Canadian Mineralogist
Vol. 25, pp. 79-90 (1987)

RE-EVALUATION OF CHEMICAL VARIATION IN THE INSIZWA COMPLEX, TRANSKEI

PETER C. LIGHTFOOT AND ANTHONY J. NALDRETT
Department of Geology, University of Toronto, Toronto, Ontario M5S 1A1

CHRISTOPHER J. HAWKESWORTH
Department of Earth Sciences, The Open University, Milton Keynes, England MK7 6AA

ABSTRACT

The Insizwa Complex, located in Transkei, Southern Africa, consists of four layered intrusive bodies (Tabankulu, Tonti, Insizwa and Ingeli). Each one is divided into a Basal Zone, which consists of gabbros, picrites and troctolites, a Central Zone of gabbros, and an Upper Zone containing granophyres. Whole-rock trace-element results (Rb, Ti, Sr, Y, Zr, Nb, V, Cr, Ni, Cu, and Zn) for the lower part of the Basal Zone show variations in Ti, Y, Sr, and Rb *versus* Zr. These define tight trends, anchored at one end by the picrites, with low trace-element contents, and at the other end by the olivine-poor gabbros, with an abundance of these trace elements. Compositional data for Karoo diabases and Lesotho basalts fall on these trends at the trace-element-enriched extreme. Olivine control on a low-Mg parent magma presumably produced these trends. The constant ratios of selected incompatible elements (Y/Zr, Rb/Zr, Sr/Zr), in the lower Basal Zone rocks, argue against significant crustal contamination after the intrusion of the magma. Similar ratios of incompatible elements in both the Basal Zone rocks and the ubiquitous Lesotho basalts argue for a similar or common source for both. Compositional data for ilmenite crystals from the lower Basal Zone reveal a wide range in Mg content. This compositional variation is definitely related to the composition of the host grain and the olivine content of the rocks. These observations appear consistent with subsolidus re-equilibration of ilmenite crystallizing from a low-Mg magma.

Keywords: Insizwa, low-Mg liquid, interelement ratios, subsolidus re-equilibration, Transkei, South Africa.

SOMMAIRE

Le complexe d'Insizwa, situé au Transkeï, en Afrique du Sud, comprend quatre massifs intrusifs en couches (Tabankulu, Tonti, Insizwa et Ingeli). Chacun d'eux se subdivise en trois zones: inférieure, centrale et supérieure, caractérisées respectivement par un ensemble de gabbros, picrites et troctolites, par des gabbros et par des granophyres. L'analyse des éléments en traces (roche totale), sur échantillons prélevés à la base de la zone inférieure, portait sur Rb, Ti, Sr, Y, Zr, Nb, V, Cr, Ni, Cu et Zn; elle indique des variations dans les rapports au Zr de Ti, Y, Sr et Rb. Ces variations définissent deux tendances bien nettes, ancrées l'une par les picrites, pauvres en éléments-traces, l'autre par les gabbros pauvres en olivine, mais riches en éléments-traces. La composition des diabases du Karoo et des basaltes du Lesotho respecte ces tendances et prend place au maximum d'éléments-traces. L'olivine du magma à faible teneur en Mg gouverne vraisemblablement ces tendances. La constance des rapports entre éléments incompatibles Y/Zr, Rb/Zr, Sr/Zr, à la base de la zone inférieure, milite contre l'hypothèse d'une contamination appréciable de la croûte terrestre après l'intrusion du magma. La similitude des rapports entre éléments incompatibles, tant des roches de la zone inférieure que des basaltes du Lesotho, est un argument en faveur d'une source commune ou de deux sources analogues. La composition des cristaux d'ilménite de la base de la zone inférieure révèle un large domaine de variation de la teneur en Mg. Cette variation est certes en rapport avec le contenu des roches en olivine. Nos observations semblent concorder avec l'hypothèse d'une rééquilibration subsolidus de l'ilménite issue d'un magma pauvre en Mg.

Mots-clés: Insizwa, liquide pauvre en Mg, rapports entre éléments, ré-équilibration subsolidus, Transkeï, Afrique du Sud.

INTRODUCTION

There is currently a consensus that most Continental Flood Basalts (CFB) are derived by partial melting of lherzolitic mantle to produce picritic liquids, which subsequently evolve to tholeiitic liquids by the polybaric fractionation of olivine, bronzite, augite, and plagioclase (*e.g.*, Cox 1980). Whereas the evidence suggests that most of the magma compositions recognized amongst the Karoo basalts and associated diabases (including the Lesotho type: Marsh & Eales 1985) had evolved to tholeiitic compositions by the time of their eruption and emplacement, opinions differ concerning the state of fractionation of the magmas that were emplaced into large crustal holding-chambers and subsequently solidified to form major layered intrusive complexes (*e.g.*, the Insizwa Complex: Cawthorn 1980, Lightfoot & Naldrett 1984). This paper complements our earlier contribution, in which we differed with the claim of Cawthorn (1980) and Tischler *et al.* (1981) that the Insizwa magma was significantly more magnesian than those that gave rise to the Karoo diabases. Subsequently, Cawthorn *et al.* (1985) argued that the presence of unusually magnesian ilmenite in the Insizwa rocks supports their case for a magnesian parent magma. In conjunction with their arguments for a magnesian parent liquid, Cawthorn and coworkers claimed that contamination is responsible for the less magnesian compositions of some of the chill-zone material analyzed from Insizwa. Proponents of a universal Karoo dolerite magma hold that some of the most magnesian chill-zone rocks contain a component of cumulus olivine (*e.g.*, Eales & Marsh 1979, Eales 1980).

This paper presents new whole-rock geochemical data and chemical data on the minerals of the Insizwa Complex. These data are used to address three fundamental questions: 1. How extensive was the contamination by crustal material before the introduction of the magma at Insizwa, and how much of this occurred *in situ*? 2. What is the relationship of the Insizwa parent magma to the types of Karoo magma? 3. What was the state of fractionation of the Insizwa parent magma at the time of its emplacement?

