



Compositional classification of “kimberlitic” and “non-kimberlitic” ilmenite

Bruce A. Wyatt^{a,*}, Mike Baumgartner^b, Eva Anckar^c, Herman Grutter^d

^a*De Beers Canada Exploration Inc., 1 William Morgan Drive, Toronto, Ontario, Canada M4H 1N6*

^b*Mineral Services South Africa, Cape Town 7430, South Africa*

^c*University of Cape Town Kimberlite Research Group, Cape Town 7700 South Africa*

^d*Mineral Services Canada, North Vancouver, British Columbia, Canada V7P 3S7*

Received 27 June 2003; accepted 14 December 2003

Abstract

Ilmenite is one of the common kimberlitic indicator minerals recovered during diamond exploration, and its distinction from non-kimberlitic rock types is important. This is particularly true for regions where these minerals are present in relatively low abundance, and they are the dominant kimberlitic indicator mineral recovered. Difficulty in visually differentiating kimberlitic from non-kimberlitic ilmenite in exploration concentrates is also an issue, and distinguishing kimberlitic ilmenite from those derive from other similar rocks, such as ultramafic lamprophyres, is practically impossible. Ilmenite is also the indicator mineral whose compositional variety has the most potential to resolve provenance issues related to mineral dispersions with contributions from multiple kimberlite sources.

Various published data sets from selected kimberlitic (including kimberlites, lamproites, and various ultramafic lamprophyres) and non-kimberlitic rock types have been compiled and evaluated in terms of their major element compositions. Compositional fields and bounding reference lines for ilmenites derived from kimberlites (*sensu stricto*), ultramafic lamprophyres, and other non-kimberlitic rock types have been defined primarily on MgO–TiO₂ graphs as well as MgO–Cr₂O₃ relationships.

© 2004 Elsevier B.V. All rights reserved.

Keywords: Picroilmenite; Geikielite; Hematite; Kimberlite; Exploration; Classification

1. Introduction

Ilmenite, together with pyrope garnet and chromite, is one of the dominant indicator minerals found in kimberlite. The ilmenite present in kimberlites derives from a number of sources (see, e.g., Mitchell, 1973,

1977, 1986; Haggerty, 1975, 1976, 1991), but most commonly as discrete ilmenite xenoliths belonging to the megacryst suite of minerals (Schulze, 1987; Schulze et al., 1995), ilmenites of metasomatic origin (Wyatt and Lawless, 1984; Harte, 1987; Haggerty, 1989; Dawson et al., 2001; Moore and Lock, 2001), ilmenites intergrown with megacrysts, MARID (Dawson and Smith, 1977), and Granny Smith silicates (Boyd et al., 1984), and groundmass ilmenite and phenocrysts in the host magma (Tompkins and Haggerty, 1985; Mitchell, 1986; Moore, 1987). Less com-

* Corresponding author. Tel.: +1-416-423-5811x225; fax: +1-416-423-9944.

E-mail address: bruce.wyatt@ca.debeersgroup.com (B.A. Wyatt).

mon sources of ilmenite in kimberlite include primary ilmenites from disaggregated peridotite (both cold-coarse and hot-deformed varieties) and eclogite xenoliths, and rare ilmenites included in diamond (Meyer and Svisero, 1975; Sobolev and Yefimova, 2000). Ilmenites are also present in a wide variety of non-kimberlitic igneous (gabbros, norites, granites, and anorthosites) and metamorphic (orthogneisses) rocks that may occur in areas hosting kimberlite intrusions. In Southern Africa, ilmenites are present in the volcanic successions of Karoo lavas (Bristow, 1980), and in other gabbroic and picritic intrusions such as those found in the Mount Ayliff Intrusion of the Insizwa Complex in Transkei (Cawthorn et al., 1988).

The distinction of ilmenites derived from kimberlitic versus non-kimberlitic rocks is important in the context of diamond exploration in regions in which ilmenites are present in relatively low abundance but where they are the dominant kimberlitic indicator mineral recovered. Ilmenite is also the indicator mineral whose compositional variety could be used to greatest effect in provenance studies related to mineral dispersions with contributions from one or more kimberlite sources. This study focuses on a simple and practical scheme for separating kimberlitic from non-kimberlitic ilmenite on the basis of major element compositions, but does not address the detailed analysis of crystal–chemical issues and phase relationships that are the subject of comprehensive studies such as Haggerty (1976, 1991), Haggerty and Tompkins (1984), Tompkins and Haggerty (1985), and references referred to therein.

