogical units to be separate injections.

Between the two extremes are advocates of a few separate injections. Gijbels *et al.* (1974), using partition coefficients of Os, Ru, Ir, and U between silicate and spinel cumulate minerals, proposed a new injection of magma at the transitional-critical zone boundary of Cameron, 1970 (see fig. 1). However, a mineralogical study by Cameron (1978), across this boundary in the eastern lobe of the Bushveld Complex indicated no reversals in the cumulate mineral compositions, which would be

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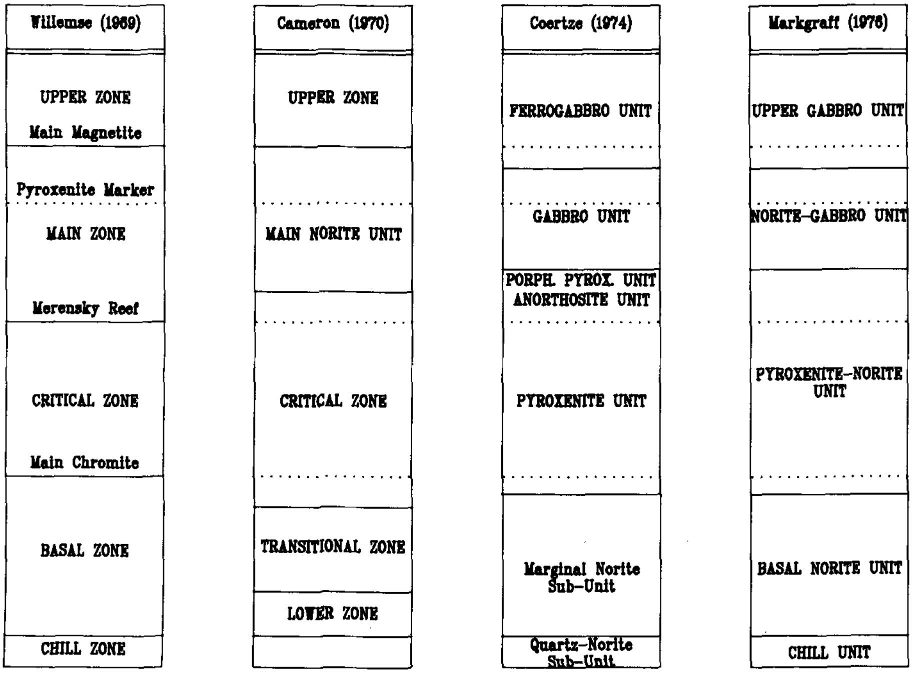


FIG. 1. The subdivision of the Rustenburg Layered Suite used by various authors.

expected if the proposal of Gijbels *et al.* (1974) were true.

Hamilton (1977), using Sr isotopic data from the cumulate rocks of the Layered Suite, obtained an age of 2094 ± 24 Ma. He grouped his samples using the subdivision of Cameron (1970), finding an usually high Sr^{87}/Sr^{86} initial ratio of 0.70563 for the transitional zone which increased progressively upward in the layered mafic rocks. This he suggested was due to new magma injections (at least four), with each successive magma having a higher Sr^{87}/Sr^{86} ratio than its predecessor. The main zone has a variable initial Sr^{87}/Sr^{86} ratio which Hamilton was unable to explain. McCarthy and Cawthorn (1980) re-evaluated these isotopic data and their model required two injections of magma, the second of which intruded at about the middle of the main zone. The mixing of this magma with the residual liquid of the earlier injection could explain the variable isotopic values found for the main zone. This model was based on the data of von Gruenewaldt (1970, 1973) who produced mineralogical evidence from the eastern Bushveld Complex which indicated at least one new magma injection at about the middle of the main zone. The work of Molyneux (1974) in the Sekhukhuneland area supported von Gruenewaldt's data. Pyroxene compositions from the western lobe of the Bushveld Complex (Markgraaff, 1976) show two reversals in the cryptic layering of the main zone. Markgraaff (1976) concluded that two injections of magma were responsible for the main and upper zones. The first formed the 'Norite-Gabbro' unit (lower and middle part of the main zone, see fig. 1) and the latter the 'Upper-Gabbro' unit (approximately the top quarter of the main zone and all of the upper zone; Coertze's (1974) ferrogabbro unit).

Sharpe (1980, 1981), from work in the eastern lobe, believes there are at least six major injections of magma into the Rustenburg Layered Suite. He proposed three injections of high-MgO magma (*c.* 20 to 32 % MgO) at the base of the lower zone, at the Merensky Reef and at the Pyroxenite Marker. One injection of magnesium basalt (*c.* 12 % MgO); at the base of the critical zone, and two injections of tholeiitic magma (*c.* 7 % MgO) at the base of the main zone and at the Pyroxenite Marker.

The mineralogical, chemical, and experimental petrological data presented by Davies *et al.* (1980), Cawthorn *et al.* (1981), and Cawthorn and Davies (1983) suggests that the lower portion of the Rustenburg Layered Suite formed from a magnesian basaltic liquid similar in composition to micropyroxenitic sills found in the floor below the Layered Suite. A second, tholeiitic suite of sills and chill phases have compositions and mineralogy consistent with that found for the main and upper zones. This led Cawthorn *et al.* (1981) to suggest that these sills and chills could be representatives of the liquid from which the main and upper zones crystallized.

The transgressive nature of the ferrogabbro unit near Northam, documented by Coertze (1958, 1974), the reversal in cryptic layering in the main zone in both lobes of the Complex (von Gruenewaldt, 1973; Molyneux, 1974; and Markgraaff, 1976), and the work of Sharpe (1980, 1981) and Cawthorn *et al.* (1981), indicate the possibility of substantial additions of magma during the formation of the upper and main zone.

Mapping of an area on the margin of the western lobe of the Complex, east of Rustenburg, has produced evidence of multiple injections which will be discussed below.