General Geology, Petrology, Petrography and Mineralogy

The Insizwa Complex is located in the Central Karoo Province of Southern Africa at the contact of the Ecca and Beaufort Series sediments in one of the deepest parts of the Karoo basin (Fig. 1). The intrusion of the magma that solidified to form the Complex largely postdates the emplacement of the majority of the Karoo dolerite dykes and sills, with the exception of dykes found at the northern extremity of Tabankulu Mountain (Lightfoot 1982). The

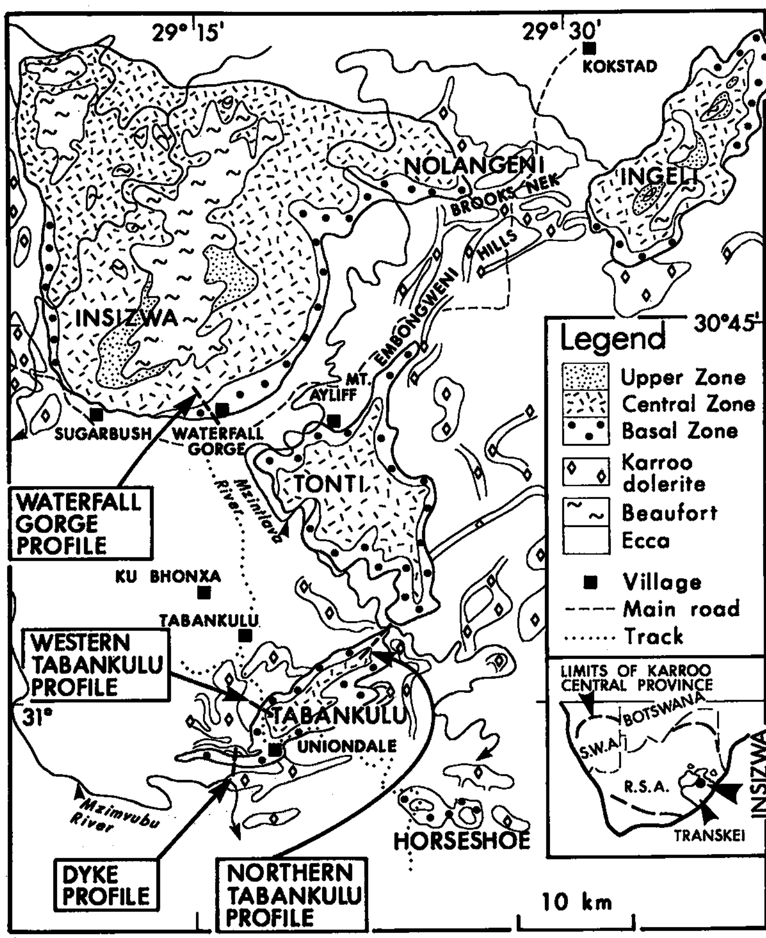

FIG. 1. Map showing the location and general geology of the Insizwa Complex. Shown are the locations of the Waterfall Gorge section and the sampled profiles at Tabankulu.

relationship of the Insizwa Complex to the extrusive suites of basalts is uncertain.

Details of the general geology, petrology, and mineralogy are given elsewhere (Du Toit 1946, Scholtz 1937, Bruynzeel 1957, Van Zijl 1962, Maske 1966, Lightfoot & Naldrett 1983, 1984, Lightfoot *et al.* 1984), but salient features are reviewed here insofar as they are relevant to this discussion.

The Tabankulu and Insizwa sections of the Insizwa Complex (Fig. 1) provide excellent exposures of the Basal Zone gabbros, picrites and troctolites. The basal zone consists of a chilled margin (<5 cm thick), overlain by a gabbro (<30 m thick), a picrite unit (0–300 m thick), and a troctolite unit (0–300 m thick).

The contact of the chill zone with the footwall hornfels and granophyres (which occur as veins cutting the lower Basal Zone) is never sharp. Fragments of granophyre and crystals of quartz and K-feldspar are commonly observed within the chilled margin. The chill zone contains virtually no cumulus olivine (<1 %), but less than 5 cm from the contact, the proportion of olivine increases dramatically.

A combination of these two factors may well account for the wide variation in the estimates of the composition of the chilled margin. For example, Scholtz (1937) estimated from a thin section that the chill zone contains less than one % modal olivine, whereas he noted that a wet-chemical whole-rock analysis of the chill by Goodchild (1916) gave 14% MgO. In contrast, Lightfoot & Naldrett (1984) noted that the chilled margin (sample INS302) from the derelict underground workings at Waterfall Gorge contains less than one % modal olivine and only 7.5% MgO. They also noted that this sample contains xenoliths of granophyre and fragments of granophyric material presumably derived from the footwall. However, the incorporation of granophyre is unlikely to alter the MgO/FeO ratio of the rocks,

TABLE 1. WHOLE-ROCK TRACE ELEMENT ABUNDANCES (PPM) FOR SAMPLES FROM THE INSIZWA AND TABANKULU INTRUSIONS

SAMPLE	ROCK TYPE	Ti	V	Cr	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Nb
					PICRITES (Basal Zone)								
TAB234	Picrite	750	157	2274	466	183	108	9	7	55	2	19	2.3
TAB225	Picrite	908	158	3801	1098	240	100	8	5	49	2	19	2.0
TAB227	Picrite	753	102	1549	272	103	91	8	5	55	2	19	2.6
SN15	Picrite	2472	145	2591	453	143	110	7	13	85	9	46	3.7
					TROCTOLITES (Basal Zone)								
TAB214	Troctolite	1107	181	3128	973	15	103	11	7	88	2	24	2.3
TAB210	Troctolite	1262	81	2324	831	23	110	8	5	148	2	22	2.1
TAB208	Troctolite	1280	139	2584	887	19	85	6	6	115	3	21	1.7
TAB217	Troctolite	1318	220	1562	84	82	43	14	5	210	3	21	2.1
					GABBROS (Central Zone)								
TAB203	Gabbro	1016	167	737	146	186	42	16	4	286	3	15	1.5
TAB207	Gabbro	1204	141	537	187	17	50	13	4	242	4	24	2.7
TAB204	Gabbro	1932	176	2434	357	66	75	11	5	151	6	22	2.5
TAB101	Gabbro	1117	111	713	158	26	44	15	5	275	3	19	2.5
ES1	Gabbro	na	na	na	194	52	57	14	7	212	12	46	5.0
					BASAL ZONE GABBROS								
HG1	B. gabbro	4811	240	1971	270	142	99	16	24	177	21	92	5.9
TAB101	B. gabbro	4052	164	2842	256	114	102	12	18	136	15	73	4.8
KDS1	B. gabbro	4542	225	3295	405	100	87	11	16	156	17	75	6.3
					DIABASES (Tabankulu District)								
KDS5	Dolerite	6434	201	496	21	31	91	20	35	205	32	130	7.9
KDS7	Dolerite	3446	193	599	129	61	57	16	10	248	13	48	4.5
KDS3	Dolerite	6501	255	614	96	108	81	18	13	328	22	108	14.6
KDS8	Dolerite	3337	217	473	142	93	92	19	17	156	25	89	4.4
KDS4	Dolerite	5811	244	720	115	104	70	17	12	332	22	100	13.3
					GRANOPHYRES AND HORNFELS								
HG9	Hornfels	nd	na	na	5341	5005	95	12	127	279	25	162	12.0
109	Hornfels	nd	na	na	17820	28130	612	0	63	208	9	144	8.0
SD1	Granophyre	4147	156	323	44	6	77	25	109	319	28	171	14.5
SD7	Granophyre	6614	224	415	51	105	98	16	20	186	26	111	7.9
SD5	Granophyre	3983	83	145	17	25	109	14	58	447	24	338	14.7
					STANDARDS								
UTB1 (n=2)	STANDARD	18125	432	115	19	30	142	20	37	317	44	203	16.1

(HG9 has 33 ppm Pb, 13 ppm Th; 109 has 507 ppm Pb, 8 ppm Th; SD1 has 15 ppm Pb and 14 ppm Th; SD5 has 17 ppm Pb and 12 ppm Th; and UTB1 gave 4 ppm Pb and 3 ppm Th). na - not available. nd - not detected.

and therefore it is interesting that INS302 has an Mg number {molar MgO/(MgO+FeO)} of 0.58, whereas that of Goodchild (1916) has an Mg number of 0.78. Every effort was made to ensure that INS302 contained no cumulus olivine; however, it is not known whether similar precautions were taken by Goodchild.