Because ilmenite is a key kimberlitic indicator mineral, its correct identification is critical, yet the visual distinction of kimberlitic from non-kimberlitic ilmenite during the extraction of these grains from exploration sample concentrates is imperfect. In addition, ilmenite populations derived from kimberlites or lamprophyres share similar mantle-derived petrogenetic origins but have different significance in the context of diamond exploration. Visually differentiating kimberlite derived ilmenite from grains derived from similar ultramafic rocks, such as ultramafic lamprophyres, is practically impossible, even for highly trained mineral sorters. The latter problem is a direct result of a compositional overlap in the range 4 to 6 wt.% MgO, as well as the visual similarity of ilmenites having 4 to 18 wt.% MgO

which represents the compositional range of ilmenite from kimberlites and related rocks. This study highlights the need to determine the compositions and paragenesis of ilmenites extracted from exploration sample concentrates by analytical means, particularly during early phase reconnaissance.

2. Methods and data sources

The compositions of ilmenite derived from potentially diamondiferous sources (kimberlites and lamprophyres) and other non-kimberlitic sources (e.g., ultramafic lamprophyres, basalt, and gabbro) have been compiled from selected published and internal Mineral Services and De Beers data sets. Compositional fields for ilmenites derived from kimberlites (*sensu stricto*), and other non-kimberlitic rock types have been defined on selected bivariate graphs and form the basis of a robust and simple classification scheme. Ilmenite MgO–TiO₂ diagrams (Sobolev, 1977) are particularly useful to discriminate kimberlitic from non-kimberlitic ilmenite compositions. Equations for kimberlitic and non-kimberlitic reference lines that are given in the text below are for convenience and can be used to filter ilmenite analyses for classification purposes using a simple spreadsheet.

Sobolev (1977, Fig. 42) utilised a MgO–TiO₂ plot overlaid with Fe₂O₃ contours to display various kimberlitic ilmenite populations, which was also used to make some inferences regarding the oxidising environment. In this study, we have inserted reference lines of constant hematite content in scatter plots of TiO₂ versus MgO. The Fe₂O₃ contents of the ilmenites were calculated stoichiometrically using Finger (1972), and the isopleths were established empirically using contours of the data on the TiO₂ versus MgO plots. These stoichiometric Fe₂O₃ reference contours are based on the kimberlite data set discussed below, and are only an indication of the hematite content. They can be used to assess data quality. For example, data points should not plot above the 0% Fe₂O₃ contour (implying negative Fe₂O₃ content) and such analyses should be scrutinised for quality. In many cases inconsistencies, especially for non-kimberlitic ilmenite, may be due to the microprobe beam inadvertently impinging on submicroscopic rutile inclu-

sions resulting in abnormally high TiO₂ content (and often high totals). In some cases, such analyses may in fact derive from other high-TiO₂ minerals such as the pseudobrookite series or Nb–Ta-rich rutiles. While the contours illustrate that the Fe₂O₃ content of ilmenites increases with decreasing TiO₂, extreme caution should be used in attempting to infer the *f*O₂ environment associated with the ilmenites. The reader is referred to Haggerty (1976, 1991), Haggerty and

Tompkins (1984), Tompkins and Haggerty (1985) and references therein for a full discussion of ilmenite, Fe₂O₃ and *f*O₂ systematics.

Bivariate graphs of MgO versus Cr₂O₃ (after Haggerty, 1975, 1976, 1991) are also presented for selected data sets. Such graphs, which are commonly used by the diamond exploration fraternity, illustrate certain compositional criteria that also aid in the distinction of kimberlitic from non-kimberlitic ilmenites.

