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MAGNESIAN ILMENITE: CLUE TO HIGH-Mg PARENTAL MAGMA OF THE INSIZWA COMPLEX, TRANSKEI

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Abstract

Ilmenite containing up to 6% MgO and 55% TiO_2 occurs in olivine gabbro from the base of the Insizwa complex in the Transkei, southern Africa. Such ilmenite is chemically distinct from the ilmenite found elsewhere in the igneous rocks of the Karoo Province and in tholeiitic rocks world-wide. Its occurrence emphasizes the atypical nature of the Insizwa complex, which contains Ni–Cu sulfide mineralization, in contrast to other Karoo intrusive bodies. Magnesian ilmenite is enclosed by both sulfides and silicates, arguing against significant subsolidus re-equilibration as the cause of such compositions. This ilmenite probably crystallized from a magnesian tholeiitic parental magma, atypical of the Lesotho-type composition. The near-liquidus crystallization of ilmenite, indicated by its partial inclusion in plagioclase and pyroxene, may have been the result of contamination, which also caused the separation of an immiscible Ni–Cu sulfide liquid. A separate generation of ilmenite occurs in the granophyric patches, also with sulfide concentrations heterogeneously distributed through the basal olivine gabbro. Ilmenite in the granophyre and associated sulfide is depleted in Mg but enriched in Mn, reflecting the more acid composition and possibly higher oxygen fugacity of the magma from which it crystallized.

Keywords: ilmenite, magnesian tholeiite, magmatic sulfide, contamination, Insizwa, Karoo, South Africa.

Sommaire

On trouve de l'ilménite contenant 6% de MgO et 55% de TiO_2 dans le gabbro à olivine du complexe d'Insizwa (Transkeï, Afrique méridionale). Elle diffère en composition de celle que l'on trouve ailleurs, soit dans les roches ignées de la province du Karoo, soit dans les roches tholéiitiques partout au monde. Cette distinction souligne l'aspect atypique du complexe d'Insizwa, qui seul parmi les intrusions du Karoo contient des sulfures de Ni et de Cu. L'ilménite magnésienne constitue une inclusion aussi bien dans les sulfures que dans les silicates, ce qui exclut la possibilité que la composition soit due à une rééquilibration subsolidus. Cette ilménite a probablement cristallisé à partir d'un magma tholéiitique magnésien apparenté, atypique de la composition du type Lesotho. La cristallisation près du liquidus de l'ilménite, que révèle son inclusion partielle dans plagioclase et pyroxène, pourrait avoir été le résultat d'une contamination, laquelle aurait aussi causé la séparation d'un liquide de sulfure de Ni–Cu immiscible. Une génération différente d'ilménite se trouve par endroits, là où la roche est granophyrique; elle aussi est accompagnée de concentrations de sulfures distribuées au hasard dans le gabbro à olivine de la base. L'ilménite du granophyre et des sulfures associés est appauvrie en Mg et enrichie en Mn, témoignant ainsi de la composition acidique, et peut-être aussi de la forte fugacité d'oxygène du magma dont elle provient.

(Traduit par la Rédaction)

Mots-clés: ilménite, tholéiite magnésienne, sulfure magmatique, contamination, Insizwa, Karoo, Afrique du Sud.

Introduction

The deposit of magmatic Ni–Cu–PGE sulfides at the base of the Insizwa complex in the northern Transkei in southern Africa has been known and mined since the 1890s (Hammerbeck & Vermaak 1976). It is the only deposit of this type in the whole of the Karoo Province. The original extent of the intrusion may have exceeded 2,500 km^2, but it is now dissected by erosion into four nearly contiguous bodies, Insizwa, Ingeli, Tonti and Tabankulu (Tischler *et al.* 1981). The geology of the mineralized Waterfall Gorge section of Insizwa has been described by Scholtz (1937), Bruynzeel (1957) and Lightfoot *et al.* (1984); Ingeli by Maske (1966), and Tabankulu by Lightfoot & Naldrett (1983). Pertinent features have been highlighted by Cawthorn (1980), Tischler *et al.* (1981) and Lightfoot & Naldrett (1984) and are only briefly reviewed here.

The intrusive complex is 600 m thick, with a basal olivine-rich zone 100 to 300 m thick, a central zone 300 to 500 m thick composed of hypersthene gabbro with olivine or quartz, and a thin upper zone of diorite and quartz monzonite. The basal zone has been studied in most detail because of the associa-

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ted sulfide mineralization. From the base up, it consists of a chill zone, an olivine gabbro, a thick picrite and a thin troctolite. The mineralization occurs as disseminated blebs (up to 5 cm) and veins of sulfide in the olivine gabbro and underlying hornfels. It is commonly associated with granophyric veins and diffuse patches enriched in biotite, quartz and alkali feldspar.