The problems with cumulus olivine on the one hand, and granophyre derived from the footwall rocks on the other, mean that the interpretation of these rocks as chilled margins *sensu stricto* and, by implication, parent-magma compositions, must be made with extreme caution.

The basal gabbro shows a progressive increase in both grain size and modal content of cumulus olivine with distance from the contact. The olivine and plagioclase are poikilitically enclosed in bronzite and augite. The base of the picrite is marked by the appearance of intercumulus plagioclase and a maximum in the proportion of modal olivine. The base of the troctolite is marked by the appearance of glomeroporphyritic clusters of plagioclase and chains of cumulus olivine.

Accessory phases are ubiquitous within the lower Basal Zone, and include ilmenite in the basal gabbro and lower part of the picrite, spinel in the upper part of the basal gabbro and picrite–troctolite units, and biotite (commonly intergrown with sulfide or ilmenite) throughout the lower Basal Zone.

MAJOR- AND TRACE-ELEMENT GEOCHEMISTRY

Lightfoot & Naldrett (1984) presented compositional data on the rock-forming minerals for a

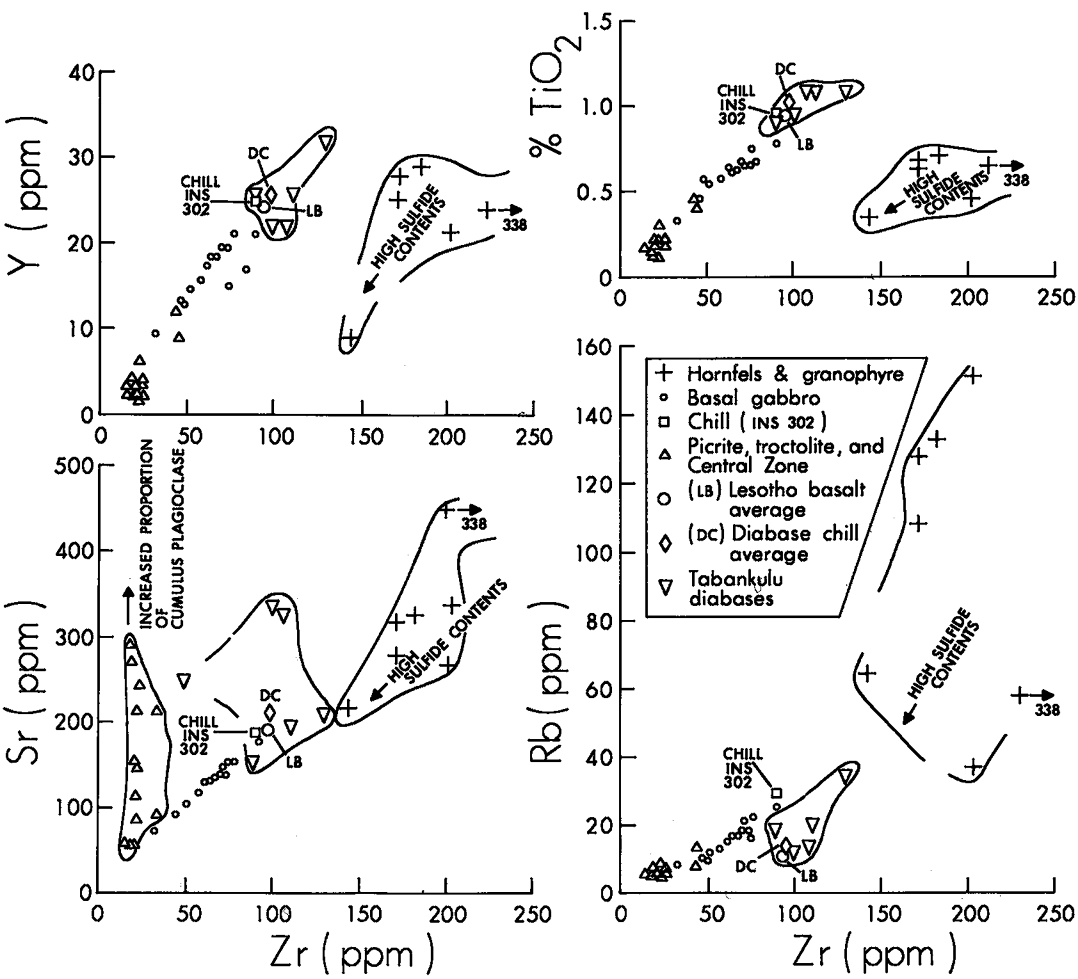

FIG. 2. Variation in concentration of selected incompatible elements with Zr in the basal gabbro, cumulates, granophyres and hornfels. Also shown are representative samples of diabase from the Tabankulu district. Samples of granophyre and hornfels with high contents of sulfide are indicated.

traverse of the lower Basal Zone at the Waterfall Gorge section of the Insizwa Complex. Lightfoot & Naldrett (1983, 1984) presented mineral chemical data for the entire exposed sequences of cumulates at both Tabankulu and Insizwa sections. Utilizing these data, they suggested that both mineralogical and whole-rock major- and trace-element data are consistent with olivine control of an essentially low-Mg parent magma with many of the geochemical traits of the ubiquitous Lesotho type. As indicated above, these conclusions have been questioned by Cawthorn *et al.* (1985).

In this section we present additional major- and trace-element data for rocks from the Basal and Central Zone from Tabankulu and Insizwa, Waterfall Gorge, granophyres and hornfelsed sediments from Insizwa and Tabankulu, and Karoo diabases from the Tabankulu District. In subsequent sections, we present ilmenite data for the traverses described by Lightfoot *et al.* (1984) and Lightfoot & Naldrett (1983).

