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CONTRASTING MAGMA TYPES IN THE MOUNT AYLIFF INTRUSION (INSIZWA COMPLEX), TRANSKEI: EVIDENCE FROM ILMENITE COMPOSITIONS

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ABSTRACT

Ilmenite is a near-liquidus mineral in picrite near the base of the Mount Ayliff Intrusion, Transkei. The ilmenite contains up to 11 wt.% MgO and over 1% Cr_2O_3, and is texturally and chemically anomalous with respect to all other tholeiitic suites. In a single sample ilmenite compositions are similar, regardless of enclosing silicate phases, which precludes extensive subsolidus re-equilibration. The overlying gabbro contains ilmenite that is low in magnesium and chromium, and that is texturally comparable to typical ilmenite in tholeiitic rocks where it usually forms as a near-solidus mineral. These differences in the two types of ilmenite are attributed to the emplacement of two distinct magma types, one tholeiitic, the other more magnesian. The nickel content of olivine has been studied in samples from two profiles through the picrite and gabbro, and provides evidence for the timing and extent of formation of an immiscible sulfide liquid. In one profile (Ingeli) these data suggest continuous separation of olivine and very minor sulfide liquid in the picrite. In contrast, the data for the second profile (Tonti) suggest the separation of larger quantities of sulfide near the base and top of the picrite, which may result from mixing between distinct magma pulses.

Keywords: magnesian ilmenite, high-magnesium basalt, multiple intrusion, nickel–copper sulfide mineralization, Insizwa, Transkei, South Africa.

SOMMAIRE

L'ilménite apparaît près du liquidus dans les picrites de la section profonde du massif intrusif de Mount Ayliff, au Transkei (Afrique du Sud). Elle contient jusqu'à 11% de MgO et plus de 1% de Cr_2O_3; elle est donc anormale tant dans ses relations texturales que dans sa composition, en comparaison de l'ilménite des autres suites tholéiitiques. A l'intérieur d'un même échantillon, toutes les compositions d'ilménite sont semblables, sans égard à la phase silicatée qui pourrait l'enfermer, ce qui semble minimiser les effets d'une ré-équilibration subsolidus importante. Le gabbro qui recouvre la section picritique contient une ilménite à faibles teneurs en magnésium et chrome; elle ressemble donc à l'ilménite courante dans les massifs tholéiitiques, qui fait son apparition près du solidus. Les différences entre ces deux sortes d'ilménite reflètent la mise en place de deux sortes distinctes de magmas, l'un tholéiitique, l'autre encore plus magnésien. La teneur en nickel de l'olivine le long de deux coupes à travers la séquence picrite - gabbro donne une indication du point auquel apparaît un liquide sulfuré immiscible et de son importance. Dans la section d'Ingeli, ces données semblent indiquer une séparation continue de l'olivine et une proportion infime d'un tel liquide dans l'horizon picritique. Par contre, les données pour le profil de Tonti révèlent de plus grandes quantités de sulfure près de la base et du sommet de l'unité picritique, ce qui pourrait être une conséquence du mélange de deux fractions distinctes de magma.

(Traduit par la Rédaction)

Mots-clés: ilménite magnésienne, basalte magnésien, intrusion multiple, minéralisation, sulfures Ni–Cu, Insizwa, Transkei, Afrique du Sud.

INTRODUCTION

Igneous activity during the period 200–130 Ma has been recorded over an area in excess of one million km² in southern Africa (Cox 1970). Volumetrically, tholeiitic basalt is predominant in this Karoo Province, but rhyolites, alkali basalts, limburgites and picritic basalts also are found in the volcanic sequences (Bristow & Saggerson 1983). There has been a long debate concerning whether the picritic basalts are simply olivine-enriched tholeiites (as advocated by Carmichael *et al.* 1974) or a fundamentally different magma, rich in magnesium (Cox 1983). Strontium isotope and trace-element constraints favor the latter interpretation (Bristow 1984, Cox *et al.* 1984).

Associated intrusive rocks are mainly doleritic to gabbroic, depending upon thickness, although some syenites (Bristow & Cleverley 1983) and kimberlites (Smith 1983) were emplaced in this time range. Walker & Poldervaart (1949) recognized several different types of basic intrusive bodies based on crystallization sequence and pyroxene relations. One of these, the Kokstad type, contains abundant olivine. The Insizwa intrusion is of this type, and is unusual in that it contains nickel–copper sulfides in its picritic base (Scholtz 1937). As with the volcanic suite, this has been the subject of a debate on whether the magma from which the picrite-hosted sulfides formed was more magnesian than normal basalt (Cawthorn 1980, Tischler *et al.* 1981, Cawthorn *et al.* 1985), or whether there was physical accumulation of olivine into a low-magnesium basalt (Eales & Marsh 1979, Lightfoot & Naldrett 1983, 1984, Lightfoot *et al.* 1984). The establishment of criteria for the recognition of igneous bodies that have produced immiscible magmatic sulfide deposits is important, and hence the identification of the magma type at Insizwa is crucial to an understanding of the origin of the sulfides.

Cawthorn *et al.* (1985) suggested that the presence of magnesian ilmenite in the sulfide-bearing picrite at Insizwa constitutes one such criterion for characterizing the magma type. On chemical and textural

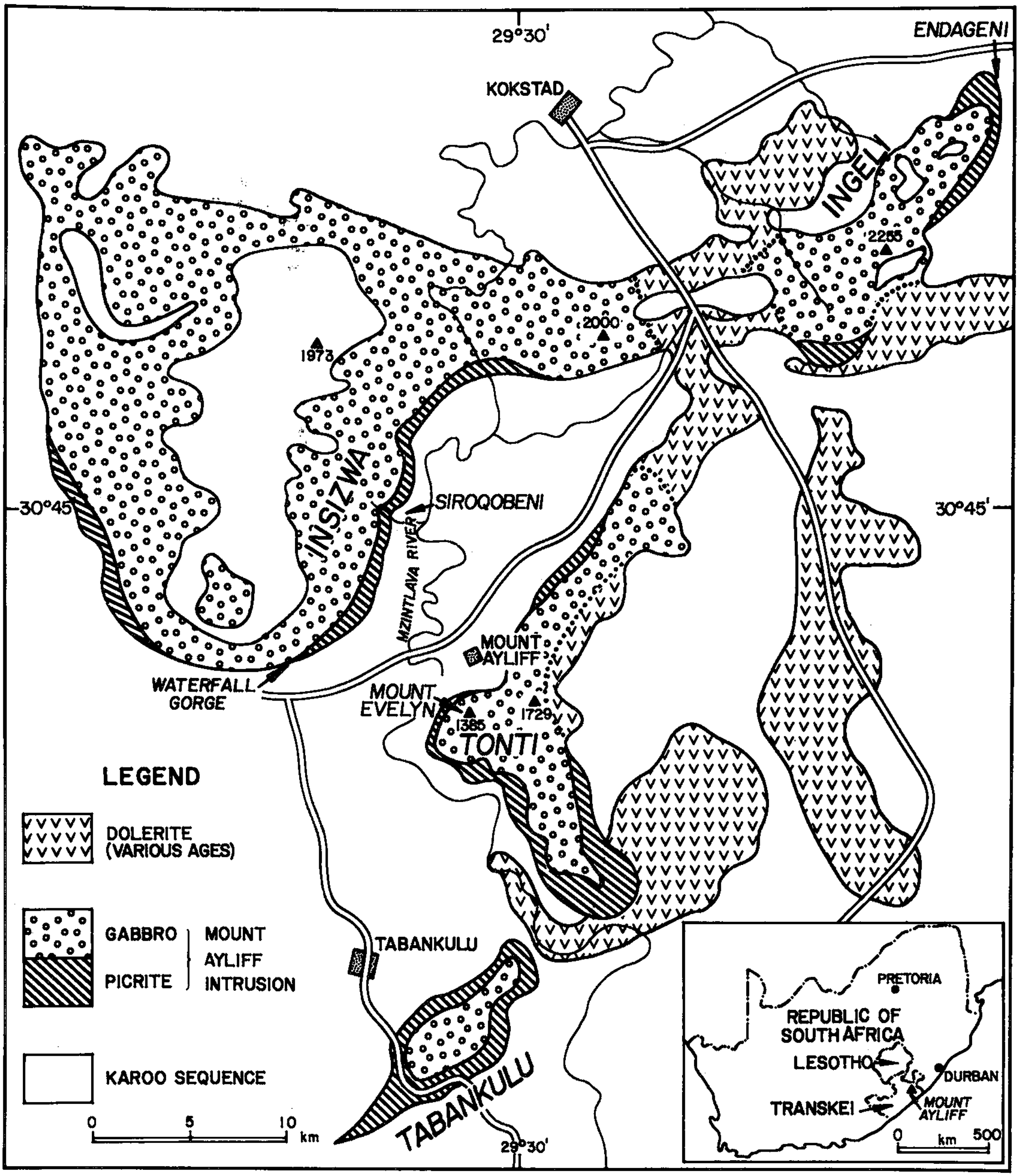

FIG. 1. Geological map of the Mount Ayliff Intrusion, showing the locations of the four profiles studied: Waterfall Gorge, Siroqobeni, Mount Evelyn and Endageni. Compiled from Scholtz (1937), Maske (1966), Lightfoot *et al.* (1984) and remapping for this study.

grounds they argued that these ilmenites could not have crystallized from a typical low-magnesium basalt, but rather were crystallized from a high-magnesium magma. Lightfoot *et al.* (1987) suggested that data for ilmenite from the lower chilled zone are consistent with crystallization from a low-magnesium basaltic parent, and that ilmenite compositions had changed owing to re-equilibration with the host rock.