Debates on the composition of basic magmas such as those producing the Insizwa complex involve an evaluation of (i) the composition of the liquid at the time of intrusion (*i.e.*, excluding any intratelluric and, hence, possibly accumulated crystals), and (ii) the possibility that those liquids underwent some change in composition subsequent to their generation in the mantle. Intrusive and extrusive rocks of the Karoo Province of southern Africa have been extensively investigated with regard to these problems. Carmichael *et al.* (1974) and Eales & Marsh (1979) favored a status of primary magma for many of these tholeiitic rocks, whereas Cox (1980) argued for significant degrees of fractionation. Eales & Marsh (1979) suggested that Mg-rich compositions in the Central Karoo represent physical concentration of olivine and are not compositions of true liquids. In contrast, Bristow & Saggerson (1983) reviewed evidence supporting the existence of picritic liquids at least in the Lebombo region of Natal, Swaziland, eastern Transvaal, Mozambique and Zimbabwe. Cawthorn (1980) and Tischler *et al.* (1981) presented evidence that the Insizwa complex is atypical of the Lesotho-type of Karoo magmas, and formed from a Mg-rich parent liquid. This model has been refuted by Lightfoot & Naldrett (1983, 1984).

In this paper, new data are presented on the composition of magnesian ilmenite from the basal rocks of the intrusive complex, which indicate that these rocks are highly anomalous compared to others of the Karoo Province. Secondly, the criteria used by previous authors to estimate the composition of the primary liquid, from which the Insizwa complex evolved, are reassessed. In particular, the relevance of liquid compositions based on olivine-control lines and olivine compositions, presented by Lightfoot & Naldrett (1984), are examined in the light of previous reports of a basal high-Mg rock with minimal olivine content (Scholtz 1937).

Magnesian Ilmenite from the Insizwa Complex

Ilmenite is a minor phase in all basic rocks as well as in the granophyric facies and associated massive and disseminated sulfides in the Insizwa complex. In the olivine gabbro it occurs enclosed in plagioclase and pyroxene as euhedral to slightly elongate blades (Fig. 1A). Ilmenite from the Waterfall Gorge section has been analyzed from the basal olivine gabbro and associated sulfide, and from the granophyric patches and their associated sulfides. Material was provided by Professor W.J. Verwoerd of Stellenbosch University from the original collection made by Scholtz (1937), and includes underground samples and borehole core. Some of the analyses were performed by D.I.G. at Cambridge University,

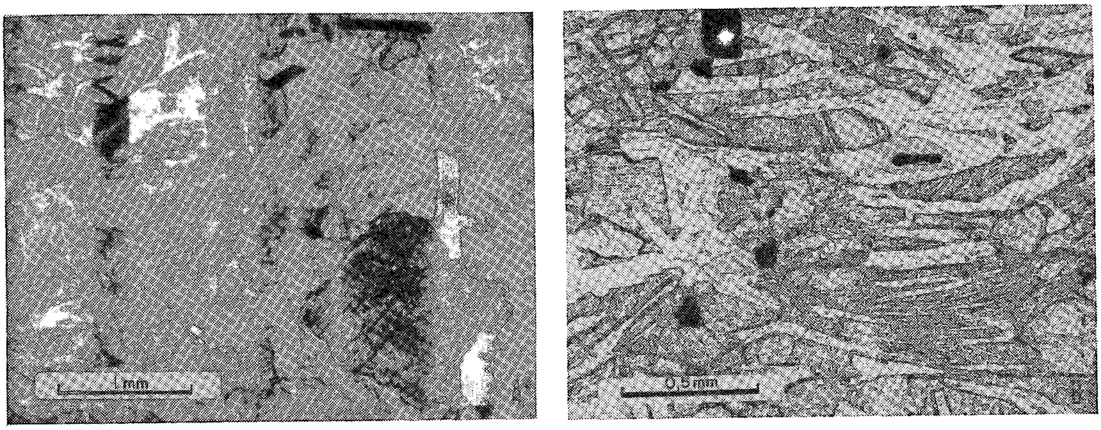

Fig. 1. Photomicrographs of olivine gabbro. A. Resorbed olivine grain is visible in lower right. Tabular plagioclase and euhedral to anhedral orthopyroxene comprise most of field of view. Euhedral to bladed ilmenite grains are present; one at top left is embedded in pyroxene, and below it are grains in plagioclase. These features demonstrate the near-liquidus crystallization of ilmenite, which contrasts with interstitial ilmenite in other Karoo dolerites (Reynolds 1983). Sample from base of Waterfall Gorge profile, Insizwa. B. Trachyophitic texture produced by parallel growth of olivine and pyroxene blades with interstitial plagioclase. Other areas show a more typical ophitic texture (centre, left) and euhedral olivine (top left and bottom right). Sample from 30 cm above contact on Ingeli (Maske 1966, Plate II.5).