Analytical Techniques

All trace-element data were determined on powder pellets by energy-dispersion X-ray-fluorescence analysis following the procedures of Potts *et al.* (1984, 1985), and are given in Table 1. All chemical data on minerals were obtained at the Open University on a wavelength-dispersion Cambridge Instruments microprobe. Analytical details are given in Lightfoot (1985). Results for Si, Al, Fe, Mg, Mn, Ca, K, Ti, Ni and Cr are available from the Depository of Unpublished Data, CISTI, National Research Council of Canada, Ottawa, Ontario K1A OS2. A small beam-size (<3 μm) was used to prevent overlap with the silicate, oxide and sulfide phases hosting the ilmenite grains.

Trace-Element Variations

Geochemical data determined in this study are presented in Figure 2 as a function of Zr, which is used as an index of the degree of enrichment in cumulus phases exhibited by the rocks. Zr is considered to be a good index as it is determined with high precision and accuracy, it is immobile during alteration, and is generally considered to be incompatible in most rock-forming silicate phases. Data for Ti, Y, Sr and Rb for all lower Basal Zone rocks define tight linear arrays if plotted against Zr. The trends are anchored at the trace-element-depleted extreme by the picrites, troctolites and higher cumulates of the Central Zone, and at the trace-element-enriched extreme by the chilled margin and adjacent olivine-poor gabbros on diagrams that plot Ti, Y and Rb against Zr. Interestingly, the gabbros of the Central Zone, the troctolites of the Basal Zone and some of the picrites (containing cumulus plagioclase reminiscent of the troctolite) are enriched in Sr relative to Zr, presumably because Sr is preferentially partitioned into plagioclase, which is an important cumulus phase in most of these rocks. The trends of the data pass through or close to the origin in all the diagrams. With the exception of Rb, they also pass close to the chilled margin (sample INS302). The compositional data for the Karoo diabases from the Tabankulu District (Lightfoot 1982) and the average compositional data for the Lesotho basalts, and chilled margins of the Karoo diabases (Marsh & Eales 1985) are also shown. The Karoo diabases are presumably the intrusive equivalents of the Lesotho basalts, and it is therefore important to note that in all cases, except for Rb, the trends illustrated in Figure 2 pass through the field of the Tabankulu diabase chilled margins.

The granophyres derived from the melting of footwall rocks and the hornfelsed footwall rocks fall below the trends of the lower Basal Zone, being depleted in Ti, Y and Sr relative to the rocks of the lower Basal Zone. In contrast, they are enriched in Rb. The granophyres and hornfelsic rocks show a wide spectrum of compositional variation that presumably reflects the large concentration of sulfides in the rocks, which dilutes the concentration of the incompatible elements. However, the presence of sulfides is unlikely to fractionate these elements, and the interelement ratios will be independent of sulfide control.

These observations are reinforced by the plots of interelement ratios shown in Figure 3. Here the variation in Y/Zr, Rb/Zr, Sr/Zr and $^{87}Sr/^{86}Sr$ are plotted against Ti/Zr. Significantly, the fields of the Tabankulu diabases and Lesotho-type rocks (averages) are similar to the Insizwa basal gabbro, picrite, troctolite, and Central Zone gabbros. In contrast, the granophyres occupy a tight field displaced away from the Karoo diabases to higher Rb/Zr and $^{87}Sr/^{86}Sr$, but lower Ti/Zr, Y/Zr, and Sr/Zr.

Discussion of the Role of Contamination

The possibility that contamination of mafic magma by siliceous crustal material could initiate sulfide segregation was first suggested by MacLean (1969) and Irvine (1975). Subsequently, Naldrett & Macdonald (1980) suggested that this mechanism could account for the presence of nickel sulfides at Sudbury and in other mafic and ultramafic intrusive complexes. Cawthorn (1980) and Tischler *et al.* (1981) suggested that this mechanism could have played a role at Insizwa (Waterfall Gorge).

Lightfoot *et al.* (1984) and Lightfoot & Naldrett (1984) found no conclusive support for this argument in either the whole-rock geochemistry or mineral chemistry. Cawthorn *et al.* (1985) disagreed with this,

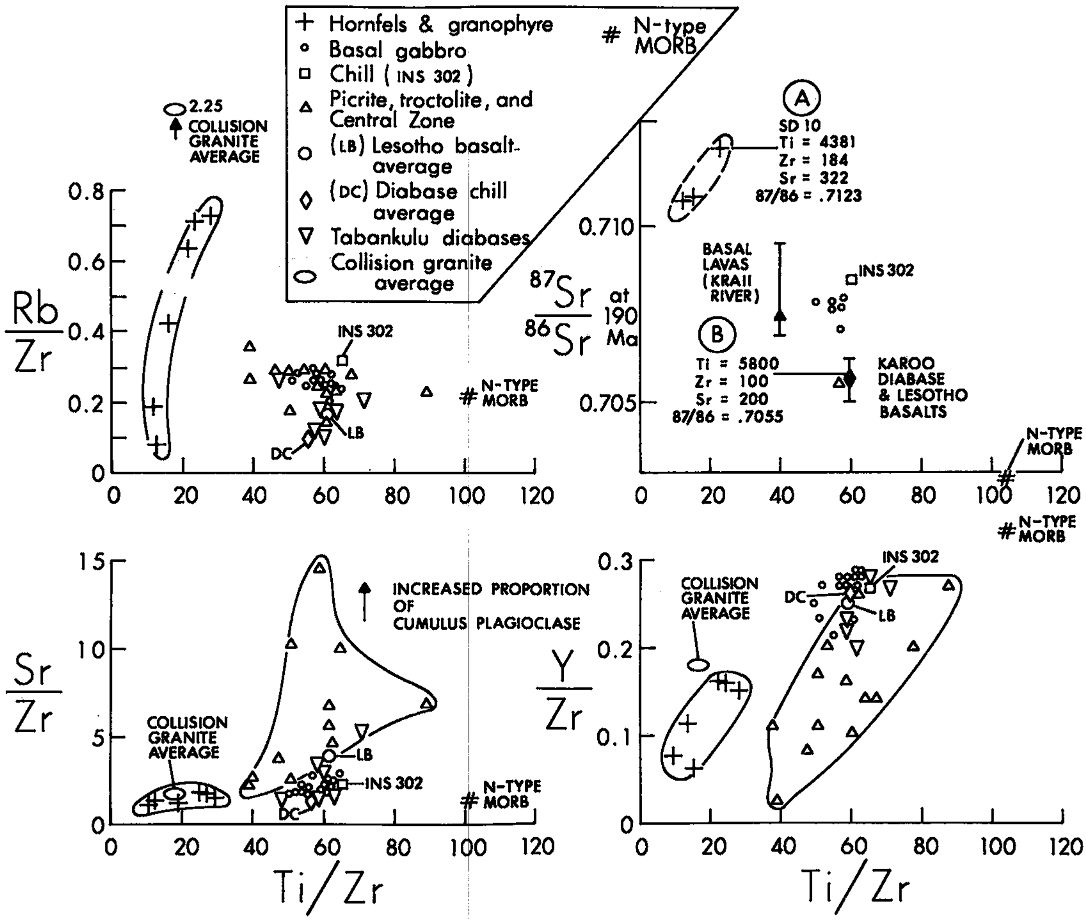

FIG. 3. Variations in interelement ratio in the basal gabbro, cumulates, hornfels, granophyres and diabase. Rocks of the lower Basal Zone define a tight field that is displaced away from the granophyres and hornfels but overlaps with the field of diabases (for Sr/Zr, Ti/Zr, and Y/Zr) from the Tabankulu District, and average Lesotho basalts and diabases from Marsh & Eales (1985).

arguing that assimilation of crustal material is sometimes accompanied by crystal fractionation (Assimilation Fractional Crystallization or AFC; DePaolo 1981). Consequently, they suggested that the olivine-control lines documented by Lightfoot & Naldrett (1984) point to the composition of a magma produced by contamination of a magma with higher Mg than the Lesotho basalts and Karoo diabases (Fig. 4).