Both studies of the ilmenite compositions have concentrated primarily on samples from the area of sulfide mineralization at Waterfall Gorge. In this study, investigations are extended both laterally and vertically to determine the distribution of magnesian ilmenite in different host rocks.

General Geology

The sediments of the Karoo Sequence have been intruded extensively by dolerite sheets in the Natal and Cape Provinces of South Africa (Winter & Venter 1970). Among the thickest of these are four adjacent bodies known as Insizwa, Ingeli, Tonti and Tabankulu (du Toit 1920). Deep incision by rivers has separated these, but it is probable that they once formed a single sheet swelling to over 600 m thick in places and covering an area 65 km east–west by 60 km north–south (Fig. 1). The Insizwa mountain range is the most extensive of these and, because of the early mining for nickel–copper sulfides (Maske & Cawthorn 1986), is the most intensively studied. As a consequence, all four lobes commonly have been referred to collectively as the Insizwa Complex. The use of the name Insizwa for one of the lobes as well as for the entire body is confusing. The name Mount Ayliff, after the largest village situated at the centre of the body, was proposed by Schlotz (1937) for the entire suite of igneous rocks and is reintroduced here. The names Insizwa, Ingeli, Tonti and Tabankulu define lobes of the intrusive sheet in this scheme.

Each lobe has a similar sequence of rock types, divided into three zones by Scholtz (1937). The basal zone has a chilled margin, grading upward into coarse-grained olivine-rich rocks. On Tabankulu, this picrite reaches a thickness of 200 m, whereas in parts of the other three lobes it is missing (Fig. 1). The central zone, reaching over 400 m in thickness, consists of a series of gabbros. An upper dioritic zone or roof zone is only intermittently preserved, as ero-

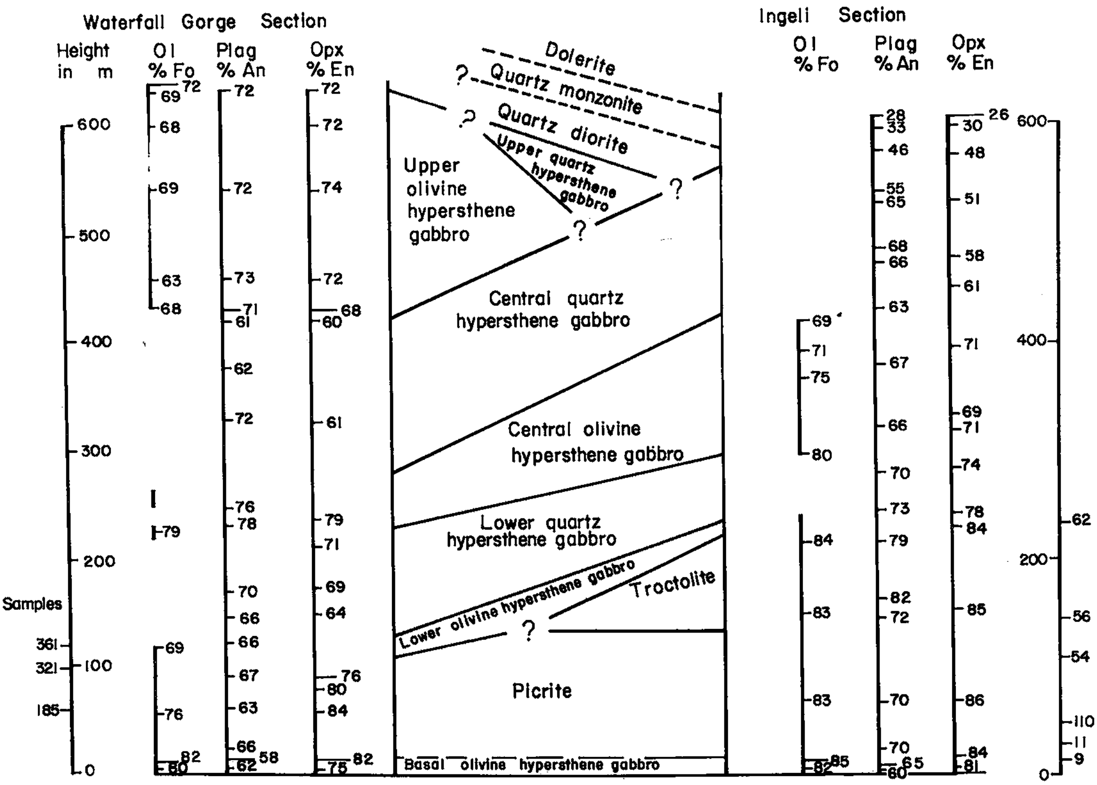

FIG. 2. Typical profiles through the Insizwa (Waterfall Gorge section) and Ingeli lobes of the Mount Ayliff Intrusion, compiled from the data of Scholtz (1937), Bruynzeel (1957), Maske (1966) and Lightfoot *et al.* (1984). The positions of samples used in this study are indicated for both profiles.