TABLE 1. MEAN COMPOSITION OF ILMENITE FROM INSIZWA

	1 (n*=43)	2 (n=30)	3 (n=33)	4 (n=9)
SiO_2	1.0	0.3	0.6	0.6
Al_2O_3	0.2	0.1	0.2	0.3
Cr_2O_3	0.3	0.2	<0.1	<0.2
TiO_2	52.6	53.0	49.5	50.6
FeO**	40.5	40.9	45.8	42.8
MnO	0.6	0.9	3.5	5.2
MgO	4.8	4.6	0.3	0.3

* n number of analyses. ** Total Fe expressed as FeO.
1. Ilmenite intergrown with silicates in mineralized olivine gabbro. 2. Ilmenite intergrown with sulfides in mineralized olivine gabbro. 3. Ilmenite intergrown with silicates in granophyre. 4. Ilmenite intergrown with sulfides in granophyre.
Most electron-microprobe analyses performed at CSIRO Division of Mineralogy, Floreat Park, Western Australia using an ORTEC energy-dispersion system. Operating conditions: 15 kV, 40 s counts, rutile as standard and reductions of data using CSIRO "oxide minerals" program. Additional samples analyzed at the Department of Earth Sciences, University of Cambridge, U.K. on a Cambridge microprobe with energy-dispersion system. Operating conditions: 15 kV, 40 s counts and Co as a standard.

TABLE 2. COMPOSITIONAL RANGE OF ILMENITE FROM MINERALIZED OLIVINE GABBROS AT INSIZWA

	1	2	3	4	5	6	7	8
SiO_2	0.5	0.5	0.4	0.4	0.5	0.5	0.1	0.5
Al_2O_3	0.1	0.3	0.3	0.1	0.1	0.4	0.2	0.3
Cr_2O_3	0.3	0.4	0.3	0.3	0.1	0.1	0.1	0.1
TiO_2	53.0	53.5	54.1	54.3	50.1	49.6	52.3	50.9
*FeO	41.1	38.4	39.4	39.4	43.4	43.1	41.0	42.2
MnO	0.7	0.6	0.8	0.8	0.9	1.0	1.0	1.0
MgO	4.3	5.6	5.3	5.2	3.5	3.8	4.7	4.0
$*SO_3$	0.1	0.1	0.4	0.3	1.0	0.5	0.4	0.5
	99.9	99.3	101.0	100.7	99.4	98.9	99.6	99.3

* Total Fe as FeO: S as SO_3

1. Ilmenite intergrown with silicates, specimen 60:7B
2. Ilmenite intergrown with silicates, specimen 60:3A
3. Ilmenite intergrown with sulfides, specimen 60:4B
4. Ilmenite intergrown with sulfides, specimen 60:4E
5. Ilmenite intergrown with silicates, specimen 785:2A
6. Ilmenite intergrown with sulfides, specimen 785:2B
7. Ilmenite intergrown with sulfides, specimen 13:6C
8. Ilmenite intergrown with sulfides, specimen 784.WGS:3B

Ilmenite analyzed at CSIRO Division of Mineralogy: analytical conditions given in the previous Table.

England, in 1977, and others by T.M. at C.S.I.R.O. in Perth in 1983. Analytical details and results are given in Tables 1 and 2.

Two groups of compositions of ilmenite are recognized. Those from olivine gabbro and associated sulfide are rich in Mg (typically 4–5% MgO), whereas those in the granophyre are low in Mg (less than 1% MgO) and have variable Mn contents (0–8% MnO). Individual grains are slightly inhomogeneous with respect to Mg. For example, six analyses on a single grain from the olivine gabbro showed a range from 6.24 to 6.54% MgO using the C.S.I.R.O. microprobe. A single analysis using the Cambridge instrument on the same grain gave 5.90% MgO. Data on the same grains analyzed by the two different instruments indicate a slight systematic difference, with analyses from Cambridge giving MgO contents that are generally lower than the average composition on the C.S.I.R.O. instrument. However, the intragrain variation exceeds the interlaboratory variation, and so these slight systematic differences have no effect on interpretation.

Grains of ilmenite are enclosed by both pyroxene and plagioclase (Fig. 1A) in the gabbro, but no systematic difference in composition was found. The possible influence on the data of inclusions of silicate or sulfide in the ilmenite, or beam overlap onto such minerals, was tested by analyzing for SiO_2, Al_2O_3 and S. Concentrations of these elements are always low (Tables 1, 2), except in samples for which analyses were rejected.

Ilmenite compositions from the olivine gabbro are rather unusual with regards to their Mg content, as shown in Figures 2 and 3. Haggerty (1976, Fig. Hg-41D) indicated the range of typical igneous ilmenite on a TiO_2 *versus* MgO plot, which is reproduced in Figure 2. Most of the magnesian ilmenite from Insizwa has a higher Ti content than other samples. On a plot of