The arguments against significant contamination, and hence, in favor of olivine control of a low-Mg parent magma therefore need to be re-examined in the light of our new data and the arguments of Cawthorn *et al.* (1985).

The composition of the granophyres provides a means to calculate the extent of the contamination. Lightfoot (1985) proposed that "average collision granite" (Pearce *et al.* 1985) is close to "average crust" and therefore is an index of contamination as a mafic magma migrates through the crust prior to its emplacement. Since both the granophyres and collision granites have low Ti, Y and Sr, but relatively high $^{87}Sr/^{86}Sr$, Zr and Rb, the values of Ti/Zr, Sr/Zr, Rb/Zr, Y/Zr, and $^{87}Sr/^{86}Sr$ ratios should provide some index of the extent of contamination (if any) by either local rocks or average crust. Since the composition of the parent magma is not constrained until the effects of contamination are recognized, we can only note that all the ratios quoted above define tight fields in Figure 3 with no displacement of one group of samples at the expense of another group toward the compositional fields of the Insizwa granophyres. Therefore, the first key point to be emphasized is that if contamination has

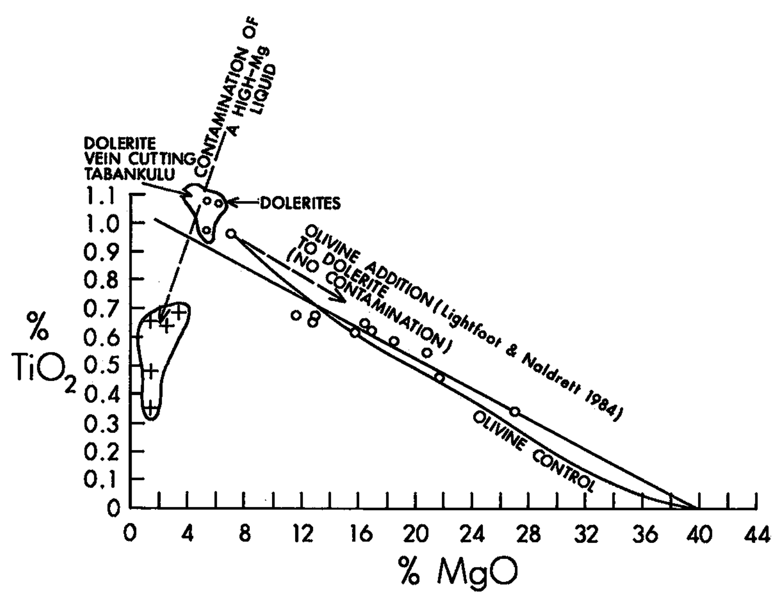

FIG. 4. Variation in MgO *versus* TiO_2 in Insizwa samples, showing the effects of olivine control (line from Lightfoot & Naldrett 1984) and inferred decontamination vector (Cawthorn *et al.* 1985).

occurred, it must have taken place before emplacement of the magma, so that during migration of the magmas, homogenization could occur to produce the constant interelement ratios of the incompatible elements.

Cawthorn *et al.* (1985) have argued that a primitive high-Mg magma could become contaminated with crustal material to produce a magma of lower Mg-content. Since all of the Insizwa data lie very close to a single olivine-control line or curve, any contamination must have occurred prior to intrusion. Whereas we cannot rule out this possibility, we would point out that the Karoo diabase magmas, which for the most part belong to an earlier igneous episode, lie very close to the same TiO_2 control line in Figure 4, and thus appear to have undergone a similar amount of contamination. This is also true for Y, Zr, Sr and the *REE* (*e.g.*, data of Lightfoot & Naldrett 1984). Furthermore, we have illustrated the similarity of interelement ratios between the Karoo and Insizwa rocks in Figure 3. We suggest that contamination of all the magmas to the same extent at Insizwa and throughout the Karoo would be an extraordinary coincidence; we prefer the interpretation that both sets of magmas have been derived from the same batch.

The trace-element data presented in this paper, combined with those of Lightfoot & Naldrett (1984), suggest that the interelement ratios of the incompatible elements and Sr of the Insizwa cumulates are indistinguishable from those of the Lesotho basalts and diabases. This is confirmed by the new data for the Tabankulu diabases. Furthermore, there is no simple linear displacement of the cumulates away from the field of the diabases toward that of the granophyres or collisional granites. Interestingly, both the Sr-isotope composition and Rb content of the cumulates differ from the Lesotho magma type. This could reflect evolution of a source with higher Rb/Sr (*e.g.*, the Kraii River magma type: Marsh & Eales 1985); however, a source enriched in radiogenic Sr would equally well explain the variation. An alternative explanation for the Rb data might be the enhanced mobility of this element compared to the other incompatible elements, but this cannot explain the Sr-isotope data.

To conclude this discussion of the trace elements, the interelement ratios and isotopes do not constrain the fractionation state of the magma at the time of emplacement; they merely confirm that the magma has the trace-element attributes of the Lesotho type. However, in the absence of evidence for contamination, we contend that the olivine-control lines of Lightfoot & Naldrett (1984) point not only to the composition of the liquid, but also to the composition of the olivine being added to the magma. The implication of this observation is that the magma contained less than 7.5% MgO at the time of emplacement, and had crystallized olivine of composition Fo_{80}.