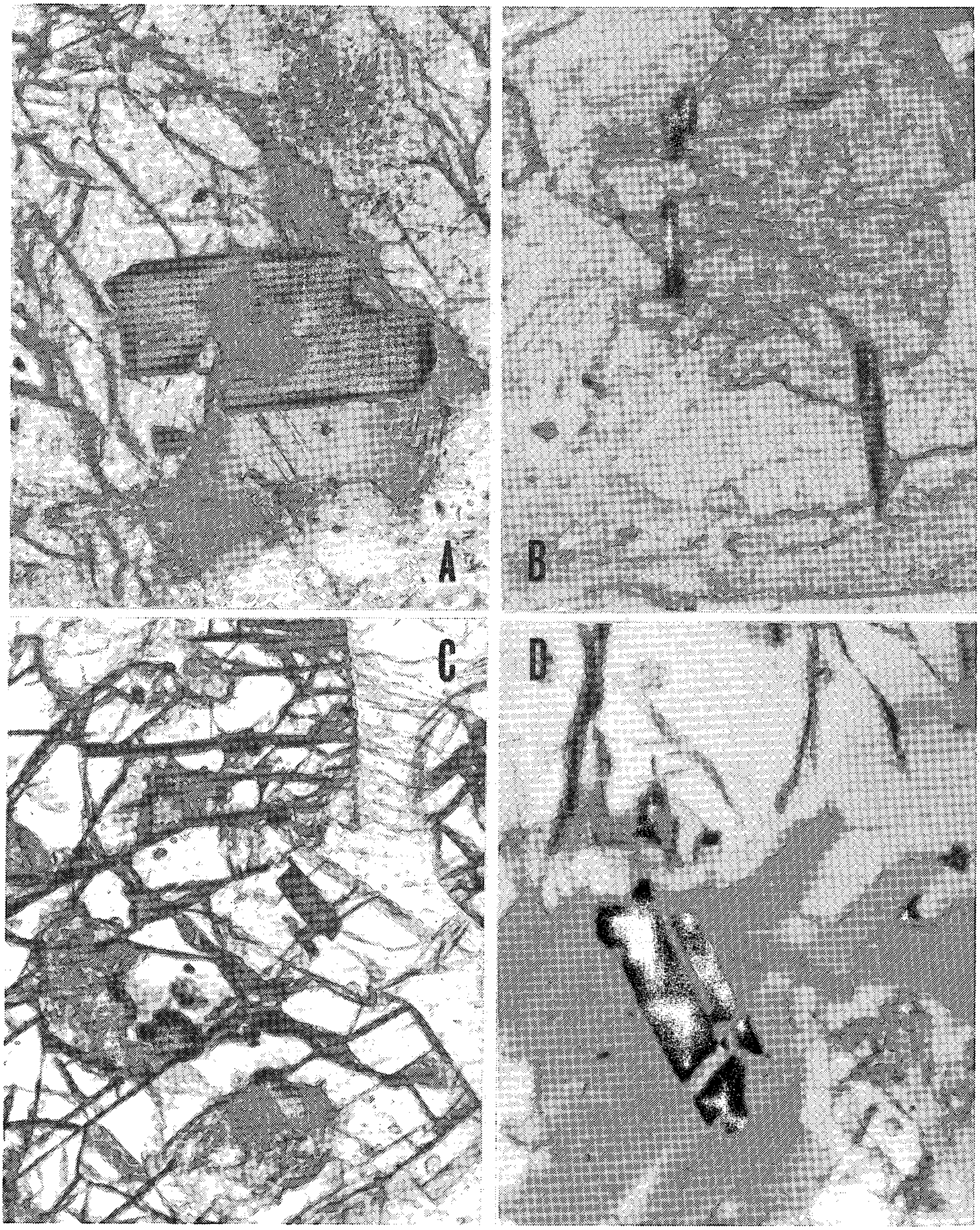

FIG. 3. Photomicrographs of Type-1 ilmenite textures in picrite. A. Ilmenite (black), partly enclosed by olivine (left) and biotite (grey). Irregular outline in biotite may indicate resorption. B. Euhedral blades of ilmenite (black) enclosed in clinopyroxene and plagioclase. C. Euhedral grain of ilmenite (black) totally surrounded by orthopyroxene which has grown in an embayment in olivine (highly fractured grain with high relief). In the lower portion of the olivine grain is an irregular inclusion of biotite (grey) which contains a subhedral grain of ilmenite. D. Elongate grain of ilmenite (black) totally enclosed in an anhedral grain of biotite (grey). Between olivine grain (top) and biotite is a thin rim of orthopyroxene. Width of photographs: A 1.5 mm, B 4 mm, C and D 2.4 mm.

TABLE 1A. AVERAGES OF ILMENITE COMPOSITIONS

MOUNT EVELYN PROFILE - TONTI

Sample	21/1	21/2	21/3	21/4	21/5	21/6	21/8	21/9	21/10	21/11	21/12	21/13	21/14	21/15
TiO_2 wt.%	53.16	55.44	56.36	55.13	56.13	56.79	54.16	54.56	54.10	54.08	53.03	50.97	53.38	51.20
FeO	44.00	35.74	34.60	35.94	36.22	33.99	37.45	38.46	40.33	39.30	41.91	47.34	42.81	47.49
MgO	1.79	7.96	8.55	7.46	7.45	8.58	7.07	6.33	4.99	5.39	2.87	0.33	2.69	0.52
Cr_2O_3	0.25	0.46	0.48	0.48	0.44	0.43	0.63	0.54	0.47	0.54	0.50	0.12	0.42	0.12
MnO	0.67	0.48	0.47	0.51	0.54	0.47	0.53	0.47	0.54	0.48	0.57	0.94	0.51	0.83
Total	99.87	100.08	100.46	99.52	100.78	100.26	99.84	100.36	100.43	99.79	98.88	99.70	99.81	100.16
No.	11	11	16	2	12	3	13	14	9	19	16	11	8	13
Height (m)	1	3	7	12	17	23	58	62	73	93	133	168	170	208

SIROQOBENI PROFILE - INSIZWA

Sample	16/1	16/2	16/3	16/4	16/5	16/6	16/7	16/8	16/9	16/10
TiO_2 wt.%	51.84	54.12	53.40	56.14	52.66	52.71	56.04	55.11	51.42	52.38
FeO	41.24	38.30	38.14	36.43	39.34	39.52	37.52	38.34	45.42	44.73
MgO	5.55	6.98	6.75	6.82	6.71	6.65	6.33	6.01	1.33	1.65
Cr_2O_3	0.79	1.03	0.81	0.35	0.91	0.85	0.57	0.61	0.20	0.25
MnO	0.44	0.44	0.46	0.52	0.47	0.46	0.55	0.56	0.50	0.51
Total	99.86	100.87	99.56	100.26	100.09	100.19	101.01	100.63	98.87	99.52
No.	4	4	9	16	10	1	5	6	4	15
Height (m)	1	16	23	36	59	89	105	130	149	153

	ENDAGENI PROFILE - INGELI						WATERFALL GORGE - INSIZWA		
Sample	NGL/9	NGL/11	NGL/110	NGL/54	NGL/56	NGL/62	INS/185	INS/321	INS/361
TiO_2 wt.%	54.09	53.33	50.43	54.41	52.28	49.52	53.28	52.78	50.36
FeO	36.11	37.35	37.54	34.23	38.61	45.03	38.68	39.03	44.10
MgO	6.76	6.59	7.32	8.49	6.07	1.48	5.82	5.38	2.94
Cr_2O_3	0.44	0.78	1.08	0.63	0.68	0.24	0.51	0.71	0.04
MnO	0.52	0.53	0.54	0.44	0.48	0.87	0.52	0.51	0.48
Total	97.92	98.58	96.91	98.20	98.12	97.14	98.81	98.41	97.92
No.	4	4	5	3	7	6	6	6	6
Height (m)	14	28	48	110	142	230	56	97	109

TABLE 1B. COMPOSITIONS OF ILMENITE IN DIFFERENT HOST SILICATE MINERALS

Sample	3/1	3/2	3/3	3/6	3/7	3/8	15/1	15/2	15/3	15/4	15/5	15/6	15/7
TiO_2 wt.%	55.89	56.17	57.43	56.54	56.98	55.35	51.05	50.35	50.80	51.01	52.25	50.97	51.26
FeO	34.88	35.33	33.19	35.47	32.39	36.07	47.93	47.54	47.60	47.66	46.38	47.04	48.11
MgO	8.44	8.14	9.26	7.75	10.22	7.78	0.45	0.28	0.81	0.75	0.34	0.28	0.61
Cr_2O_3	0.58	0.55	0.52	0.55	0.48	0.29	0.13	0.12	0.12	0.12	0.09	0.14	0.10
MnO	0.46	0.48	0.43	0.53	0.40	0.50	0.85	1.30	0.45	0.48	1.28	1.35	0.52
Total	100.25	100.67	100.83	100.84	100.47	99.99	100.31	99.59	99.78	100.02	100.34	99.78	100.60
No.	3	3	3	1	2	3	3	1	1	2	1	1	2

Samples from Mount Evelyn profile: 3/1 - 3/8 from picrite at 7 m above base; 15/1 - 15/8 from gabbro at 208 m. Silicate host phases: 3/1 ol, opx, bi; 3/2 opx, bi; 3/3 opx, cpx, bi; 3/6 ol, plag, bi; 3/7 opx; 3/8 ol, opx; 15/1 opx, plag, bi; 15/2 cpx, bi; 15/3 cpx, plag; 15/4 bi, q; 15/5 opx, bi; 15/6 bi; 15/7 cpx. Analyses from Ingeli and Waterfall Gorge were performed at the University of Western Australia on an ARL SEMQ instrument, using an acceleration potential of 15 kV, specimen current on benitoite of 20 nA. Data correction: method of Bence & Albee (1968). Analyses from Mount Evelyn and Siroqobeni were performed at the Anglo American Research Laboratories, Johannesburg. Analytical details are given in Apter *et al.* (1984). SiO_2, Al_2O_3 and CaO concentrations do not exceed 0.18, 0.75 and 0.10%, respectively, in any ilmenite composition.

sion has removed the upper contact in most areas. Typical sections through the Insizwa and Ingeli lobes are presented in Figure 2.

All lobes except Tonti have been described in detail: Insizwa by Scholtz (1937), and Bruynzeel (1957); Ingeli by Maske (1966), and Tabankulu by Lightfoot & Naldrett (1983). Specific recent discussions on the mineralization have been presented by Cawthorn (1980), Tischler *et al.* (1981), Lightfoot *et al.* (1984), Cawthorn *et al.* (1985) and Groves *et al.* (1986).