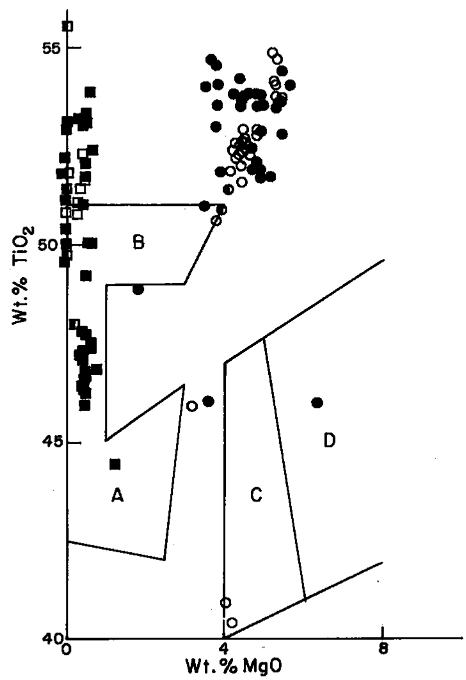

FIG. 2. Plot of TiO_2 *versus* MgO in ilmenite from Insizwa. Typical compositional fields are from Haggerty (1976). Ilmenite from acid rocks (field A), tholeiitic rocks (B), basanitic rocks (C), and kimberlites (D). Circles refer to samples from the olivine gabbro, squares from granophyre. Solid symbols represent ilmenite in silicate, open symbols, ilmenite in sulfide, half-solid symbols, ilmenite on sulfide-silicate contact.

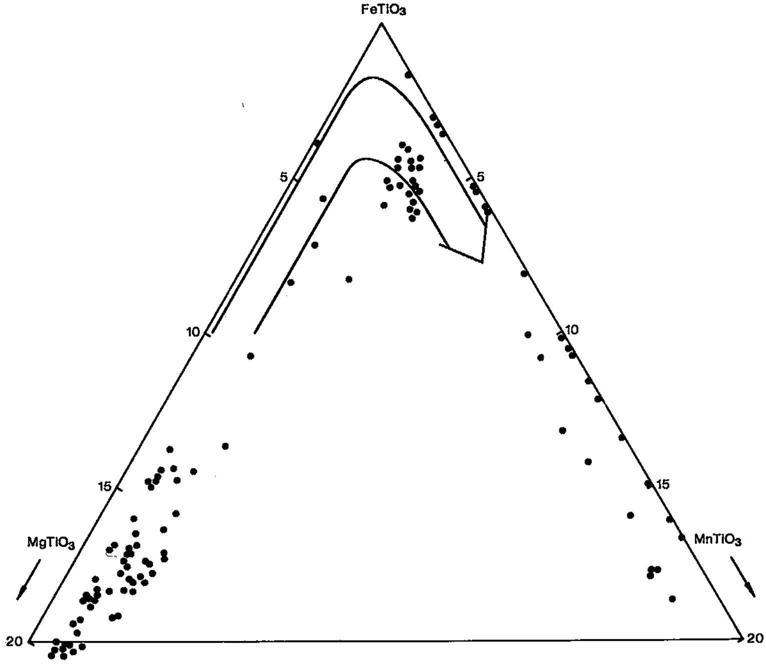

FIG. 3. Triangular plot $FeTiO_3$-$MgTiO_3$-$MnTiO_3$ showing the compositions of ilmenite from Insizwa. Compositions with greater than 4% $MgTiO_3$ component are from the olivine gabbro and associated immiscible sulfide phase. Low-$MgTiO_3$ compositions are from the granophyric veins and their associated sulfides. The arrow indicates the total range of compositions and inferred differentiation trend for all ilmenite compositions found in other Karoo dolerites (Reynolds 1983).

$FeTiO_3$-$MgTiO_3$-$MnTiO_3$ proportions in ilmenite in Figure 3, the Insizwa ilmenite extends up to much higher geikielite, $MgTiO_3$, component than found elsewhere in the Karoo Province (Reynolds 1983).

Interpretation

Ilmenite with greater than 4% MgO is extremely rare on a world-wide basis, the only exception being that found in rocks crystallized from highly alkaline and kimberlitic magmas and in carbonatites (Haggerty 1976). Orthopyroxene is present throughout most of the Insizwa complex (Scholtz 1937), and so an alkaline affinity can be ruled out. Furthermore, the Insizwa ilmenite is distinct from that usually found in alkaline rocks in that it contains more Ti (Fig. 2). However, one example of ilmenite nodules in a basanite from southern Algeria has been reported (LeBlanc *et al.* 1982) to contain more Ti than suggested by the generalized fields in Figure 2. The high Ti content in the Insizwa ilmenite is attributed to the lower proportion of Fe_2O_3 in solid solution. Recalculation of the typical compositions into end members gives less than 5% hematite component for the Mg-rich ilmenite, as shown in Figure 4. This is consistent with the findings of Green & Sobolev (1975), who showed that Ti in ilmenite decreases with increasing $f(O_2)$ as more hematite dissolves in the mineral structure.