Locality and field evidence

The study area lies about 30 km east of Rustenburg on the southern margin of the western lobe of the Bushveld Complex (see fig. 2). The marginal rocks of the Rustenburg Layered Suite in this area consist of a cumulate assemblage of feldspathic

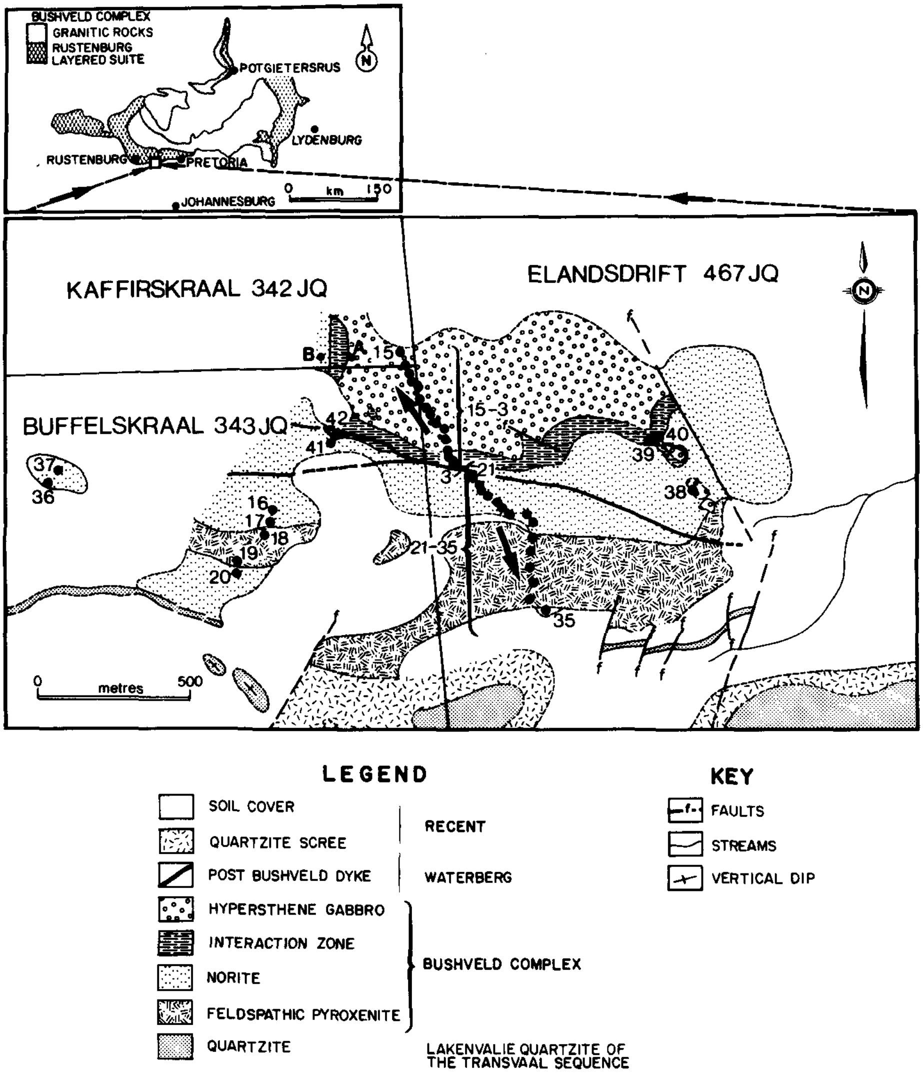


FIG. 2. Locality and geological map of the study area. Dots indicate sampling points and numbers are sample numbers.

pyroxenites and norites which overlie hornfels and quartzites of the Vermont and Lakenvalie Formations of the Transvaal Sequence. These rocks are stratigraphically below the chromitite layers which crop out on the farm Elandsdrift 647 JQ (to the north of the present area) and which are generally equated with the middle group chromitites of the critical zone (Cousins and Feringa, 1964). The outcrop is discontinuous in the area and so it is not possible to establish whether the cumulate marginal rocks are part of the critical zone or not.

About 700 m north of the sedimentary-igneous contact, a fine- to medium-grained hypersthene gabbro body is present. It is approximately rectangular in outcrop, about 1 × 2 km and elongated in an E–W direction. To the east it terminates against a prominent NNW-trending fault; along most of the western portion and to the north, it disappears under soil cover. Along the southern contact small irregular veins of fine- to medium-grained hypersthene gabbro are found cutting the coarser grained norite up to eight metres from the norite–hypersthene-gabbro contact. The contact zone is generally very irregular with blocks of coarse-grained norites engulfed in the finer grained hypersthene gabbro. The norite disaggregates into small clusters of grains and single crystals (see fig. 3). The NW contact is of particular interest. At point A (fig. 2) true norite is found, and at point B hypersthene gabbro is developed. Between these two points a zone of mixing is found where ghost blocks of what presumably was norite merge into only slightly finer grained hypersthene gabbro. The exact contact where norite ends and hypersthene gabbro begins is impossible to define in the field.