For this study samples have been taken from four profiles shown in Figure 1. A borehole drilled from the top of the Waterfall Gorge and documented by Bruynzeel (1957) was resampled. To the east of Waterfall Gorge at Siroqobeni and on Mount Evelyn on the Tonti lobe, two further profiles were taken where there is nearly continuous exposure of the picrite. For the fourth section, samples were used from the original collection of Maske (1966), from the Endageni profile in the Ingeli lobe.

PETROGRAPHY

Sampling from each profile began as close to the basal contact as possible, although in the case of the Siroqobeni profile the exact position of the lower contact is concealed. For the other two profiles medium-grained material, obviously close to the chilled contact, was sampled. Further samples were taken at approximately 10-m intervals through the picrite and overlying olivine gabbro and gabbro.

The general petrography of the picrite and basal chill zone has been described in detail by Scholtz (1937), Maske (1966) and Lightfoot & Naldrett (1984). Only a brief description is presented here; the emphasis is on the occurrence of ilmenite which is considered to be critical to arguments concerning the composition of the parental magma. The main features of the marginal zone are the presence of highly resorbed anhedral grains of olivine enclosed in two pyroxenes and plagioclase, and up to 2% biotite as interstitial grains. In the picrite, subhedral olivine grains predominate with poikilitic bronzite, augite and plagioclase. Euhedra of chromite are especially common within olivine grains, but also occur in other silicate phases. Biotite is common as an interstitial phase. Rarely, ilmenite is enclosed in olivine grains, but more commonly occurs as elongate blades enclosed in plagioclase and pyroxene (Fig. 3A), and as a core to biotite flakes (Fig. 3B), It usually is euhedral with an equant to elongate outline in the picrite. Cores of some ilmenite grains consist of an opaque isotropic phase with a grey color, which may belong to the armalcolite–kennedyite solid-solution series (S.E. Haggerty, personal communication).

In the olivine gabbro overlying the picrite, plagioclase becomes a common euhedral phase, whereas both pyroxenes remain as subhedral to anhedral grains. Olivine is subhedral to anhedral and steadily decreases in abundance with increasing height and grades into olivine-free gabbro. Ilmenite and biotite make up 1% of the rock, although in this subzone the ilmenite is subhedral to interstitial.

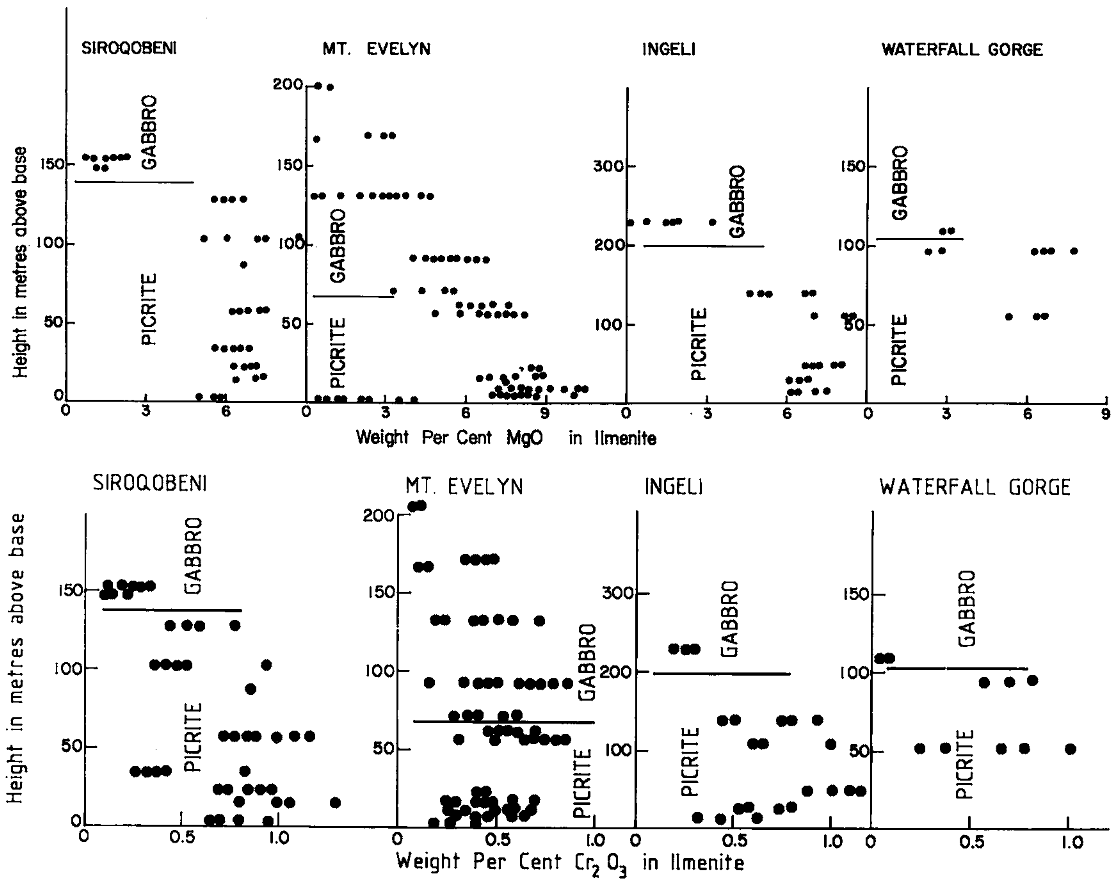

FIG. 4. Plot of MgO and Cr_2O_3 contents of ilmenite as a function of height in the four profiles studied. The change from picrite to gabbro is shown in all profiles. The lowest sample in the Mount Evelyn profile occurs in basal olivine gabbro (see Fig. 2). Not all analyses are plotted because of overlap of compositions; for example, in the basal sample from Mount Evelyn, four analyses from three different grains have 0.17 to 0.19% Cr_2O_3, four have from 0.25 to 0.27% Cr_2O_3, and two have 0.38 to 0.39% Cr_2O_3.