The magnesian ilmenite from Insizwa is also fundamentally different from that occurring in other typical Karoo dolerites. A recent compilation of data from numerous dolerites by Reynolds (1983) shows that in most cases, ilmenite contains less than 1% MgO, and that the highest content recorded is 3.2%, equivalent to 3.3 and 10% $MgTiO_3$ component, respectively (pers. comm., I.M. Reynolds, 1984). This difference is evident in the plot of the end-member parameters $FeTiO_3$-$MgTiO_3$-$MnTiO_3$ shown in Figure 3. Reynolds (1983) used this diagram to tentatively suggest a trend of decreasing $MgTiO_3$ at constant low $MnTiO_3$, followed by an increase in $MnTiO_3$ as a function of differentiation. The data presented here extend this trend backward from 10% to 20% $MgTiO_3$. There is a bimodality in this plot, with very few compositions between 4 and 12% geikielite component. Those with greater than 4% geikielite content all come from olivine gabbro, whereas those with less geikielite are from granophyre.

Ilmenite from granophyre is more $MnTiO_3$-rich than that from fractionated portions of typical Karoo dolerites. This is probably because the granophyre is not the residuum from fractionation of the basic magma, but is remobilized hornfels, and hence not genetically related to the complex. The high $MnTiO_3$ (pyrophanite) component may be due to crystallization at high oxygen fugacity, as suggested by Czamanske & Mihalik (1972).

There is at least one other example of such high-Mg ilmenite in tholeiitic rocks. It comes from the picrite basalts of the Lebombo area near the border of South Africa and Mozambique (see Bristow & Saggerson 1983, Fig. 1A). Bristow (1980) has analyzed microphenocrysts of ilmenite containing up to 6.1% MgO. The normal Lesotho-type, low-Mg lavas overlying the picrite basalts contain ilmenite with less than 2% MgO. The suggestion is made (Bristow 1980) that high-Mg ilmenite forms from high-Mg magmas. A similar conclusion is favored here, but other possibilities are first assessed.

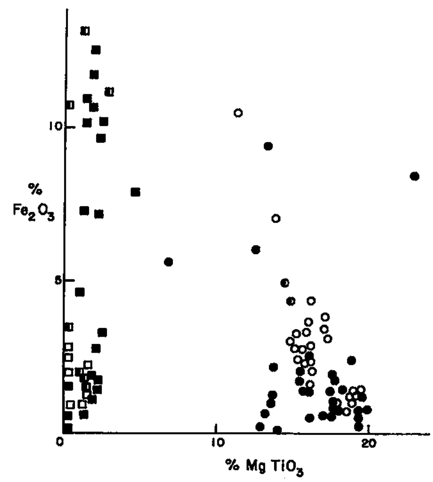

FIG. 4. Calculated Fe_2O_3 content plotted against $MgTiO_3$ content of ilmenite from Insizwa. Symbols as in Figure 2.

Possible subsolidus re-equilibration

A major uncertainty with interpretation of compositions of ilmenite is the possibility of subsolidus re-equilibration. As the grains of ilmenite are very small, only a trivial change in the composition of enclosing mafic minerals or magnetite may have a major effect on the composition of ilmenite (Reynolds 1980). The Insizwa ilmenite is far more Mg-rich than any found in any other Karoo dolerite. It is highly unlikely that subsolidus re-equilibration should have produced such Mg-rich ilmenite *only* at Insizwa. Lack of extensive subsolidus re-equilibration is also supported by the occurrence of similar Mg-rich ilmenite enclosed in sulfide blebs in the marginal gabbro (Tables 1, 2; Groves *et al.*, in press). In view of the virtual absence of Mg in an immiscible sulfide liquid, it would be highly anomalous for magnesian ilmenite to have formed by subsolidus effects. In fact, addition of Fe to the ilmenite would be a far more likely process, particularly by analogy with magnetite rims on magmatic ferrochromite grains in Ni–Cu sulfide ores of komatiitic affinity (Groves *et al.* 1977, 1983).

Bishop (1980) showed that the partitioning of Mg and Fe between ilmenite and pyroxene is temperature-dependent. Cores of hypersthene grains from the basal olivine gabbro at Insizwa have a Mg/(Mg + Fe) value of $\pm$ 0.80, which is more Fe-rich than that determined by Lightfoot & Naldrett (1983) from the originally contiguous Tabankulu body. The most magnesian pyroxene in the olivine gabbro analyzed by them has an Mg/(Mg + Fe) value of 0.87. The temperature can be calculated using the method of Bishop (1980), assuming that the pyroxene has a Mg/(Mg + Fe) value between 0.87 and 0.80, that the value in ilmenite is between 0.22 and 0.12 and that the pressure is 1 kbar. The extremes of temperature range from 880°C to 560°C. Orthopyroxene from the granophyre was not analyzed, and so no calculations of temperature are possible for these rocks. The orthopyroxene rims immediately adjacent to an ilmenite grain have not been analyzed, but it is probable that margins in contact with ilmenite will be more iron-rich, thus increasing the equilibration temperature.