TABLE I

TYPICAL MINERAL ANALYSES FROM THE VARIOUS ROCK UNITS

	Feldspathic Pyroxenite				Norite				Hypersthene Gabbro			
	Opx	Cpx	Plag	Spinel	Opx	Cpx	Plag	Spinel	Opx	Cpx	Plag	Spinel
SiO2	54.31	52.75	48.53	00.04	53.49	52.12	48.42	00.04	50.91	51.22	52.26	00.20
TiO2	00.16	00.30	00.00	01.56	00.21	00.37	00.01	00.73	00.36	00.58	00.01	02.06
Al2O3	01.02	01.30	32.90	03.36	00.68	01.48	32.02	01.73	00.56	01.41	30.14	01.01
Cr2O3	00.22	00.22	n.d.	29.48	n.d.	n.d.	n.d.	07.62	n.d.	n.d.	n.d.	00.63
V2O3	n.d.	n.d.	n.d.	01.19	n.d.	n.d.	n.d.	01.49	n.d.	n.d.	n.d.	01.28
Fe2O3	n.d.	n.d.	n.d.	31.68 *	n.d.	n.d.	n.d.	55.97 *	n.d.	n.d.	n.d.	60.71 *
FeO	14.15	05.76	00.31	29.91	20.41	07.54	00.33	31.06	29.02	14.05	00.25	32.57
MnO	00.31	00.16	00.00	00.38	00.42	00.18	n.d.	00.15	00.64	00.33	n.d.	00.05
MgO	28.63	16.27	00.01	02.07	24.02	15.08	00.00	00.48	16.77	11.65	00.00	00.08
CaO	00.86	22.58	15.68	00.00	00.79	22.07	15.70	00.01	01.26	20.33	12.70	00.09
Na2O	00.00	00.26	02.41	n.d.	00.00	00.34	02.48	n.d.	00.02	00.30	04.15	n.d.
K2O	n.d.	n.d.	00.09	n.d.	n.d.	n.d.	00.09	n.d.	n.d.	n.d.	00.18	n.d.
Total	99.66	99.60	99.93	99.67	100.02	99.18	99.05	99.28	99.54	99.87	99.69	98.68
No. of O	6.	6.	32.	32.	6.	6.	32.	32.	6.	6.	32.	32.
Si	1.956	1.952	8.889	0.012	1.974	1.951	8.954	0.012	1.977	1.954	9.513	0.062
Ti	0.004	0.008	0.000	0.345	0.006	0.010	0.001	0.167	0.011	0.017	0.001	0.479
Al	0.043	0.057	7.104	1.163	0.030	0.065	6.981	0.621	0.026	0.063	6.468	0.368
Cr	0.006	0.006	n.d.	6.846	n.d.	n.d.	n.d.	1.835	n.d.	n.d.	n.d.	0.154
V	n.d.	n.d.	n.d.	0.280	n.d.	n.d.	n.d.	0.364	n.d.	n.d.	n.d.	0.317
Fe 3+	n.d.	n.d.	n.d.	7.004	n.d.	n.d.	n.d.	12.828	n.d.	n.d.	n.d.	14.112
Fe 2+	0.426	0.178	0.047	7.347	0.630	0.236	0.051	7.910	0.942	0.448	0.038	8.414
Mn	0.009	0.005	0.000	0.095	0.013	0.006	n.d.	0.039	0.021	0.011	n.d.	0.013
Mg	1.537	0.897	0.003	0.906	1.321	0.840	0.000	0.218	0.970	0.662	0.000	0.037
Ca	0.033	0.895	3.077	0.000	0.031	0.885	3.111	0.003	0.052	0.831	2.477	0.030
Na	0.000	0.019	0.856	n.d.	0.000	0.025	0.889	n.d.	0.002	0.022	1.465	n.d.
K	n.d.	n.d.	0.021	n.d.	n.d.	n.d.	0.021	n.d.	n.d.	n.d.	0.042	n.d.
Total	4.014	4.017	19.997	23.998	4.005	4.018	20.008	23.997	4.001	4.008	20.004	23.986

n.d. Element not analysed for.

* Ferric iron was calculated by making the number of cations equal 24.

Mineral analyses were completed using the correction factors of Albee and Roy (1970). International mineral standards were used for standardizations. These standards were reanalysed after every 5 unknown mineral analyses and only if the variation for each element was less than 2% were the analyses retained.

Petrography and mineral chemistry

Mineral analyses were carried out on an ARL SEMQ electron microprobe at 15 kV and a sample current of about 0.5 μA. Typical analyses are given in Table I.

Feldspathic pyroxenite. These are hypidiomorphic coarse-grained mesocratic to melanocratic rocks. Orthopyroxene (En_{73-8}) makes up about 70% of the rock and is present as euhedral to subhedral laths 1 to 4 mm in length. Thin exsolution lamellae of clinopyroxene are present in most grains (see fig. 4). Interstitial plagioclase (An_{72-81}) makes up 20 to 25% of the rock and occurs as subhedral to poikilitic grains often with inclusions of euhedral orthopyroxene. Clinopyroxene ($Wo_{45-6}En_{44-6}Fs_{8-9}$) is a minor constituent (1–2%) of all specimens examined. In contrast to the orthopyroxene, exsolution lamellae are absent in this mineral, which is found as anhedral intercumulus crystals with plagioclase and orthopyroxene inclusions. The clinopyroxene is often found adjacent to green-brown hornblende which also has an anhedral outline. Hornblende forms about 3 to 5% of this rock type.

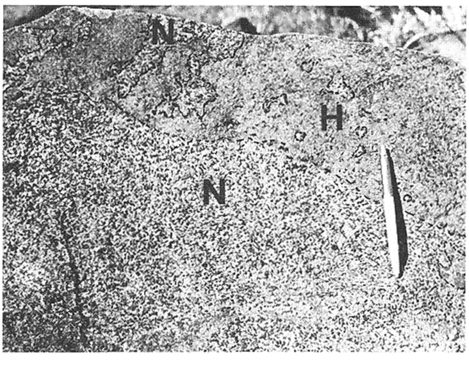
A chrome-rich spinel (ferritchromite) and a sulphide phase are present in trace amounts. The spinel is found within orthopyroxene crystals and occasionally within plagioclase crystals. The sulphide phase, which is pyrrhotite, is scarce and is usually found only in the plagioclase crystals.

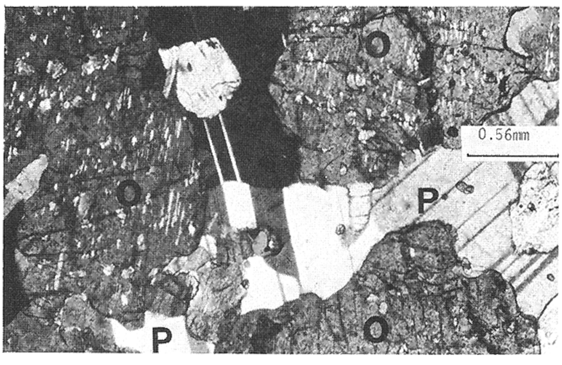
Norite. Plagioclase (An_{60-77}) is generally the most abundant mineral in these rocks, and is present in amounts from 33 to 65%. It forms euhedral to subhedral laths 1 to 3 mm in length. Orthopyroxene (En_{67-73}) varies from about 22 to 50% and occurs as subhedral crystals between 1 and 4 mm in length. Clinopyroxene ($Wo_{44-6}En_{42-6}Fs_{12-13}$) is more abundant (up to 5%) in these rocks than the feldspathic pyroxenites. The clinopyroxene has a distinct subophitic texture to the plagioclase (see fig. 5).