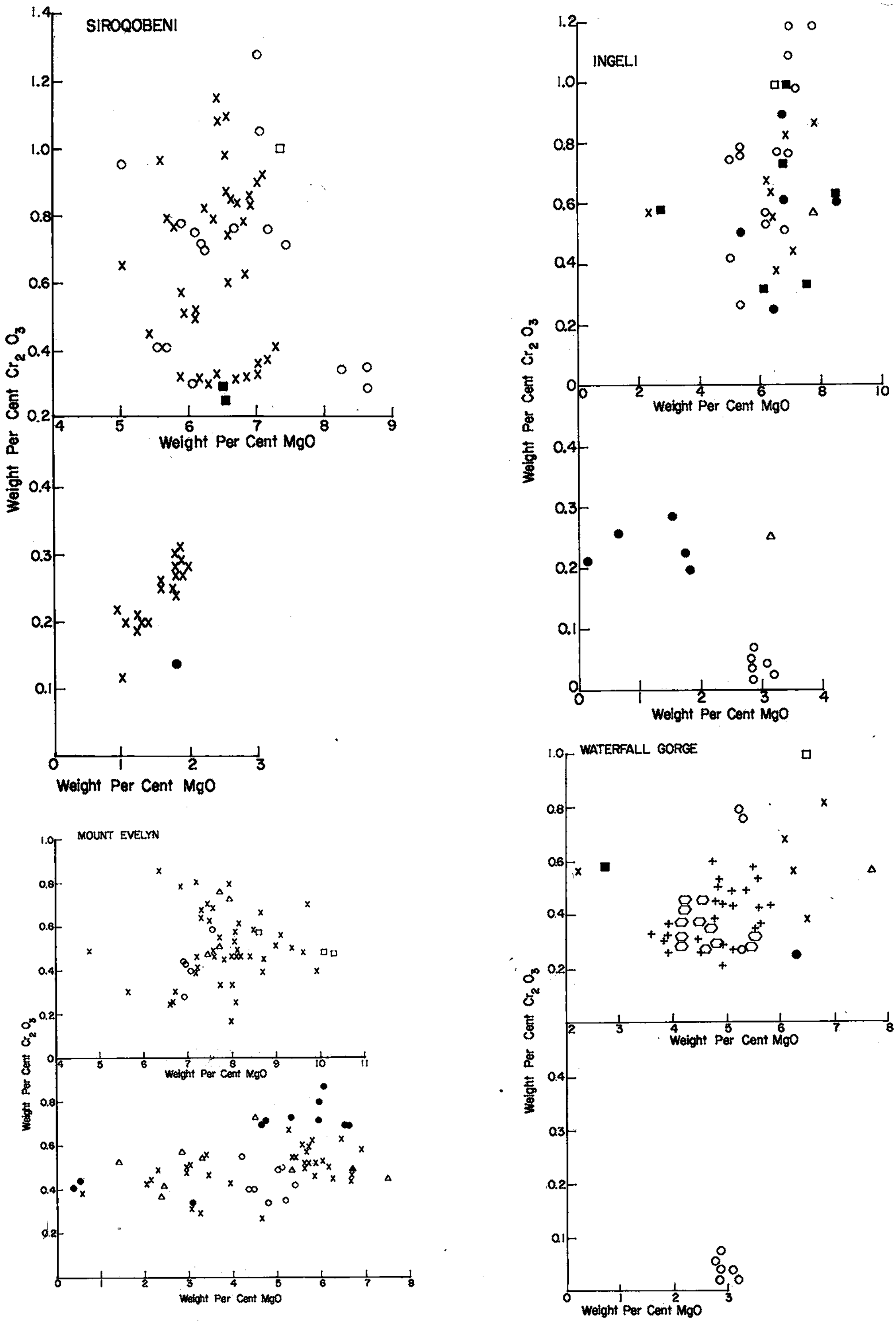

FIG. 5. Plot of MgO *versus* Cr_2O_3 content of ilmenite for the four different profiles as a function of host silicate phase and host rock. Symbols are: ilmenite enclosed in olivine – solid square; in orthopyroxene – open square; in clinopyroxene – solid triangle; in plagioclase – solid circle; in biotite – open circle; in sulfide – hexagon; in pyroxene and plagioclase – open triangle; unspecified silicate – plus. Ilmenite in contact with two or more silicates is shown by a cross. Upper graph for each profile refers to ilmenite from picrite, lower graph from gabbroic rocks.

Mineral Compositions

Ilmenite

The highly atypical composition of the ilmenite discovered in the picrites and associated sulfides (Cawthorn *et al.* 1985, Groves *et al.* 1986) prompted a more systematic study of its composition and distribution in the four profiles. Analyses of samples from Endageni (Ingeli lobe) and the top of the Waterfall Gorge (Insizwa lobe) were undertaken by K.F.C. and D.I.G. at the University of Western Australia in Perth, and analyses from the Mount Evelyn (Tonti lobe) and Siroqobeni (Insizwa lobe) were undertaken by M.d.W. at the Anglo American Research Laboratories in Johannesburg.

A summary of all data is presented in Table 1 and in Figures 4-6. As well as documenting the changing composition as a function of height in the different profiles (Fig. 4), the composition of ilmenite grains in different silicate host minerals has been investigated (Fig. 5).

The most important feature of the data is the very wide range of concentrations of magnesium and chromium in ilmenite (Fig. 4). The highest values of 11% MgO far exceed the maximum concentration

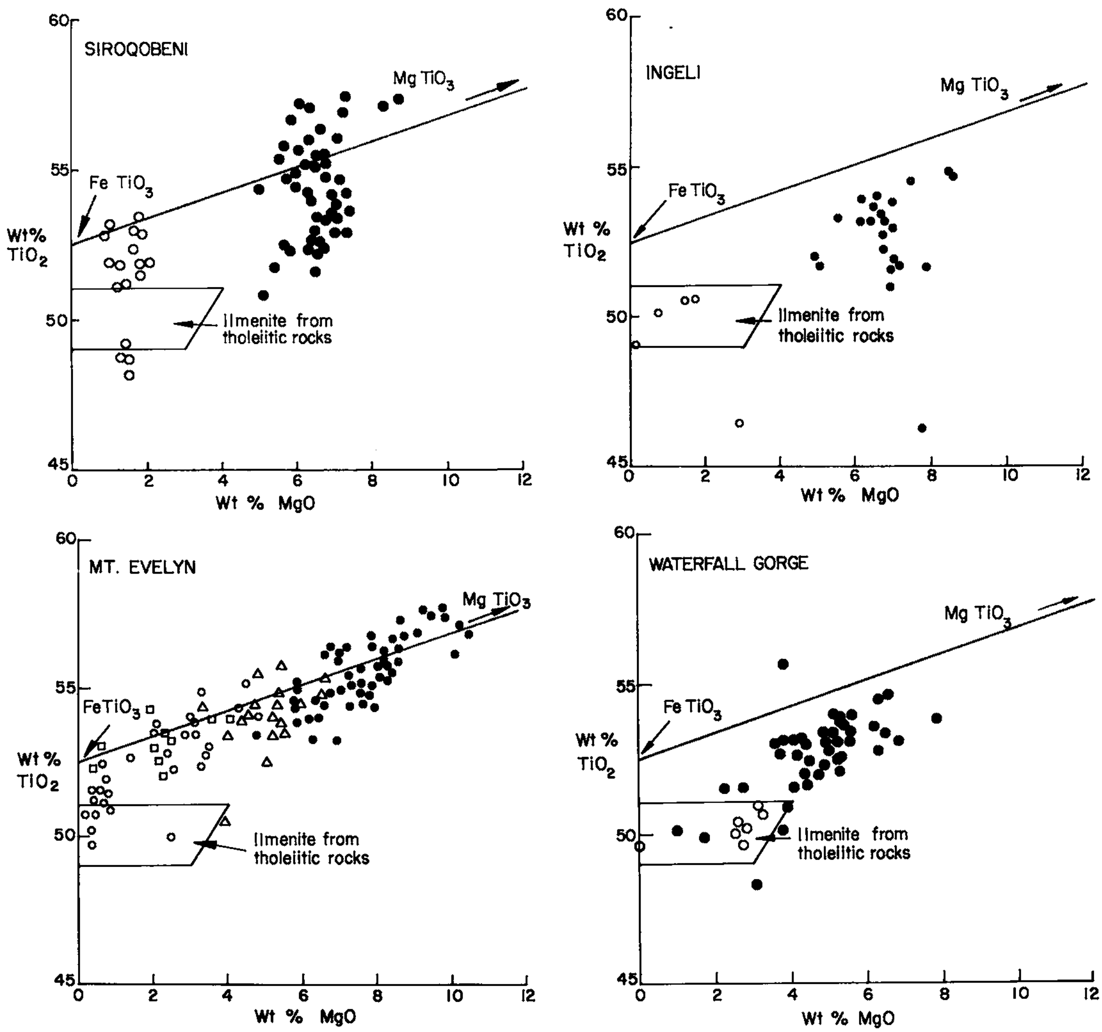

FIG. 6. Plot of TiO_2 against MgO content of ilmenite in all four profiles. Solid circles represent analyses from picrite, open circles from gabbro. In the case of the Mount Evelyn profile the gabbros are subdivided into the basal olivine gabbro (squares), olivine gabbro above picrite (triangles) and overlying olivine-free gabbro (open circles). The field of typical ilmenite from tholeiitic rocks is from Haggerty (1976), and the ideal compositions for solid solution between ilmenite and geikielite are shown for reference.

of 5.6% reported previously from picrite at Waterfall Gorge (Cawthorn *et al.* 1985, Lightfoot *et al.* 1987). Samples from the olivine-free gabbro overlying the picrite in all four profiles contain ilmenite with low contents of magnesium (Fig. 6) and so conform to ilmenite compositions typically found in tholeiitic rocks (Haggerty 1976, Reynolds 1983).

In samples of the olivine gabbro which forms the transitional top to the picrite subzone from the Mount Evelyn profile, the ilmenite crystals are euhedral and included in all silicate phases. The crystals have a high magnesium and chromium composition more compatible with those in the picrites than those in the olivine-free gabbros (Figs. 4, 5). In contrast, the one sample of olivine gabbro from below the picrite at Mount Evelyn contains ilmenite low in these elements.

The variation in contents of magnesium and chromium in ilmenite enclosed in different host minerals is shown in Figure 5, where it can be seen that there is considerable overlap of the compositional fields of ilmenite in different hosts. The ilmenite in the picrite samples is usually enclosed in one single phase, whereas in the gabbro it occurs as interstitial grains so that it is not possible to be as definitive as in the picrite with regard to the host phase. In certain profiles, systematic differences may exist in Figure 5, as for example, between the ilmenite in orthopyroxene and biotite in picrite from the Mount Evelyn profile. However, in the Ingeli and Siroqobeni profiles no such differences are evident, although there are fewer analyses of ilmenite in orthopyroxene. Similarly, the compositions of ilmenite in plagioclase and biotite in gabbro samples from the Mount Evelyn and Ingeli profiles occupy distinct areas in Figure 5, but in one case the ilmenite in plagioclase has higher magnesium contents than when in biotite, and the reverse chemical relationship in the other profile. Thus in both rock types there do not seem to be any generally applicable patterns to the composition of ilmenite as a function of enclosing silicate host. A comparison of the composition of ilmenite enclosed in sulfide blebs and adjacent silicate minerals in picrite at Waterfall Gorge (Fig. 5) reveals similar, high chromium and magnesium contents. The addition of magnesium to a grain embedded in sulfide seems highly improbable and this similarity suggests that these compositions are not significantly influenced by re-equilibration.