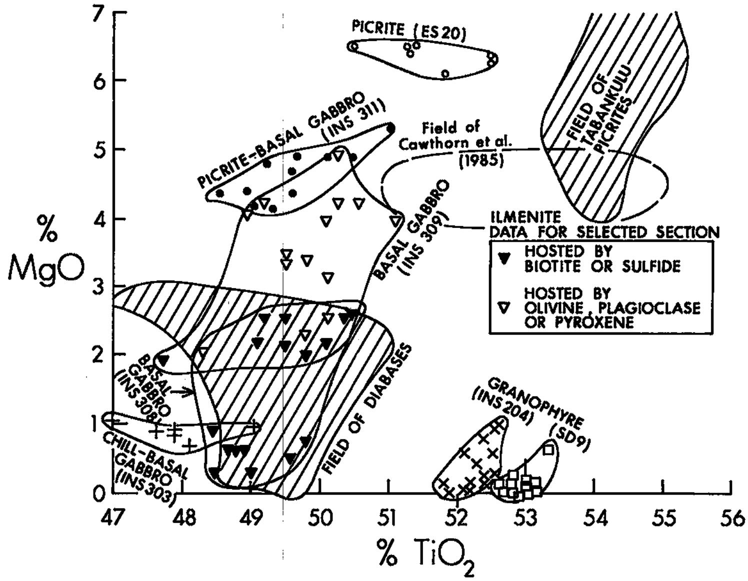

FIG. 5. Variation in MgO *versus* TiO_2 in ilmenite of the basal gabbro, picrite, granophyre, hornfels, and diabase. The plot also shows the dependence of ilmenite composition on the composition of the host phase.

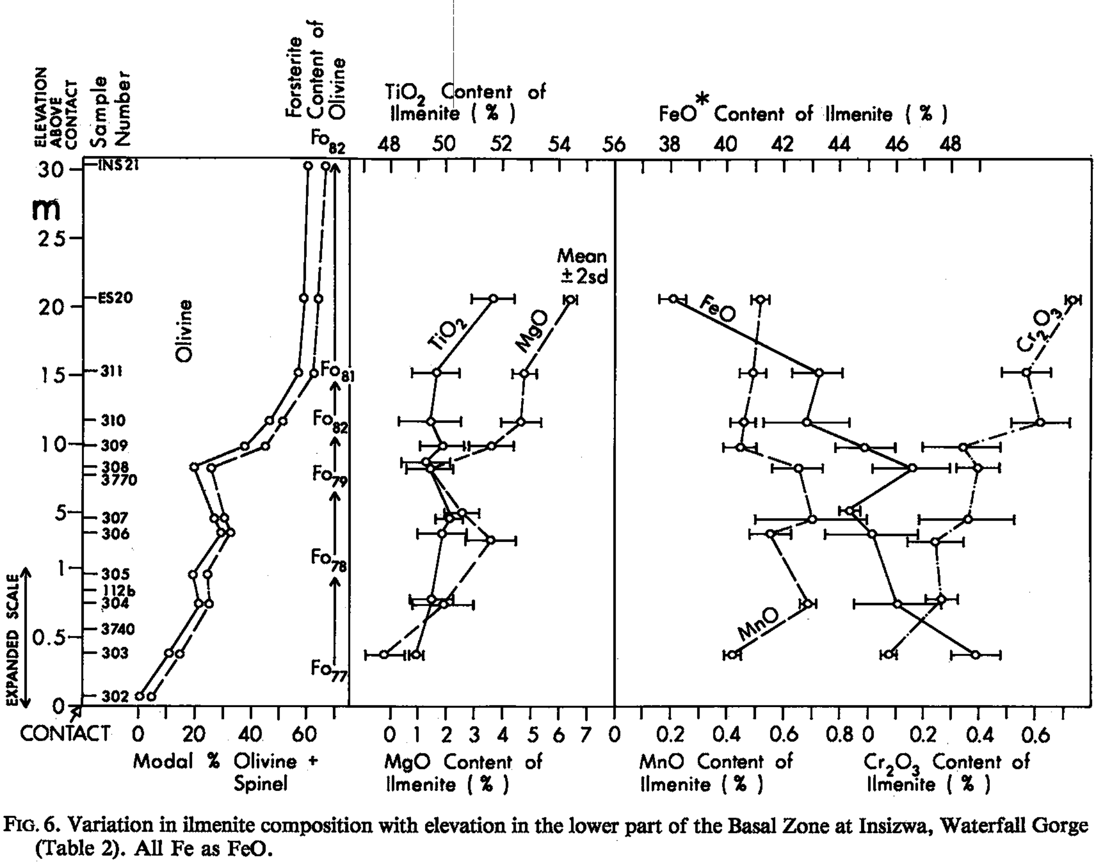

FIG. 6. Variation in ilmenite composition with elevation in the lower part of the Basal Zone at Insizwa, Waterfall Gorge (Table 2). All Fe as FeO.

The Composition of Ilmenite

In this section, new data for ilmenite at Insizwa are presented, and are examined in the light of the claim that the ilmenite compositions are supportive of a Mg-rich magma for Insizwa (Cawthorn *et al.* 1985).

Ilmenite occurs as an accessory phase in the basal gabbro, part of the picrite, and the granophyre. The crystals are sometimes enveloped in biotite, but rarely do they occur enclosed totally within any one of the main silicate phases. Rather, they tend to fall along grain boundaries, where biotite and sulfide also concentrate.

Overlap of the microprobe beam with other phases was monitored by analyzing for the complete range of elements, from which poor analyses could be filtered out using the data for Si, Al, Ca, Na and K.

Multiple analysis of single grains revealed no evidence of zoning or exsolution (*e.g.*, Reynolds 1983). Multiple analysis of different grains showed that those grains bounded by biotite and sulfide generally have lower Mg-contents than those within plagioclase or pyroxene and adjacent to olivine (Fig. 5). This suggests that there has been some re-equilibration of Fe and Mg between ilmenite and coexisting mafic minerals. In order to evaluate the variation in composition of ilmenite among different samples, analyses of a large number of different grains from each thin section were averaged.

Figure 5 shows that the ilmenite compositions from the basal olivine gabbro analyzed in this study are distinctive when compared to those of Cawthorn *et al.* (1985). The compositions of ilmenite from the unmineralized olivine gabbro presented by Cawthorn *et al.* (1985) more closely resemble those of ilmenbite from the picrite unit.

Results of these analyses for the Insizwa, Waterfall Gorge profile (Table 2) are plotted against stratigraphic elevation in Figure 6, along with modal olivine and spinel content and olivine composition. MgO *versus* TiO_2 and Cr_2O_3 *versus* MgO plots are illustrated in Figures 5 and 7. Average data are shown in Figure 7. In general, Mg, Cr and Ti contents of ilmenite increase upward away from the contact. Ilmenite in the basal gabbros displays a range of Mg and Cr contents, with both increasing upward. Ilmenite from the Insizwa picrite is rich in Mg, Cr and Ti, as is that from picrites at Tabankulu. The ilmenite of the diabase tends to coincide with that near the lower contact of the basal gabbro insofar as Mg, Ti and Cr contents are concerned.