Table 1
Paragenesis and data sources used in this study

Paragenesis ^a	Region	Localities (no. grains) ^b	Data source ^c
Kimberlites Off-craton	Southern Africa	Abiquaputs ^o (5), Amalia ^o (1), Andries ^o (46), Berseba ^o (11), Brandvlei ^o (20), Deutsche Erde II ^o (3), East Griqualand ^o (6), Gibeon ^o (51), Hebron ^o (37), Lichtenfels ^o (6), Nouzees ^o (78), Pofadder ^o (1), Uintjiesberg ^o (33), Witputs ^o (94)	UCT–KRG
Kimberlites On-craton	Southern Africa	Balmoral ^l (50), Borrelskop [*] (37), Bultfontein [*] (46), De Beers [*] (2), Dutoitspan [*] (2), Frank Smith [*] (62), Franspoort ^l (835), Goedehoop ^l (47), Good Hope ^l (49), Jagersfontein [*] (1), Kimberley [*] (53), Koffiefontein [*] (6), Last Hope ^l (50), Monastery [*] (159), Montrose ^l (6), Palmietfontein ^l (21), Premier [*] (329), Riverton ^l (4), Schuller ^l (222), Smithdale ^l (7), Victoria ^l (50), Washington ^l (52), Wesselson [*] (3)	UCT–KRG
Kimberlites	West Africa	Sierra Leone-Koidu [*] (52), Liberia [*] (33)	UMASS
Kimberlites	North America	Attawapiskat [*] (33), Dry Bones Bay ^l (148), Iron Mountain ^l (54), Kelsey Lake ^l (2), Kirkland Lake ^l (558), Lake Ellen ^l (4), Lake Temiskaming ^l (135), Mt. Horeb Church ^l (2), Stockdale ^l (42), Williams ^l (93)	Schulze et al. (1995)
Kimberlites	Australia	Cleve ^b (1343), Skerring ^b (261)	DBGSC
Kimberlites	Siberia	Udachnaya [*] (975), Mir [*] (1654)	DBGSC
Kimberlites	Southern Africa, N. America, Russia	Various—see text	UMASS
KRR–Melnoite	Southern Africa	Entilombo (1417)	DBGSC
KRR–Melnoite	Malaita	Malaita (901)	DBGSC
KRR–Melnoite	Australia	Lake Bullenmerrie (92)	DBGSC
KRR–Melnoite	Canada	Selco Alnoites (95)	Sage (2000)
KRR	Namibia	Okenyanya (45)–Ultramafic Lamprophyre	Baumgartner (1994)
NK–Gabbro	Namibia	Okenyanya (55)	Le Roux (UCT) (pers. comm.)
NK–Dolerite	South Africa	Insizwa Gabbro (58), Insizwa Picrite (163)	Cawthorne et al. (1988)
NK–Karoo Basalt	Botswana	Bobonong (1564)	DBGSC
Prospecting	Canada	Slave Province (4743)	DIAND NWT
Prospecting	Southern Africa	Soil sampling programme: Southern Africa (142)	Mineral Services

^a KRR: Kimberlite-related rock. NK: Non-kimberlitic.

^b Locality or area from which the ilmenites derive. Numbers in () refer to no. of grains. NOTE: Diamond content of primary kimberlites: o—barren; l—at best low (subeconomic); *—near economic or economic. All other rock types are barren.

^c UCT–KRG: University of Cape Town—Kimberlite Research Group. UMMASS: University of Massachusetts 1987 Ilmenite Database given to UCT by Steve Haggerty in the late 1980s. DBGSC: De Beers GeoScience Centre. DIAND NWT: Department of Indian and Northern Affairs, North West Territories, Canada—Geology Division, Kimberlite Indicator Mineral Chemistry Database, Slave Province. Schulze et al. (1995)—data available from web site: <http://www.geology.utoronto.ca/faculty/schulze/ilmenite.html>.