Minor amounts of ferritchromite, ilmenite, and sulphide are present in most sections studied. The spinel appears as small inclusions within orthopyroxene and to a lesser extent in the plagioclase crystals. Ilmenite is usually present as larger grains up to 3 mm in diameter and is usually found at orthopyroxene–plagioclase boundaries. Sulphide blebs, again pyrrhotite, are almost exclusively found in plagioclase.

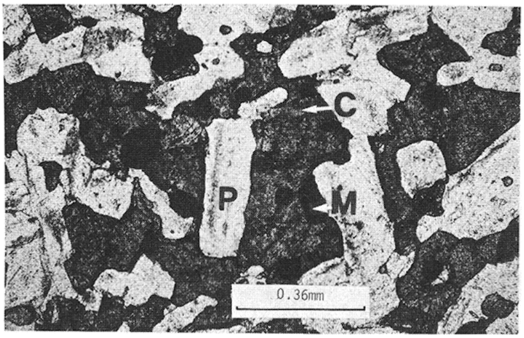
Hypersthene gabbro. This rock-type is characterized by a variable grain-size but a very uniform mineralogy and chemistry. In hand specimen it is characterized by a distinctly granular texture. However, microscopically a subophitic to poikilitic texture is found with euhedral to subhedral plagioclase partially or occasionally wholly included in poikilitic clinopyroxene and orthopyroxene aggregates (see fig. 6). The poikilitic texture is more evident in the finer grained rock types; the medium-grained areas tend to have a subophitic texture.

Plagioclase makes up about 60% of the rock and occurs as euhedral to subhedral laths ranging in lengths up to 1 mm in the finer grained areas and up to 3 mm in the medium-grained specimens. The plagioclase is more sodic than in the previous two rock types, varying from An_{48-65} with an average composition of An_{53}. Clinopyroxene and orthopyroxene are present in roughly equal proportions and are usually intimately associated. The orthopyroxene is Fe-rich hypersthene (En_{50-2}) and clinopyroxene is a Ca-rich ferroaugite ($Wo_{43-5}En_{34-8}$ Fs_{18-23}). The two pyroxenes often have inclusions of





FIGS. 3 and 4. FIG. 3 (*left*). Contact between coarse grained norite (N) and finer-grained hypersthene gabbro (H). Note irregular contact and the small clots of norite in the fine-grained hypersthene gabbro. FIG. 4 (*right*). Photomicrograph of typical texture of the feldspathic pyroxenite. Note subhedral orthopyroxene (O) with irregular clinopyroxene exsolution lamellae. Anhedral plagioclase (P) also visible in photograph.



FIGS. 5 and 6. FIG. 5 (*left*). Photomicrograph showing typical texture of the norite. Note subhedral to euhedral plagioclase (P), subhedral orthopyroxene (O) and anhedral clinopyroxene (C). FIG. 6 (*right*). Photomicrograph showing subophitic texture in the hypersthene gabbro. Minerals present are plagioclase (P) clinopyroxene and orthopyroxene (C) and magnetite (M).

magnetite and ilmenite. These two oxides are fairly abundant and combined are present in quantities up to 6%. Biotite very occasionally mantles the magnetite.

The norite–hypersthene-gabbro boundary. A traverse through the stratigraphy indicates a dramatic change in the composition of the minerals making up the norites on approaching the hypersthene gabbro (fig. 7). The change occurs over a horizontal distance of about 30 m in the area sampled. The orthopyroxene in the norite becomes progressively more unstable across the contact zone. This is manifested in the rocks by the mantling or partial mantling of orthopyroxene by clinopyroxene (see fig. 8). The ratio of orthopyroxene to clinopyroxene also decreases on moving from the norite to the hypersthene gabbro with orthopyroxene appearing to break down to clinopyroxene and dusty magnetite. The composition of the orthopyroxene changes in a regular fashion and progressively becomes more Fe-rich towards the hypersthene gabbro, changing from En_{70} to En_{50}.

The plagioclase in this interaction zone tends to be very strongly zoned. The centres are generally not very different from the apparently unaffected norite; however, the edges of the plagioclase grains become progressively more sodic on approaching the hypersthene gabbro (fig. 7).

The quantity of spinel (which changes from a ferritchromite to magnetite) increases from about 2% in the apparently unaffected norite to about 4%

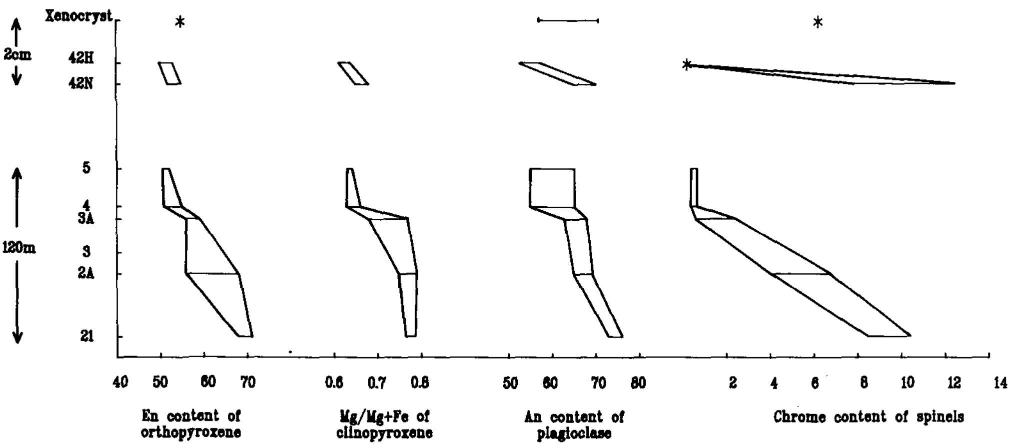


FIG. 7. Variation in the composition of minerals across the interaction zone from two traverses. Sample 42 was taken where the contact was sharp. Sample 42N is the norite and 42H is the hypersthene gabbro while 'Xenocryst' are the large crystals within the fine-grained hypersthene gabbro which are thought to be xenocrysts from the norite.