Olivine

Olivine has been analyzed from picrite and overlying and basal olivine gabbro from the Mount Evelyn profile, and from picrite in the Endageni profile. These results are presented in Table 2 and compared in Figure 7 with the data from Waterfall Gorge (Lightfoot *et al.* 1984) and Tabankulu (Lightfoot & Naldrett 1983). Multiple analyses across single grains indicate that they are unzoned. Within one sample the maximum variation observed is 2.3% in the forsterite content. Similarly, nickel contents, based on multiple analyses of different grains from one thin section, show a standard deviation of 0.015%. Relative accuracy of analyses for nickel from the two electron microprobes has been checked by analyzing a sample from the Waterfall Gorge mine from a section where Lightfoot *et al.* (1984) reported a constant nickel content in olivine of 1,650 ± 80 ppm. Analysis at the Anglo American Research Laboratories gave a value of 1,810 ± 120 ppm (6 analyses, 1 standard deviation), and at the University of Western Australia 1,640 ± 240 ppm (10 analyses). Hence, the direct comparison of the nickel profiles shown in Figure 7 is justified.

The Endageni profile shows that the forsterite content of olivine does not change substantially or systematically through the picrite, but that the nickel content shows a steady and significant decrease with increasing height from 2,400 ppm at the base to 500 ppm at the top. The Mount Evelyn profile is more complicated. The forsterite content shows a slight upward increase over the bottom 40 m from Fo_{80} to Fo_{82}. It then shows a normal differentiation trend

TABLE 2. COMPOSITIONS OF OLIVINE FROM MOUNT AYLIFF INTRUSION

	ENDAGENI PROFILE - INGELI					MOUNT EVELYN PROFILE - TONTI										
Sample	NGL9	NGL11	NGL110	NGL54	NGL56	21/1	21/2	21/3	21/4	21/5	21/6	21/7	21/8	21/9	21/10	21/11
SiO_2 wt.%	38.12	39.07	39.31	39.73	38.75	38.83	38.84	38.76	39.05	39.32	39.17	39.34	39.02	38.68	38.34	38.48
Al_2O_3	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02
FeO	13.91	17.66	15.61	15.45	17.91	17.93	17.63	17.13	16.09	15.85	15.73	15.66	18.28	20.20	21.30	22.37
MnO	0.24	0.25	0.23	0.24	0.25	0.22	0.24	0.24	0.23	0.22	0.22	0.22	0.25	0.27	0.30	0.33
MgO	43.84	42.26	43.91	44.33	42.47	43.05	43.30	43.84	44.54	44.70	44.75	45.17	43.20	41.43	40.66	39.60
CaO	0.06	0.07	0.07	0.09	0.07	0.10	0.11	0.09	0.09	0.10	0.08	0.08	0.11	0.08	0.09	0.07
NiO	0.31	0.24	0.21	0.15	0.06	0.12	0.12	0.10	0.08	0.14	0.17	0.18	0.10	0.06	0.07	0.12
Total	96.46	99.55	99.34	99.99	99.51	100.27	100.25	100.17	100.10	100.35	100.14	100.67	100.98	100.75	100.79	100.99
Av. Fo	84.9	81.0	83.7	83.6	80.9	81.1	81.4	82.0	83.1	83.4	83.5	83.7	80.8	78.5	77.3	75.9
Max. Fo	85.0	81.1	83.8	84.0	81.2	83.0	81.7	82.1	83.2	84.2	83.8	83.9	80.9	79.0	77.4	76.2
Min. Fo	84.6	80.9	83.3	83.4	80.7	77.1	80.9	81.8	83.0	83.1	83.3	83.5	80.7	78.3	77.1	75.7
Max. NiO	0.32	0.27	0.24	0.16	0.08	0.15	0.13	0.11	0.09	0.14	0.19	0.19	0.11	0.08	0.08	0.12
Min. NiO	0.30	0.21	0.18	0.12	0.05	0.10	0.11	0.09	0.07	0.13	0.16	0.16	0.08	0.05	0.07	0.11
No.	4	5	5	6	5	7	5	5	4	5	6	4	4	5	4	4
Height (m)	14	28	48	110	147	1	3	7	12	17	23	40	58	62	73	93

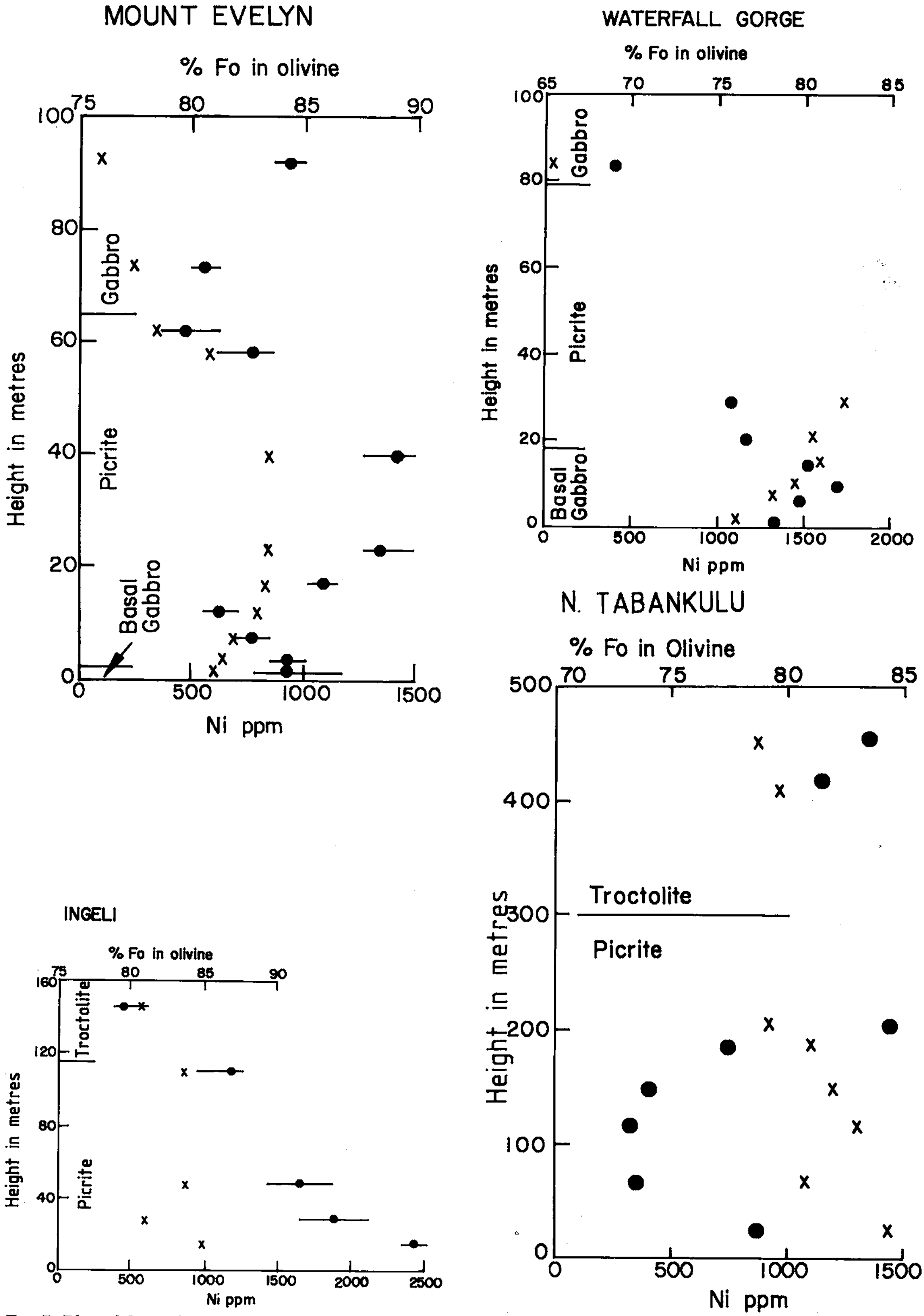

FIG. 7. Plot of forsterite and nickel content of olivine against height in the different profiles compared to that from Waterfall Gorge (Lightfoot *et al.* 1984). Crosses represent forsterite contents, solid circles are nickel contents. The bar represents the total range of nickel values found in each sample.

through the top of the picrite and overlying olivine gabbro, decreasing to Fo_{76}. The nickel profile shows a marked depletion over the bottom 15 m, followed by an increase to 1,500 ppm. There is a second substantial decrease at the top of the picrite, and a recovery in the overlying olivine gabbro.