Table 2 (continued)

Statistic	Entilombo melnoite (De Beers) $n=1417$					Selco alnoites (Sage, 2000) $n=96$				
	Min	Median	Max	Mean	S.D.	Min	Median	Max	Mean	S.D.
SiO ₂	0.00	0.00	0.44	0.00	0.02	0.00	0.01	0.10	0.02	0.01
TiO ₂	44.48	47.81	57.56	47.77	1.50	41.51	51.31	53.96	50.19	2.56
Al ₂ O ₃	0.04	0.47	0.83	0.47	0.07	0.00	0.33	1.20	0.34	0.17
Cr ₂ O ₃	0.00	0.09	1.44	0.11	0.10	0.00	0.10	2.94	0.20	0.36
FeOt	28.11	43.61	49.49	43.59	2.27	27.48	38.39	49.87	39.77	3.82
MnO	0.25	0.35	0.64	0.35	0.03	0.08	0.27	1.91	0.30	0.19
MgO	0.40	6.55	14.69	6.62	1.03	3.14	8.30	14.67	7.65	1.79
CaO	0.01	0.04	0.13	0.04	0.01	0.00	0.02	0.10	0.02	0.02
NiO						0.00	0.05	0.24	0.06	0.04

Statistic	Non-kimberlitic ilmenite (Insiswa data) $n=277$					Non-kimberlitic ilmenite (Bobonong Karoo data) $n=1564$				
	Min	Median	Max	Mean	S.D.	Min	Median	Max	Mean	S.D.
SiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.01	0.04
TiO ₂	49.52	53.36	57.43	53.48	2.17	43.79	49.95	54.96	49.77	1.29
Al ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.29	5.32	0.30	0.19
Cr ₂ O ₃	0.04	0.48	1.08	0.46	0.26	0.00	0.17	1.16	0.22	0.19
FeOt	32.39	38.65	48.11	40.11	4.79	35.11	45.49	51.08	45.21	1.69
MnO	0.40	0.51	1.35	0.58	0.23	0.09	0.40	2.91	0.42	0.18
MgO	0.28	6.20	10.22	5.06	3.07	0.13	3.31	10.11	3.37	1.10
CaO						0.00	0.02	0.30	0.02	0.02

was extracted from the University of Cape Town (UCT) Kimberlite Research Group (KRG) database (Table 1), and only from kimberlite localities allocated to that specific country and marked as Group I kimberlites. Because the KRG database is constantly being updated and the various locality related information upgraded on an ongoing basis, the South Africa and Namibia kimberlite data do not represent the full set of data available for localities in these two countries. Additional regional analyses in the University of Massachusetts (UMASS) ilmenite database from various localities (Table 1) were utilised as an independent data set to test the consistency of the data used to establish ilmenite reference lines, but as they generally embrace the same localities referred to above, they are not included in the data statistics in Table 2. The non-kimberlitic Insiswa and Karoo ilmenite data sets were obtained from tables in published references (Cawthorn et al., 1988), and through the extraction of element contents directly from incorporated bivariate plots.

It is assumed for this study that the majority of the compiled compositions represent analyses of the cores of ilmenite grains. However, core versus rim compositions are distinguished by Schulze et al. (1995) for

several of the North America kimberlite localities. The compositional trends observed in these data and implications for the classification scheme are discussed further in the latter part of this manuscript.

In a sense, we have not taken our own advice, and the mineral composition data utilised in this study have not been screened to exclude poor quality data based on the calculated Fe₂O₃ contours. However, this has been done intentionally to highlight the fact that, in reality, such analyses do occur during the routine analysis of exploration samples, and such data should be viewed as suspicious by the recipient.

3. Results

3.1. Kimberlitic ilmenites

Mineral compositions for ilmenites derived from Southern African kimberlite concentrates (Table 1) were separated into on-craton and off-craton localities. Fig. 1A and B are bivariate MgO–TiO₂ plots for the off-craton and on-craton Group I kimberlites, respectively. Fig. 2A and B show the same data plotted in MgO–Cr₂O₃ space, which was first used by Haggerty

(1975, 1976) to identify a parabolic arc typical of many kimberlitic ilmenite populations (see also Fig. 13 of Haggerty, 1991). The compositional ranges of the on-and off-craton ilmenites are given in Table 2.