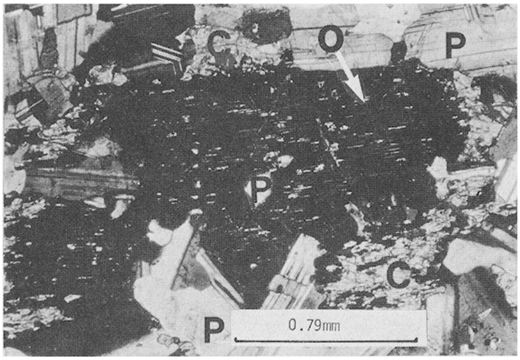


FIG. 8. Photomicrograph of an interaction zone norite showing an orthopyroxene crystal (O) which is partially mantled by clinopyroxene (C). Plagioclase (P) is also visible in the photomicrograph.

in the sample adjacent to the hypersthene gabbro. There is a progressive decrease in the Cr_2O_3 content of the spinels from the norite through to the hypersthene gabbro (see fig. 7).

The southern contact is generally irregular with inclusions of norite suspended in a hypersthene gabbro matrix. These inclusions vary from fragments 20 cm in size to single randomly orientated crystals of plagioclase and pyroxene up to 3 mm in length. A good example of the contact relationship is shown in fig. 9. Typical plagioclase compositions, one from the coarse-grained norite side of the contact, another from the finer-grained hypersthene gabbro side of the contact and the centre and edge of large plagioclase xenocrysts within the hypersthene gabbro, are presented in fig. 7.

It is clear that there is a good correlation in composition between the large plagioclase xenocrysts in the hypersthene gabbro and those in the coarse-grained norite rock, in contrast to the smaller more sodic plagioclase present in the hypersthene gabbro and found *mantling* the large plagioclase xenocrysts. In contrast, megacrystic inclusions of orthopyroxene have very similar compositions to those found in the hypersthene-gabbro groundmass (see fig. 7).

Whole-rock chemistry

The range in composition and typical chemical analyses from each of the major rock types are presented in Table II. The feldspathic pyroxenite-norite suite has a variable chemistry which reflects the ratio of the cumulate minerals in each specimen. The hyperthene gabbros have very consistent chemistries despite their variable grain size. They have higher TiO_2, total Fe, CaO, V, and lower MgO, Al_2O_3, Ni, and Cr contents than the former suite.

The feldspathic pyroxenite-norite suite shows a moderate degree of differentiation as can be seen by the FeO/(FeO + MgO) *vs.* Al_2O_3 plot (fig. 10). It can be seen that there is a relatively small increase in the FeO/(FeO + MgO) ratio from the feldspathic pyroxenite through to the norite. There is, however, a large increase in Al_2O_3 content over this same range reflecting the increase in plagioclase content in the norites. The hypersthene gabbro samples plot off this trend and form a cluster at about twice the FeO/(FeO + MgO) value found for the former suite. They have slightly lower Al_2O_3 contents than the most aluminous norites. The rocks from the interaction zone plot on what appears to be a mixing line between the most differentiated norites and the hypersthene gabbro cluster.

Trace elements also show clearly the difference between the two suites. The plot of (MgO + FeO) *vs.* V (fig. 11*a*) shows a positive trend for the cumulate

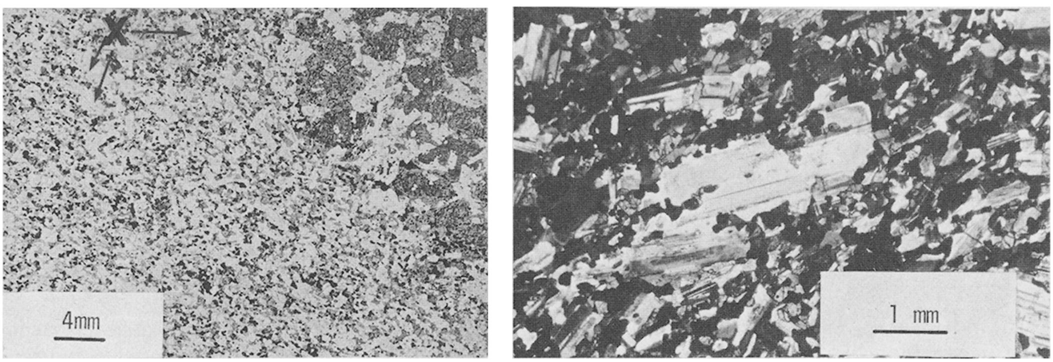


FIG. 9. Photomicrograph of the contact between norite and hypersthene gabbro. Note (left) xenocrysts (X) of plagioclase in hypersthene gabbro groundmass. On the right is an enlarged photomicrograph of one of the plagioclase xenocryst.