Some subsolidus change in composition almost certainly has occurred, but it is not the *primary* control on the formation of the Mg-rich ilmenite compositions for the following reasons. 1) Ilmenite associated with plagioclase has Mg contents similar to those associated with pyroxene. 2) Ilmenite in the sulfide phase is equally Mg-rich. 3) Mg-poor ilmenite is associated with the granophyres. In view of the close spatial relation between gabbro and granophyre, it would be difficult to imagine this group of compositions not re-equilibrating while the Mg-rich group did. 4) No other ilmenite in Karoo dolerites approaches this proportion of the geikielite component, even though some would have cooled at comparable rates to the Insizwa complex.

Timing of crystallization of ilmenite

Mitchell (1973) suggested that Mg-rich ilmenite forms at high pressure. If so, the Insizwa ilmenite could be interpreted to be a high-pressure xenocryst phase. Although there is a small change in Mg content of ilmenite with pressure (Bishop 1980), Thompson (1976) showed that this is not the sole control.

The ilmenite crystals described here are commonly euhedral and show no signs of disequilibrium with the magma (Fig. 1A). This contrasts with the only other high-Ti ilmenite, mentioned earlier (LeBlanc *et al.* 1982), and with many kimberlite occurrences, where ilmenite occurs in the form of rounded nodules. Hence, the possibility of ilmenite being a high-pressure xenocryst is rejected.

Reynolds (1983) suggested on textural grounds, and Thompson (1976) has shown experimentally, that ilmenite usually crystallizes late in a mafic melt. At that stage, the actual liquid composition from which the ilmenite forms will be evolved and hence Mg-poor and Fe-rich. The typical Mg-poor ilmenite of all other Karoo dolerites may reflect crystallization from such an evolved magma. If this is the case, Mg-rich ilmenite could be produced if it crystallized nearer the liquidus, as shown in Figure 3 of Thompson (1976). This would also be consistent with the euhedral shape of the Insizwa ilmenite.

Presumably, a major control on the appearance of ilmenite is the Ti content of magma. The high-Mg ilmenite found in alkaline magmas (*e.g.*, Anderson 1968) and in kimberlites may reflect the early appearance of ilmenite due to high activity of Ti in the magma. The average TiO_2 content of Karoo dolerites is 0.98% (Eales & Marsh 1979), and of Lesotho-type basalt is 0.95% (Bristow & Saggerson 1983). If such values approximate that of the parental magma to Insizwa, high-Ti liquids can be rejected as the cause for the early crystallization of high-Mg ilmenite.

Other controls on the stability of ilmenite are less certain, but there is another possible factor. Kushiro (1975) demonstrated that the degree of polymerization in a magma has a major effect on mineral stability. Polymerization is controlled by the proportion of network-forming to network-modifying components. The addition of monovalent cations (*e.g.*, Na, K, H) will inhibit polymerization and enhance the stability fields of nonpolymerized minerals. It has been shown elsewhere that addition of such components by contamination of the parental magma at Insizwa may have occurred (Cawthorn 1980, Tischler *et al.* 1981), although this has been disputed by Lightfoot *et al.* (1984). This contamination may have increased the stability field of ilmenite, which is a nonpolymerized phase, causing it to crystallize as a near-liquidus mineral. This would explain the euhedral shape of the ilmenite in Figure 1A, and may also explain the high Mg content of the ilmenite.

Other examples where contamination has occurred can be examined to see if there is evidence of early formation of ilmenite. Mainwaring & Naldrett (1977) attributed the disseminated sulfide mineralization found in the Duluth Complex to contamination. Furthermore, they reported peridotites with up to 15% ilmenite. Such an association is unusual and supports the idea of near-liquidus separation of ilmenite. Unfortunately, no compositions of the ilmenite were published.

Ilmenite from the Sudbury Igneous Complex, another example showing contamination (Naldrett 1981), has been analyzed by Gasparrini & Naldrett (1972). Ilmenite is a minor component in the felsic norites of the North Range, but is virtually lacking in all but the uppermost sequence in the South Range (Naldrett *et al.* 1970). Hence, it appears that early ilmenite is not a feature of this body. Furthermore, none of the ilmenite analyzed contains more than 1% MgO. However, the relationship between the norites and the sulfides is uncertain (Pattison 1979), and they may have been produced from two separate magmatic events.

In other bodies with associated sulfide deposits that may owe their origin to contamination, such as Katahdin, Noril'sk, Sally Malay, Platreef of the Bushveld Complex, there is no indication in the literature of any evidence for the early crystallization of ilmenite. It may be that a detailed search for, and analysis of, ilmenite in these bodies will show petrographic and chemical evidence for its early separation. This could be a potential tool in the exploration for sulfides, but there is insufficient evidence as yet to substantiate such a suggestion. Its application to the Insizwa body is difficult to prove, but it is a possible explanation for the Mg-rich ilmenite.

Control of ilmenite stability by composition of parental magma

Lovering & Widdowson (1968) demonstrated that there is a direct correlation between Mg/Fe ratio in ilmenite with that in the parent rock. The same control was implied by Haggerty (1973), who suggested that a lunar ilmenite with 6% MgO had formed from an ultrabasic magma, although he qualified this by suggesting that it may have crystallized at a high pressure.