Lightfoot *et al.* (1984) have argued on the basis of olivine compositional data that the picrite is from

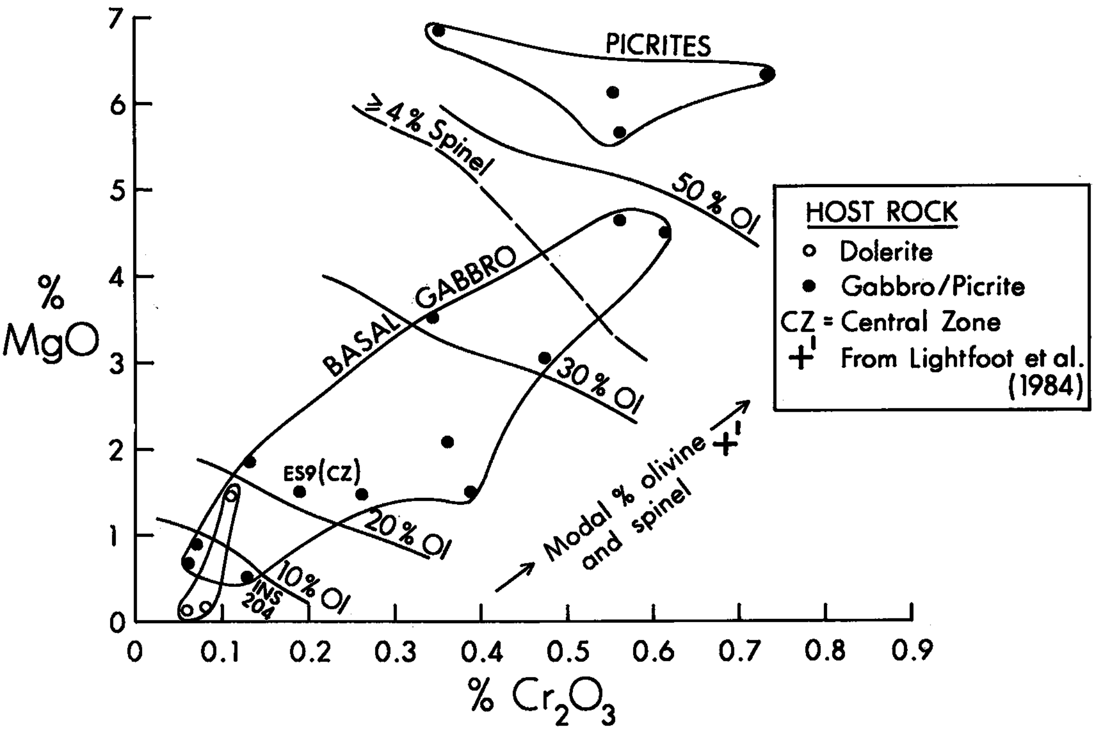

FIG. 7. Variation in modal olivine and spinel content of lower Basal Zone rocks with Mg and Cr content of the ilmenite.

a different batch of magma than the basal gabbros. Thus in discussing the nature of the magma from which the gabbros have been derived, the picrites should be ignored. There is a systematic increase in the Mg content of ilmenite in the basal gabbro with modal proportion of olivine in the rock. This, coupled with the observation that ilmenite adjacent to olivine and pyroxene tends to be more magnesian than ilmenite adjacent to biotite and sulfide in the same section, is strong evidence that some (and perhaps much) of the Mg variation in ilmenite is due to subsolidus equilibration (Fig. 8). More magnesian ilmenite occurs in rocks with larger reservoirs of Mg (*i.e.*, olivine). High-Mg ilmenite is correlated with a high content of olivine in the picrites, suggesting that subsolidus equilibration may also account for these compositions. Interestingly, the ilmenite with the highest Cr-content occurs in rocks with the largest amount of spinel, whereas that with a low Cr-content is found in rocks free of spinel. This suggests that equilibration is not limited to olivine, and that some interchange with spinel also occurs. This is not surprising, considering the evidence from the spinel data presented by Lightfoot & Naldrett (1983), which favors considerable amounts of subsolidus re-equilibration.

Significantly, the amount of ilmenite present in the Basal Zone rocks is generally low (< 1 %), and therefore the subsolidus equilibration could change the ilmenite composition by a large amount, yet leave the olivine, pyroxenes and plagioclase virtually unmodified. Thus our arguments concerning the ilmenite compositional data need not detract from earlier conclusions about magma composition suggested by the olivine compositional data (Lightfoot & Naldrett 1984).

Mg-rich ilmenite appears to be absent from other

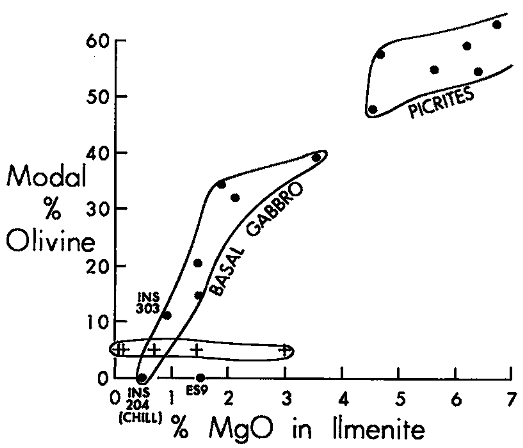

FIG. 8. Variation in modal olivine *versus* Mg content of ilmenite in samples from Insizwa and Tabankulu. Crosses represent Tabankulu diabases.

Karoo-aged intrusive complexes, and it might be considered unusual that magmas have produced Mg-rich ilmenite only in the Insizwa intrusive complex. This is not at all surprising, since no other Karoo-aged intrusive bodies show similar amounts of enrichment in cumulus olivine. Although less striking than at Insizwa, ilmenite from some of the other larger layered complexes hint at an increase in Mg content with increasing modal content of olivine (Reynolds 1983).