TABLE II. *Range and average composition of the various rock suites of the study area*

	Feldspathic pyroxenite		Norite		Hypersthene gabbro		Interaction zone norite	
	Range	Ave. (8)*	Range	Ave. (15)*	Range	Ave. (13)*	Range	Ave. (6)*
SiO_2	52.20-53.42	52.68	49.72-52.32	50.80	48.87-50.28	49.72	49.69-51.28	50.62
TiO_2	0.19- 0.30	0.24	0.17- 0.37	0.26	0.75- 0.96	0.81	0.36- 0.68	0.46
Al_2O_3	5.89- 7.28	6.44	13.11-18.59	16.38	15.27-16.39	15.67	16.44-18.07	16.98
Fe_2O_3	1.14- 3.01	1.80	0.45- 1.89	1.09	2.42- 4.35	3.25	1.11- 3.46	2.10
FeO	8.25-10.46	9.43	6.08- 9.88	7.64	9.32-10.54	9.82	7.08- 9.92	8.21
MnO	0.17- 0.22	0.20	0.13- 0.24	0.16	0.17- 0.24	0.19	0.13- 0.19	0.16
MgO	21.20-23.46	22.21	9.12-16.66	11.56	5.62- 6.64	6.08	6.46- 9.12	7.77
CaO	4.77- 5.52	5.23	7.69-10.65	9.58	10.83-11.48	10.83	19.63-10.95	10.42
Na_2O	0.44- 1.40	1.08	1.10- 2.78	1.86	2.43- 3.29	2.94	2.19- 2.96	2.51
K_2O	0.05- 0.10	0.08	0.06- 0.20	0.13	0.20- 0.27	0.25	0.11- 0.37	0.21
Ni	553- 620	584	155-408	253	61-139	77	77-155	122
Cr	1102-1874	1383	414-963	701	75-141	111	125-556	349
V	123- 167	149	86-172	115	225-261	248	117-234	159
Rb	4- 9	6	2- 9	6	1- 7	4	2- 8	5
Sr	82- 105	93	182-342	272	334-360	350	325-347	341
Zr	8- 21	13	7- 20	14	25- 53	31	15- 34	23

* Number in brackets indicates number of samples.

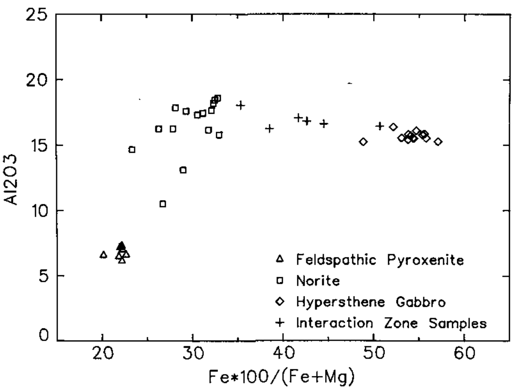


FIG. 10. A plot of FeO/(FeO + MgO) *vs.* Al_2O_3 for the maginal rocks from the study area. Note spatial separation of hypersthene gabbro suite from the feldspathic pyroxenite-norite suite. Note the spanning of the compositional gap between the two suites by the interaction zone norites.

rocks. This suggests that V is present in the orthopyroxene. The hypersthene gabbro have similar range in (MgO + FeO) values to the norites but nearly double the V content. The interaction zone samples plot between the hypersthene gabbro and norites.

The plot (MgO + FeO) *vs.* Cr (fig. 11*b*) also shows a positive relationship, indicating that Cr is present within the orthopyroxene. The hypersthene gabbro has a much lower Cr content than the norites and plots off the trend established for feldspathic pyroxenite-norite suites. The interaction zone samples again plot between the norite and the hypersthene gabbro.

Discussion

Sharpe (1981) described relationships between petrographically and chemically similar fine-grained and coarser-grained rocks within the marginal zone of the Rustenburg Layered Suite in the eastern lobe of the complex. He interpreted the fine-grained rocks as xenoliths within the coarser-grained rocks. In view of this, two possible interpretations exist for the data above. First the hypersthene gabbro may be an earlier chilled phase of the Bushveld Complex, which has subsequently been lifted from the floor by the injection of the norite magma from which the feldspathic pyroxenite and norite rocks formed.

A second explanation is that the feldspathic pyroxenite-norite suite formed prior to the hypersthene gabbro and was subsequently intruded by it.

Chemical evidence cited from the interaction zone could be used to support both contentions. However, field observations, petrographic and mineralogical evidence described earlier, strongly suggests the second of these two interpretations. The general diffuse nature of the contact, the presence of resorbed rather than angular fragments and lack of chilling around the fragments indicate further that the norite had not completely solidified at the time of the hypersthene gabbro injection.

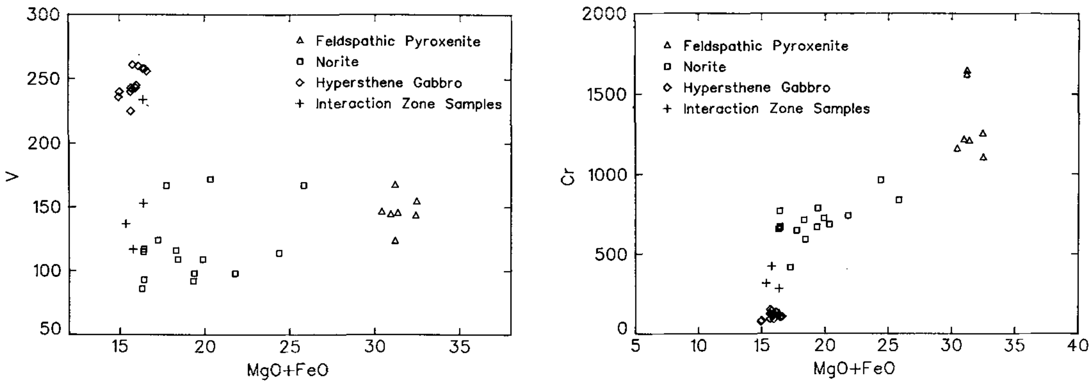


FIG. 11*a* (*left*). Binary variation diagram of (MgO + FeO) *vs*. V for the various rock suites from the present area. Note the difference in V content between the hypersthene gabbro suite and the cumulate noritic suite.

FIG. 11*b* (*right*). Binary variation diagram of (MgO + FeO) *vs*. Cr for the various rock suites from the present area. The hypersthene gabbro suite plots below the positive trend of the cumulate noritic suite. Note the spanning of the compositional gap between the two suites by the interaction zone norites.