INTERPRETATION

Ilmenite

Two texturally and chemically distinct types of ilmenite grains are recognized in at least three of the four lobes of the Mount Ayliff Intrusion. No data are available for ilmenite from Tabankulu. One group (Type 1), which includes euhedral grains with high contents of magnesium and chromium, is very unusual in terms of ilmenite previously recorded in tholeiitic bodies. The plot of MgO *versus* TiO_2, used by Haggerty (1976) to define the compositional fields of ilmenite from different rock types, illustrates how anomalous they are (Fig. 6). Those with the highest magnesium content approach the most magnesian ilmenite derived from a kimberlite magma (Tompkins & Haggerty 1985), but have higher titanium contents. This group is referred to here as Type-1 ilmenite.

Type-2 ilmenite, which occurs as interstitial grains between earlier-formed plagioclase and pyroxene, contains less than 3% MgO and 0.3% Cr_2O_3. Such ilmenite occurs in the basal olivine gabbro and in the gabbro some distance above the picrite. These textural relations and chemical features are typical of ilmenite reported from dolerites in the Karoo Province (Reynolds 1983), and are regarded as normal for ilmenite in tholeiitic rocks. These features are similar to those described by Lightfoot *et al.* (1987) from the bottommost samples of the basal zone in the Waterfall Gorge profile.

Origin of Type-1 ilmenite

The origin of Type-1 ilmenite is of major relevance to the present discussion. The two hypotheses which have been proposed are that the unusual features mentioned above are either indicative of an unusual (high-magnesium) magma composition (Cawthorn *et al.* 1985), or are the result of extensive subsolidus re-equilibration of low-magnesium ilmenite formed from a typical low-magnesium basic magma (Lightfoot *et al.* 1987).

The model of Lightfoot *et al.* (1987) demands that for some ilmenite grains Mg and Cr ions are capable of diffusing through feldspar to reach an ilmenite grain embedded within it. Diffusion rates of highly charged ions through minerals are extremely slow (Freer 1981), yet ilmenite in plagioclase in the gabbro has a higher Cr content than in any other host (Fig. 5).

Bishop (1980) showed that, during subsolidus re-equilibration with pyroxenes, the magnesium content of ilmenite should decrease with decreasing temperature for a fixed composition of the coexisting mafic mineral. The data in Figure 3 for the Mount Evelyn profile show that the lowest magnesium contents are found in the rapidly cooled marginal rocks at the base of the intrusion, and that the more slowly cooled picrites contain ilmenite with high contents of magnesium. This is the reverse of what is predicted by the experimental study of Bishop (1980), providing further evidence that these changes in ilmenite composition cannot be attributed to subsolidus re-equilibration.

Application of the olivine–ilmenite thermometer (Andersen & Lindsley 1981) also refutes the influence of subsolidus re-equilibration in this assemblage. With lower temperatures of re-equilibration, which may be equated with slower rates of cooling, a decrease in the geikielite component of ilmenite is predicted by this thermometer. The near-constancy of magnesium contents of ilmenite in picrite from 3 to 62 metres above the base in the Mount Evelyn profile argues against systematic changes in ilmenite composition due to variable rates of cooling.

A further possible process which might account for the observed variation in magnesium contents of the ilmenite would be analogous to that proposed by Roeder & Campbell (1985) for the re-equilibration of chromite in olivine in the Jimberlana intrusion. They argued that changes in composition of chromite grains embedded in olivine could be attributed to reaction at supersolidus temperatures, by infiltration of interstitial liquid inside the olivine crystals along fractures. By such a process there could be re-equilibration in the present instance between ilmenite, olivine, and interstitial liquid. This model was proposed to explain the chemical patterns in rocks from an elongate funnel-shaped igneous body 3 km wide and 6 km thick, in which cooling would have been extremely slow and intercumulus liquid would have existed for a long time. The Mount Ayliff body is less than 600 m thick and some samples under investigation lie within a few metres of the basal contact. In the Mount Evelyn profile ilmenite containing 8% MgO is found in a sample 3 m above the base. This close to the contact, cooling would have been rapid with little time for re-equilibration between ilmenite enclosed in olivine and interstitial liquid. At a height of 60 m the reaction could have proceeded for a far longer time, but the ilmenite has a magnesium content comparable to that at 3 m. Hence, it would appear that the magnesium content of ilmenite is independent of the length of time available for re-equilibration with liquid.

A second problem relates to the textures of Type-1 and Type-2 ilmenite. Type-2 ilmenite is an anhedral, interstitial phase, low in magnesium. In contrast, Type-1 ilmenite is euhedral and occurs inside olivine, pyroxene and plagioclase, and is magnesian. Although changes in composition might be attributed to reaction upon cooling, it is difficult to conceive of a textural change from interstitial Type-2 to euhedral Type-1. It would seem more probable that the two types represent two different generations of crystallization of ilmenite, a high-temperature one, rich in magnesium, and a near-solidus one with a normal magnesium content. In this model it is suggested that the differences in the composition of ilmenite in different silicate hosts reflect some subsolidus re-equilibration, but starting from a high-magnesium, high-chromium ilmenite, not a composition low in these constituents. For example, the ilmenite in plagioclase in the gabbro from Mount Evelyn is higher in chromium than the ilmenite in biotite and clinopyroxene. Diffusion of chromium through plagioclase will be very much slower than through biotite which contains minor chromium. If the original chromium content of the ilmenite had been low and had increased due to subsolidus diffusion, ilmenite in biotite should have a higher chromium content than that of ilmenite in plagioclase. This is opposite to that observed. More probably, the magmatic ilmenite had a high chromium content. For ilmenite enclosed in plagioclase, the chromium could not have diffused out of the ilmenite. However, in the case of the ilmenite in biotite, diffusion of chromium from the ilmenite would be possible; thus the chromium content of ilmenite contained in biotite could be lower than the chromium content of ilmenite in plagioclase.

Timing of crystallization of Type-1 ilmenite

The textural observations of Haggerty (1976) and Reynolds (1983), and the geochemical modelling of Walker *et al.* (1979) and Eales *et al.* (1981) show that ilmenite is generally a near-solidus phase in tholeiitic magmas. The experimental studies of Thompson (1976) and Walker *et al.* (1976), in general, support this. The only exception reported by Thompson (1976) was when ilmenite followed olivine in the crystallization sequence of a liquid which contained 4.15% TiO_2. As this ilmenite crystallized close to the liquidus while the liquid still had a relatively high content of magnesium, the ilmenite also had a higher magnesium content (5.2%) than in normal tholeiitic ilmenite. Hence it would appear that the higher the titanium content of the magma, the nearer to the liquidus at which ilmenite would crystallize; similarly, the higher the magnesium content of the liquid, the higher the magnesium content of the ilmenite. To produce ilmenite with an excess of 10% MgO, and as an early-crystallizing phase, requires a magma anomalously enriched in magnesium or titanium (or both) compared to typical tholeiite.

An analogy can be made between the crystallization and composition of ilmenite in this study and those reported by Bristow (1984). The high-magnesium, high-titanium lavas from the Lebombo volcanic belt of the Karoo Sequence contain olivine and ilmenite phenocrysts, the latter having up to 6% MgO. Their occurrence in volcanic glass precludes the ilmenite representing anything but primary igneous compositions.

Crystallization of the picrite

The major-element concentrations in the olivine do not display obvious differentiation trends (Fig. 7). Close to the base of all three profiles the forsterite content increases with increasing height, before showing a slight iron-enrichment trend in the Mount Evelyn and Ingeli profiles. The nickel contents of olivine contrast markedly with the near-constancy of forsterite content, showing extremely large variations although within a single sample the range of concentrations is restricted. This observation precludes the possibility of the intrusion of a magma carrying suspended olivine crystals which accumulated at the base to produce the picrite. Such a process would not produce the observed major variations in nickel content in olivine. The olivine must have crystallized after injection of the magma in an environment where the nickel content of the magma varied markedly.