Lipman (1971) showed that for acid lavas there is a strong positive correlation between Mg in ilmenite and both eruptive temperature and decreasing SiO_2 content of the whole rock. These data suggest a positive correlation between Mg in ilmenite and in the whole rock. Unequivocal evidence for such a relationship in basic rocks is lacking, but is substantiated by the observations of Bristow (1980), mentioned above; he found magnesian ilmenite only in picritic lavas. The similarity between the Insizwa ilmenite and that in the picrite basalts of Bristow (1980), and the dichotomy of compositions between typical Karoo dolerites (Reynolds 1983) and those from Insizwa, suggest that the Insizwa magma was not a typical low-Mg, Lesotho-type basalt.

Cox (1980) argued that Karoo magmas with ± 7% MgO are not primary magmas but have fractionated olivine. The possibility exists that the Insizwa magma is simply a less-differentiated liquid of the ubiquitous Lesotho-type. However, if this were the case, it ought to fractionally crystallize exactly the same products as the typical Karoo dolerites. In terms of ilmenite it did not. The Insizwa parental magma must have been fundamentally different in some way. Two possibilities appear likely. One is that it belongs to the more picritic magmatic suite more prominent further north in the Karoo Province (Cox 1983). The alternative is that the parental magma assimilated crustal material prior to its final emplacement, a process that also led to the formation of sulfide (Cawthorn 1980). Minor-element content may be used as a discriminant. The typical picrite basalts contain 2 – 3% TiO_2, 300 - 400 ppm Zr and 800 - 1000 ppm Sr (Cox 1983). The Insizwa samples contain $<1\%$ TiO_2, <100 ppm Zr, ± 200 ppm Sr (Lightfoot & Naldrett 1984), and so are distinct from the picrite basalts. Hence, the parental magma to Insizwa was not the same as the picrite, at least in terms of its trace-element content.

The observations and interpretations regarding the presence of ilmenite in the basal portion of the Insizwa complex suggest that it is highly atypical of all other Karoo dolerites. Its Mg-rich composition and its euhedral shape are matched by similar grains in high-Mg basalts, but are not reported from the more abundant Mg-poor lavas of the Karoo Province. These features support the idea that the parental magma to the basal portion of the complex, at least, was Mg-rich.

Nature of the Parental Magma

The debate regarding the composition of the parent magma at Insizwa hinges upon two apparently irreconcilable observations regarding the chilled contact at the base of the complex. The sample analyzed by Scholtz (1937) contains 13.2% MgO and 0.9% modal olivine, suggesting a highly magnesian liquid. In contrast, Lightfoot & Naldrett (1984) presented a composition of a chill-zone sample with 7.1% MgO and concluded that the parental magma was of the low-Mg, Lesotho-type, composition (Eales & Marsh 1979). Both contamination, as shown by the abundance of biotite in the basal zone, documented by Scholtz (1937), and by high SiO_2, Na_2O and K_2O contents, reported by Cawthorn (1980), and olivine accumulation (Eales 1980, Lightfoot & Naldrett 1984) have occurred. As the composition of the low-Mg chill does not plot on the trends shown by the other rocks from the basal zone (Lightfoot & Naldrett 1984, Figs. 9, 10), it is of dubious validity in this debate. Thus the only reasonable resolution is to suggest that the chill zone is heterogeneous and does not offer a reliable estimate of parental magma. Such a conclusion is consistent with current views on chilled margins to layered complexes.

A further complication is added by the suggestions of multiple intrusion (Scholtz 1937, Bruynzeel 1957, Maske 1966, Lightfoot & Naldrett 1983, 1984). The latter authors (1983, p. 182) concluded that for the adjacent body, Tabankulu, which was probably originally contiguous with Insizwa, "the chill and basal olivine gabbro may have formed from a magma that was less depleted in nickel than that responsible for the picrite". The arguments used to make this suggestion apply equally to their data for the basal zone at Insizwa (Lightfoot & Naldrett 1984).

As the sulfide mineralization occurs in the basal olivine gabbro, the composition of the picrites may not be relevant to the interpretation of the origin of the sulfide and its host.

The second approach to gain information on the composition of the parental magma is to study the composition of cumulus minerals. Lightfoot & Naldrett (1984) used the composition of olivine in the picrite to constrain the parent magma to the low-Mg type. Their reasoning is based on the assumption that the mineral analyzed represents the true cumulus composition. This must be questioned on two grounds. Firstly, the olivine grains are reported to be unzoned, but "it is likely that the olivines were originally zoned with magnesium-rich cores" (Lightfoot & Naldrett 1983, p. 177). This zoning has been obliterated during slow cooling. It is the composition of the original core that should be used in the calculations, not the homogenized mineral composition. Secondly, there is an upward increase in forsterite content of the olivine through the basal zone (Scholtz 1937, Bruynzeel 1957, Lightfoot & Naldrett 1984). Such trends, apparently contrary to the expected trends of fractional crystallization, are common in layered complexes. They have been reviewed by Raedeke & McCallum (1984), who concluded that they are due to postcumulus reaction between the true cumulus mineral and progressively less-trapped liquid upward in the sequence. They noted that up to 400 m of the Stillwater stratigraphy may be so affected, with a change of up to 10 mole % forsterite in the olivine compositions near the base. In view of these postcumulus changes, it would seem unwise to place any reliance upon calculations that depend upon the original, but unobtainable, composition of the cumulus mineral.