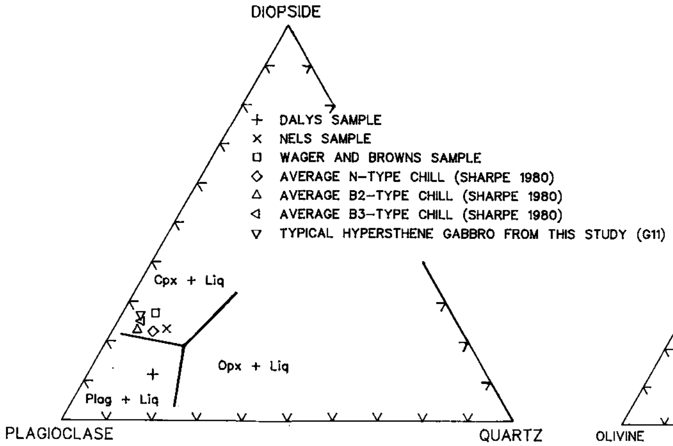
This is especially true for the NW contact area where the hypersthene gabbro is medium- to coarse-grained and a very heterogeneous mixing zone develops.

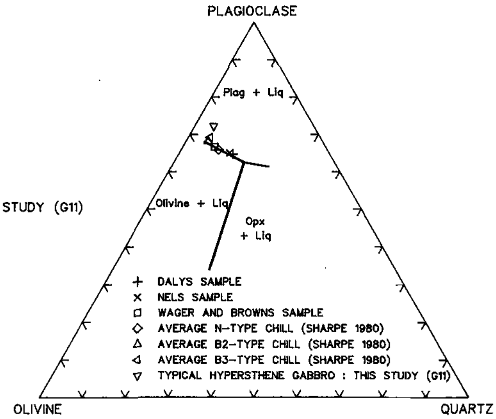
Areas of finer-grained hypersthene gabbro are found especially at the southern contact and suggest possibly more rapid cooling. This, coupled with the uniform chemistry, regardless of grain size, indicates that this rock type may represent a liquid composition. If this is true, then again at least two possibilities exist as to the relationship of this liquid to the cumulate suite. It may be analogous to the original liquid from which the feldspathic pyroxenite–norite suite formed or it may be unrelated. Generally, the chemical evidence is inconclusive. However, using the relationship between orthopyroxene composition and the Mg/Fe ratio of the liquid, found by Roeder and Emslie (1970) [obtained using the data of Medaris (1969) and Williams and Eugster (1969)], $(Fe/Mg)_{opx}/(Mg/Fe)_{liq} = 0.23$ it is possible to calculate the orthopyroxene composition likely to form from the hypersthene-gabbro liquid; an orthopyroxene composition of En_{79} is obtained. This is approximately correct for the feldspathic pyroxenite–norite suite. However, the Rb contents of the feldspathic pyroxenite–norite suite are on the whole slightly higher than that of the hypersthene gabbro (Table II). It is unlikely that a liquid will have a lower Rb content than the orthopyroxene and plagioclase cumulates which formed from it, as these two minerals strongly discriminate against Rb. This suggests no genetic link between the feldspathic pyroxenite–norite cumulates and the hypersthene gabbro liquid.

The fact that the norite disaggregates at the contact with the hypersthene gabbro suggest that these rocks were not rigid but rather in a partially consolidated state at the time of the hypersthene gabbro injection. This contention is also supported by the relatively large zone of chemically altered norites around the hypersthene gabbro. In this zone the orthopyroxene of the norite re-equilibrated to a large degree within the more Fe-rich hypersthene gabbro, whereas the plagioclase reacted only around the margin. The difference in the behaviour of these two minerals can be ascribed to their crystal structures. In the case of the orthopyroxene, substitution of Mg for Fe^{2+} does not alter the structure of the mineral, whereas for plagioclase any substitution of Na for Ca requires a coupled replacement of Al by Si bonded to oxygen, which will be much slower and apparently requires more energy than the relatively free substitution of Mg for Fe^{2+}.

The hypersthene gabbro is believed to be a later injection unrelated to the crystallization of the norite. However, since the norite does not appear to have been completely solidified at the time of injection there could not have been a large time interval between the two events.

The theoretical composition of orthopyroxene (En_{79}) in equilibrium with the hypersthene gabbro liquid can be used to determine what cumulate assemblage of the Bushveld Complex resulted from the crystallization of this liquid. It appears to be too Fe-rich for the lower reversal described by Markgraaff (1976) (En_{75} to En_{81}) but could account for those noted by von Gruenewaldt (1970, 1973) (En_{62} to En_{69} and En_{61} to En_{73}) in the main zone. However





FIGS. 12 and 13. FIG. 12 (*left*). Diagram of the Olivine projection on to the Quartz–Plagioclase–Diopside plane of the basalt tetrahedron, on which are plotted various hypersthene-gabbro compositions from the literature and this study. All samples except that of Daly (1928) lie in the diopside primary phase volume. Phase boundaries are those obtained by Cawthorn and Davies (1983). FIG. 13 (*right*). Diagram of the Diopside projection on to the Quartz–Olivine–Plagioclase plane of the basalt tetrahedron, on which are plotted the hypersthene gabbro compositions from the literature and this study. All the samples lie on or close to the plagioclase–olivine cotectic. Phase boundaries are taken from Cawthorn and Davies (1983).

the Pyroxenite Marker is an orthopyroxenite (von Gruenewaldt, 1973, and Molyneux, 1974), which implies that the composition of the magma from which it formed was within the orthopyroxene primary phase field of the basalt tetrahedron. The hypersthene gabbro liquid plots in the clinopyroxene primary phase volume (fig. 12) in the olivine projection and therefore is unlikely to have caused these reversals.