The upward increase in forsterite content may be attributed to two possible processes. Raedeke & McCallum (1984) suggested that such a trend resulted from the entrapment of variable amounts of interstitial liquid in the cumulate. Near the base of the body there would be a greater proportion of trapped liquid due to more rapid rates of cooling. This would cause overgrowth of iron-rich olivine which would then re-equilibrate with the more magnesian core. In contrast, higher in the picrite there would be less trapped liquid and so less post-cumulus reaction. This has been documented previously by Lightfoot & Naldrett (1983) for the picrite in the Tabankulu lobe.

Wilson & Engell-Sorensen (1986) suggested that this reversal in trend results from rapid multiple intrusion of magmas of different densities, with the more iron-rich magmas being denser and so underflowing their more magnesium-rich counterparts. Subsequent crystallization preserves this upward zonation in iron-to-magnesium ratio of the stratified magma. The isotopic data of Lightfoot *et al.* (1984) reveal significant inhomogeneity in the basal olivine gabbro which they interpreted as the result of multiple injection. Further, the basal olivine gabbro, the picrite and the overlying gabbro belong to isotopically discrete magmas. The concept of stratification of magmas seems to be applicable, at least in the area studied by Lightfoot *et al.* (1984), and could explain the reversed trend of olivine compositions. Thus both models could have operated either separately or in conjunction in producing the observed trends. The injection of two distinct magmas could also explain the two textural and compositional types of ilmenite and the trends in nickel content in olivine by the formation of immiscible sulfide liquid as discussed below.

Sulfide mineralization

In the Waterfall Gorge profile (Fig. 7) the nickel content of olivine reaches a maximum just below the top of the basal olivine gabbro and then shows a regular and pronounced decrease through the lower part of the picrite, even though the forsterite content increases through this zone. This decrease in nickel content is probably the result of the formation of an immiscible sulfide liquid (Naldrett 1981) and, if so, this immiscibility must have begun close to the bottom of the picrite. In this regard, it is significant that Scholtz (1937) concluded that most of the disseminated mineralization at Waterfall Gorge occurs in a 10 m-thick zone approximately 20 m above the base. This corresponds to the transition from basal olivine gabbro into picrite. Thus the distribution of nickel in olivine provides an excellent tracer for the occurrence and timing of separation of an immiscible sulfide phase using the geochemical principles developed by Duke & Naldrett (1978).

These principles can be applied to the other profiles to evaluate their evolution and sulfide potential. The Endageni profile from Ingeli (Fig. 7) shows a smooth decrease in nickel content of olivine from 2,400 to 500 ppm, whereas the average forsterite content decreases by only 4%. Using the geochemical principles of Duke & Naldrett (1978), this decrease in nickel presumably reflects the formation of an immiscible sulfide liquid concurrently with the crystallization of olivine to form the picrite. The nickel content of the first-formed olivine of 2,400 ppm is typical of that forming from a magma which has not undergone prior sulfide fractionation. The decrease to 500 ppm in the olivine near the top of the picrite is greater than predicted for olivine crystallization alone based on the compositional curves of Simkin & Smith (1970). This suggests that sulfide precipitation has accompanied the formation of olivine. Maske (1966) reported the presence of minor sulfide content, specifically pyrrhotite with small amounts of chalcopyrite and pentlandite, in the picrite from Ingeli, consistent with this geochemical interpretation. It is considered significant that the nickel content of the olivine shows a smooth decrease suggestive of continuous coprecipitation of sulfide and olivine. This contrasts with the behavior observed in the other profiles.

The Mount Evelyn profile from Tonti is fundamentally different (Fig. 7). The forsterite content of the olivine shows a slight reversed trend over the bottom 20 m and then a normal differentiation trend over the next 80 m. The nickel content decreases very rapidly from 1,000 to 500 ppm over the bottom 15 m, shows an increase to 1,400 ppm, a second rapid decrease to less than 500 ppm at the contact of the picrite and gabbro, and finally a second increase to 1,000 ppm.

The basal value of 1,000 ppm nickel for an olivine composition of Fo_{83} suggests formation from a magma already depleted in nickel by removal of a sulfide phase. The further rapid depletion to 500 ppm suggests continued segregation of considerable quantities of sulfide. The lowest three samples in this profile show a transition from Type-2 to Type-1 ilmenite, which may have been derived from fundamentally different magmas. This transition may be related to mixing of these two magmas, and the formation of the sulfides could be a consequence of the same process. The subsequent recovery in nickel through the overlying picrite suggests that there is either an addition of magma, or that only a thin zone of magma precipitated sulfide and that the rest of the magma was not chemically involved. This would be analogous to the model proposed by Campbell (1978) and Cawthorn & McCarthy (1980) of bottom crystallization with only slow chemical communication between a lower boundary layer of magma depleted in highly compatible elements and the overlying main body of magma. If sulfide formation was related to the mixing of two distinct magmas, the zone of mixed magma may have been saturated with respect to sulfide but the overlying magma need not have been. Thus the olivine crystallizing higher up in the picrite could have formed from a magma which had not precipitated any sulfide and so had a normal nickel content. In the interval from 60 to 80 m at the top of the picrite, Type-1 ilmenite shows a gradual change to Type-2. A change in initial $^{87}Sr/^{86}Sr$ values also occurs between picrite and overlying gabbro in the Waterfall Gorge profile (Lightfoot *et al.* 1984). Mixing of the two distinct magma types would explain the transition in ilmenite composition (Fig. 4). Over this same interval the nickel content of the olivine decreases to less than 500 ppm. The most plausible explanation of this rapid decrease is the formation of further sulfide. The coincidence between the depletion of nickel in olivine and the change in ilmenite type and composition suggests that both may be caused by the same process of magma mixing.

There are similarities in the nickel-in-olivine data at the base of both the Waterfall Gorge and Mount Evelyn profiles (Fig. 7). In view of the known mineralization at the base of Waterfall Gorge, there is a possibility of similar mineralization in the Mount Evelyn area. Based on an analogous nickel depletion in olivine, there may even be a second zone of mineralization at the top of the picrite.

It appears that there are differences in the extent and distribution of potential sulfide mineralization in different lobes of the Mount Ayliff Intrusion. The Waterfall Gorge and Mount Evelyn sections display specific zones enriched in sulfide, whereas on Ingeli there are inferred to be no horizons with sulfide concentrations, but minor sulfide disseminated uniformly through the entire picrite zone. Furthermore, whereas the first olivine to crystallize in the Waterfall Gorge and Mount Evelyn profiles is anomalously depleted in nickel, suggesting that the magma has already undergone a period of magmatic sulfide segregation, that from Ingeli does not appear to be similarly depleted.

The differences which exist in the distribution of sulfides may be related to the extent of mixing of the two magmas, with more extensive mixing in the Ingeli than in the Mount Evelyn profile. It may be significant that ilmenite with over 11% MgO is found on Mount Evelyn whereas the highest concentration found at Ingeli is less than 9%. This lower value may reflect a greater degree of dilution of the high-magnesium, high-titanium magma by the normal tholeiitic magma.

Conclusions

Two texturally and chemically distinct types of ilmenite are found at specific stratigraphic levels in the Mount Ayliff intrusion. The basal olivine gabbro contains ilmenite typical of tholeiitic igneous rocks. The overlying picrite contains euhedral ilmenite with up to 11% MgO and 1% Cr_2O_3. These are considered to have formed from a magma anomalously enriched in magnesium and titanium. The next stratigraphic layer, an olivine gabbro, shows a reversal to the tholeiitic ilmenite type.

The change in ilmenite type is mirrored by changes in the nickel content of olivine. In one of the profiles studied this shows two distinct minima at the top and near the base of the picrite, which is attributed to the mixing of the magma which formed the picrite, first along its base with the basal olivine gabbro magma, and subsequently along its upper surface with an overlying tholeiitic magma. Both events produced an immiscible sulfide liquid. In a second profile the behavior of nickel in olivine suggests that continuous separation of a sulfide liquid and olivine occurred as the picrite accumulated. More thorough mixing of the two magmas is thought to have occurred in this area.

The variation in ilmenite compositions, the behavior of nickel in olivine, and previously published isotope data all support the concept of intrusion of contrasting magma types, one being a typical tholeiite and the other having affinity to the high-magnesium, high-titanium magma identified in the volcanic suite of the Karoo Sequence.

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