TABLE 2. AVERAGE COMPOSITIONS OF ILMENITE FROM THE TABANKULU AND INSIZWA INTRUSIVE COMPLEXES

SAMPLE (Mean+/-2sd)	ES20	ES9	INS204	INS303
n	7	6	14	6
SiO2	0.18(0.09)	0.35(0.42)	0.09(0.02)	0.37(0.61)
TiO2	51.62(0.74)	48.91(0.95)	52.31(0.23)	47.92(0.72)
Al2O3	0.07(0.03)	0.10(0.13)	0.01(0.01)	0.12(0.23)
FeO	38.07(0.41)	46.36(1.22)	45.26(0.59)	48.98(0.78)
MgO	6.39(0.13)	1.46(0.67)	0.48(0.40)	0.91(0.11)
MnO	0.53(0.03)	0.52(0.07)	0.87(0.61)	0.42(0.14)
CaO	0.02(0.01)	0.18(0.27)	0.04(0.03)	0.06(0.05)
Na2O	0.05(0.03)	0.03(0.03)	0.03(0.01)	0.08(0.09)
K2O	0.00(0.00)	0.00(0.00)	0.00(0.00)	0.00(0.01)
NiO	0.01(0.01)	0.01(0.00)	0.00(0.00)	0.00(0.01)
Cr2O3	0.73(0.10)	0.19(0.03)	013(0.08)	0.07(0.04)
SAMPLE	INS304	INS306	INS307	INS308
n	9	13	3	17
SiO2	0.11(0.09)	0.34(0.40)	0.08(0.02)	0.19(0.20)
TiO2	50.31(1.18)	51.67(0.95)	50.52(0.59)	49.26(0.78)
Al2O3	0.04(0.04)	0.11(0.15)	0.02(0.00)	0.07(0.08)
FeO	46.02(1.47)	45.13(1.85)	44.39(0.11)	46.65(1.45)
MgO	1.43(1.05)	1.86(0.95)	2.05(0.42)	1.48(0.92)
MnO	0.68(0.13)	0.56(0.10)	0.71(0.22)	0.66(0.11)
CaO	0.06(0.04)	0.05(0.03)	0.05(0.03)	0.03(0.03)
Na2O	0.01(0.02)	0.02(0.04)	0.03(0.00)	0.03(0.02)
K2O	0.00(0.00)	0.02(0.05)	0.01(0.02)	0.01(0.04)
NiO	0.01(0.01)	0.01(0.01)	0.01(0.02)	0.01(0.01)
Cr2O3	0.26(0.09)	0.24(0.10)	0.36(0.19)	0.39(0.07)
SAMPLE	INS309	INS310	INS311	KDS3
n	14	16	11	5
SiO2	0.14(0.14)	0.20(0.18)	0.11(0.10)	0.06(0.01)
TiO2	49.86(0.74)	49.50(1.19)	49.58(0.72)	49.99(0.70)
Al2O3	0.05(0.05)	0.08(0.06)	0.04(0.03)	0.04(0.02)
FeO	44.94(1.21)	42.79(1.51)	43.28(0.80)	47.99(0.90)
MgO	3.56(0.83)	4.52(0.75)	4.63(0.37)	0.65(0.46)
MnO	0.44(0.04)	0.47(0.04)	0.50(0.03)	0.56(0.11)
CaO	0.05(0.04)	0.05(0.02)	0.04(0.02)	0.04(0.02)
Na2O	0.01(0.02)	0.08(0.30)	0.02(0.02)	0.02(0.02)
K2O	0.01(0.02)	0.02(0.02)	0.00(0.01)	0.00(0.00)
NiO	0.02(0.02)	0.01(0.02)	0.03(0.02)	0.00(0.00)
Cr2O3	0.34(0.15)	0.61(0.11)	0.56(0.09)	0.06(0.04)
SAMPLE	KDS4	KDS7	KDS8	SD9
n	9	9	7	12
SiO2	0.11(0.11)	0.13(0.07)	0.09(0.04)	0.10(0.03)
TiO2	50.54(0.42)	49.54(3.68)	52.09(0.18)	52.91(0.19)
Al2O3	0.05(0.02)	0.14(0.06)	0.01(0.01)	0.02(0.01)
FeO	47.14(1.08)	46.67(3.82)	45.92(0.47)	42.66(1.37)
MgO	1.45(0.54)	3.01(0.33)	0.12(0.10)	0.12(0.17)
MnO	0.48(0.03)	0.45(0.06)	0.75(0.29)	
CaO	0.03(0.02)	0.07(0.09)	0.03(0.01)	0.03(0.02)
Na2O	0.03(0.01)	0.03(0.02)	0.05(0.02)	0.05(0.03)
K2O	0.01(0.02)	0.00(0.00)	0.00(0.00)	0.00(0.01)
NiO	0.00(0.01)	0.01(0.01)	0.oo(0.00)	0.00(0.00)
Cr2O3	0.11(0.04)	0.47(0.20)	0.06(0.11)	0.08(0.03)
SAMPLE	TAB105	TAB108	TAB251	
n	8	10	9	
SiO2	0.06(0.03)	0.07(0.06)	0.05(0.01)	
TiO2	54.95(0.65)	54.62(0.42)	54.57(0.54)	
Al2O3	0.03(0.02)	0.03(0.02)	0.02(0.02)	
FeO	38.63(1.43)	37.36(0.96)	35.80(1.13)	
MgO	5.64(0.97)	6.14(0.47)	6.93(0.78)	
MnO	0.57(0.07)	0.52(0.04)	0.51(0.04)	
CaO	0.02(0.01)	0.06(0.02)	0.02(0.01)	
Na2O	0.01(0.01)	0.01(0.01)	0.00(0.01)	
K2O	0.00(0.01)	0.00(0.00)	0.00(0.01)	
NiO	0.01(0.01)	0.00(0.00)	0.00(0.01)	
Cr2O3	0.56(0.15)	0.55(0.16)	0.35(0.03)	

n: number of analyses.

Summary and Conclusions

Whereas it is now generally accepted that Continental Flood Basalts are derived by polybaric fractional crystallization of picritic precursors, no consensus exists regarding the composition of the magma that crystallized to produce the large intrusive complexes subjected to cumulus processes.

Cawthorn (1980) and Tischler *et al.* (1981) have suggested, on the basis of data of Scholtz (1937), that a high-Mg parent magma produced the Insizwa Complex. Lightfoot & Naldrett (1984) and Lightfoot *et al.* (1984) disputed this conclusion on the basis of new whole-rock geochemical data. They also concluded that the magma had undergone negligible amounts of crustal contamination *en route* to the surface.

Cawthorn *et al.* (1985) suggested that assimilation and olivine control worked together (Assimilation Fractional Crystallization) to produce the compositional variation in the lower Basal Zone. However, we question their suggestion that the parent magma has a high Mg-content, not only on the grounds of the arguments of Lightfoot & Naldrett (1984), but also on the basis of the interelement ratios for the silicates, which provide no convincing new evidence for contamination.

In this paper we demonstrate that the conclusions of our earlier papers are consistent with our new data, and are not invalidated by the arguments of Cawthorn *et al.* (1985). Significantly, their ilmenite data appear not to be representative of the lower Basal Zone, and appear to reflect equilibration processes during cooling.

Acknowledgements

We thank Grant Cawthorn for a preprint of his 1985 paper. John Watson and Andy Tindle helped with XRF and WD-microprobe work. Phil Potts is in charge of analytical facilities at the Open University. Research was completed under an Open University scholarship to PCL, and field work was sponsored by the Johannesburg Mining and Finance Co. Ltd. The Transkei Government is thanked for supplying transportation. Dick Ward of the Department of Commerce gave logistic support. The Moncur family of Tabankulu were kind and hospitable during the first author's field seasons in the Insizwa and Tabankulu districts. Professor R.F. Martin and Dr. J.M. Duke provided constructive reviews of the first draft of this manuscript.

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Received January 24, 1986, revised manuscript accepted May 3, 1986.