The second reversal described by Markgraaff (1976) En_{60-2} at the base of what Coertze (1974) termed the ferrogabbro unit could have resulted from the hypersthene gabbro liquid if one assumes some mixing between it and the Fe-rich residual liquid of the previous injection. The mineralogy and composition (An_{60}) of plagioclase (Coertze, 1974) in the lower part of the ferrogabbro unit, fits well with that of the hypersthene gabbro. This, with the relatively large amount of magnetite in this rock type would make it a reasonable magma composition from which the ferrogabbro unit with its magnetite layers formed.

When the hypersthene gabbro is compared with analyses published in the literature, a marked similarity both petrographically and chemically is found to the fine-grained marginal rocks studied by Daly (1982), Nel (1940), Wager and Brown (1968), and the N, B2, and B3 tholeiitic suite of Sharpe (1980, 1981) (see Table III). Both Daly (1928) and Wager and Brown (1968) suggested that their samples might represent parental magmas to the Bushveld Complex. However, experimental petrological work carried out on these samples by Tilley *et al.* (1967) (both samples) and Biggar (1974) (Wager and Brown's sample only) showed that these compositions would not produce the right crystallization sequence for the Bushveld Complex as a whole, since in all cases clinopyroxene was an early phase. Sharpe (1980, 1981) proposed that the N and B2 magma types were parental magmas to the critical zone. The critical zone cumulates are, however, dominated by the minerals orthopyroxene, plagioclase, and chromite. Clinopyroxene is generally an interstitial phase in this zone. When plotted on the diopside projection of the basalt tetrahedron, the N and B2 samples lie close to the olivine–plagioclase cotectic line as established by Cawthorn and Davies (1983) at 3 kbar (see fig. 13). In the olivine projection (fig. 12) these same samples lie close to the plagioclase–clinopyroxene cotectic. The implied early appearance of clinopyroxene from figs. 12 and 13 is inconsistent with the observed crystallization sequence for the critical zone. Sharpe (1980, 1981) used the phase diagram of Irvine (1970) which indicates that at 4.5 kbar the crystallization sequence for these samples would be olivine–orthopyroxene–plagioclase (which is the correct sequence for the critical zone). Irvine (1970) constructed the 4.5 kbar phase boundaries using the data of Kushiro (1969) who did experimental work at 20 kbar only. This therefore required dubious extrapolations and casts considerable

TABLE III. *Whole rock analyses of hypersthene gabbros from the margin of the Rustenburg Layered Suite, obtained from the literature*

	1	2	3	4	5	6
SiO_2	51.45	50.30	50.55	50.81	48.50	50.70
TiO_2	0.34	2.13	0.66	0.68	0.75	0.41
Al_2O_3	18.67	15.02	15.23	15.97	16.49	16.03
Fe_2O_3	0.28	2.63	1.04	—	—	—
FeO	9.04	8.64	10.07	10.91*	12.41*	9.14*
MnO	0.47	0.17	0.23	0.19	0.19	0.17
MgO	6.84	7.43	8.30	7.86	7.57	9.21
CaO	10.95	10.49	11.30	10.78	11.15	11.14
Na_2O	1.58	2.02	2.24	2.17	2.17	2.52
K_2O	0.14	0.28	0.19	0.29	0.14	0.23

* Total Fe as FeO.

1. Fine-grained sample from the margin of the Rustenburg Layered Suite, Western Lobe (Nel, 1940).
2. Fine-grained sample from the margin of the Rustenburg Layered Suite, Eastern Lobe (Daly, 1928).
3. Fine-grained sample from the margin of the Rustenburg Layered Suite, Eastern Lobe (Wager and Brown, 1968).
4. Average of N marginal rocks (Sharpe, 1981).
5. Average of B2 marginal rocks (Sharpe, 1981).
6. Average of B3 marginal rocks (Sharpe, 1981).

doubt on the phase volume constructed by Irvine (1970). That these boundaries may not be valid, as a result of the lack of data available pre-1970, has been discussed by Cawthorn and Davies (1983). Another argument against the N and B2 liquids being parental to the critical zone is the low Cr content of these liquids. This is supported by the fact that magnetite is the opaque phase rather than chromite. Cameron (1978) estimated that to account for the Cr contents of the silicates and chromite layers of the whole complex would require a liquid with at least 1300 ppm Cr; this is six times higher than the Cr content of the N and B2 rocks.

Another way of interpreting the given data in light of the present findings is that these tholeiitic liquids were injected after most of the lower, critical, and main zones had solidified and the reason they are found so low in the stratigraphy is that they were injected at the igneous-sedimentary rock interface, with some tongues injecting into the partially consolidated layered suite.

Conclusions

Multiple intrusion in the Rustenburg Layered Suite is demonstrated from field, mineralogical, and geochemical data. It should be noted that it was particularly fortuitous that the intrusive contact described came to light and probably owes its existence to the fact that the hypersthene gabbro injected close to the margin of the complex where the rocks were sufficiently cool to allow freezing of the intrusive relationship. The grain size within the hypersthene gabbroic body generally increases northwards and the contact relationship documented from the NW corner of the body would probably be more characteristic of any multiple intrusions which may exist further into the complex. This sort of contact relationship would not readily be interpreted as intrusive in the field, and only if the new injection was significantly different chemically from the magma from which the earlier cumulate rocks formed, would mineralogical or chemical data reveal its existence. The layered complex of Rhum is thought to have been produced by multiple injections based on mineralogical and chemical evidence (Wager and Brown, 1968; Dunham and Wadsworth, 1978), however, little field evidence has been reported of the later injections cutting the pre-existing cumulates. It seems clear that if a liquid injects into hot cumulates and then itself cools down slowly no readily discernible intrusive relationship need result. Therefore to reject multiple injections on the absence of dykes and sills of the later liquids is not valid.

The similarity between the hypersthene gabbro described here and those found by Daly (1928), Wager and Brown (1968), Nel (1940), and possibly some of Sharpe's (1980, 1981) tholeiitic marginal rocks suggest that these may belong to a suite from which the ferrogabbro unit or upper zone formed. The feeders to this unit appear in many places to have been sited at the interface between the pre-existing cumulates and the floor.

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