Apart from the new data on ilmenite compositions and the composition of the chill published by Scholtz (1937), our preference for a magnesian parental magma is based on the following observations. There is up to 100 m of picrite with greater than 60% olivine in the Insizwa, Ingeli and Tabankulu portions of this intrusive complex (Scholtz 1937, Maske 1966, Lightfoot & Naldrett 1983). This represents a very large proportion of olivine in relation to the entire complex. In fact, Maske (1966) calculated a weighted average for the Ingeli body of 13.3% MgO, very similar to the composition of the chill of Scholtz (1937). This could be regarded as an original liquid composition or a highly porphyritic injection of a low-Mg liquid plus entrained olivine, as envisaged by Lightfoot & Naldrett (1984). However, there are significant variations in the Ni content of the olivine through the basal zone (Lightfoot & Naldrett 1984, Lightfoot *et al.* 1984), which would not be expected if the olivine accumulated from suspension in the original liquid, but is consistent with *in situ* crystallization. Also consistent with *in situ* growth is the observation of Bruynzeel (1957, p. 489) that the size of olivine grains increases at progressively higher levels in the basal olivine gabbro. This is to be expected with progressively slower cooling rates, but not if crystals are sinking out of suspension, where the reverse variation in grain size might be anticipated.

The olivine gabbro within 30 cm of the contact on Ingeli shows another unusual feature. Maske (1966, p.24) described the texture as trachyophitic owing to the parallel alignment of many of the olivine crystals, which have "elongation indices of 3:1". This texture is shown in Figure 1B. Such elongate olivine crystals do not normally form from basic liquids but tend to develop from slightly undercooled liquids containing large proportions of normative olivine (Donaldson 1976).

Walker & Poldervaart (1949, p.684) made a study of dolerites throughout South Africa and recognized a Kokstad-type (named after a town 25 km north of Insizwa). This type has notably more olivine than average Karoo dolerite and is particularly abundant in the northern Transkei. They noted that this area represents the deepest portion of the Karoo basin and occupies the focal point of igneous activity. This could explain why more magnesian liquids, and thick and extensive intrusive bodies, are found in the Insizwa area.

SUMMARY

The nature of the parental magma to the mineralized Insizwa complex in Transkei, southern Africa has been debated by Cawthorn (1980) and Tischler *et al.* (1981), who suggested that it is highly magnesian, and Lightfoot & Naldrett (1983, 1984), who regarded it as a low-Mg liquid carrying an excess of suspended crystals of olivine. The use of chill compositions and cumulus mineralogy in resolving this debate is shown to be invalid. Other evidence presented here based on olivine grain-size and shape and the location of this intrusive complex at the centre of igneous activity are *consistent* with the liquid being Mg-rich. However, these data are clearly equivocal.

The occurrence of high-Mg ilmenite at Insizwa, more magnesian than *any* recorded elsewhere from Karoo dolerites, provides a potential discriminant in this debate. There are a number of factors that potentially could explain the occurrence of magnesian ilmenite in the basal units of Insizwa. These include i) a Mg-rich parent liquid, ii) high-pressure crystallization, iii) early crystallization, iv) subsolidus re-equilibration with Mg-rich silicate phases and v) contamination. From the evidence presented here, near-liquidus crystallization of magnesian ilmenite from a Mg-rich parent liquid is preferred. Indirect support for a hotter, more Mg-rich liquid comes from the relative abundance of crustal remelts (granophyres) near the base of the Insizwa complex at Waterfall Gorge and the degree of assimilation of country rocks, as indicated by abundant biotite in the olivine gabbros (Scholtz 1937). The Waterfall Gorge section is also anomalous on the scale of the Karoo Province because of the occurrence of Ni–Cu sulfide ores, and in this respect the interpretation of Insizwa as due to the intrusion of a high-Mg melt is not surprising.

The possibility exists that the crystallization of Mg-rich ilmenite is related to formation of an immiscible sulfide liquid. A search of the literature reveals that anomalous concentrations of ilmenite may occur in some contaminated intrusive complexes (*e.g.*, Duluth Complex), but there are no compositional data on ilmenite from such situations. If contamination could influence the composition of ilmenite, it would be a potential tool for exploration, analogous to chromite from komatiite-associated Ni–Cu sulfide deposits (*e.g.*, Groves *et al.* 1983). However, in the absence of such data, the formation of high-Mg ilmenite from an anomalously Mg-rich parent magma at Insizwa is most likely.

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