An arc encompassing approximately 90% of the data has been estimated on the MgO–TiO₂ plots. The area to the MgO–rich side of the arc is defined as the “Kimberlitic” ilmenite field. This kimberlitic ilmenite

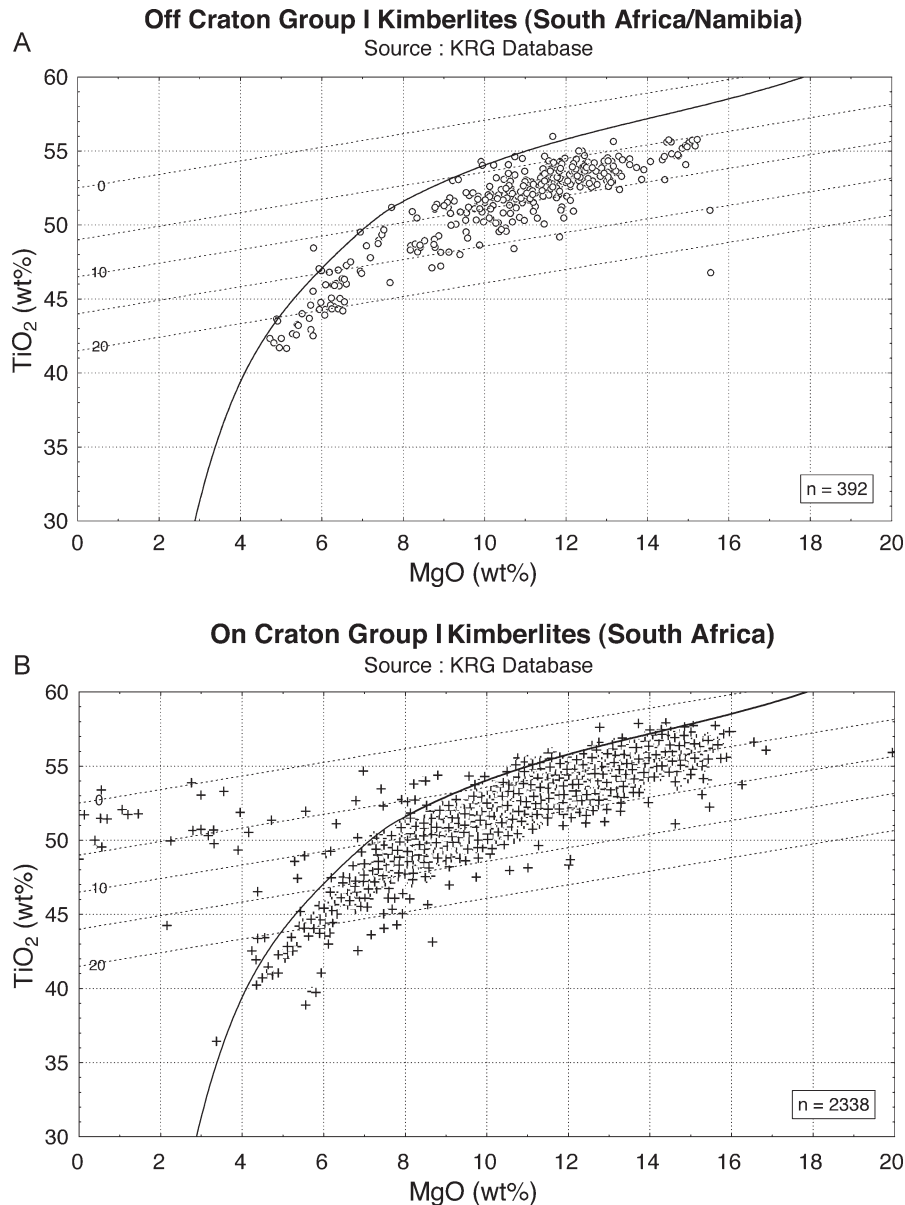


Fig. 1. Plot of MgO versus TiO₂ for (A) off-craton group I kimberlites from South Africa and Namibia, and (B) on-craton group I kimberlites from South Africa. The black line represents the bounding reference line of the kimberlitic ilmenite field. Percentage Fe₂O₃ was calculated using simple ilmenite stoichiometry (Finger, 1972) for individual analyses, and lines of equal Fe₂O₃ were contoured from the data set (dashed light-grey). These lines are also displayed on subsequent MgO–TiO₂ plots for reference (see text).

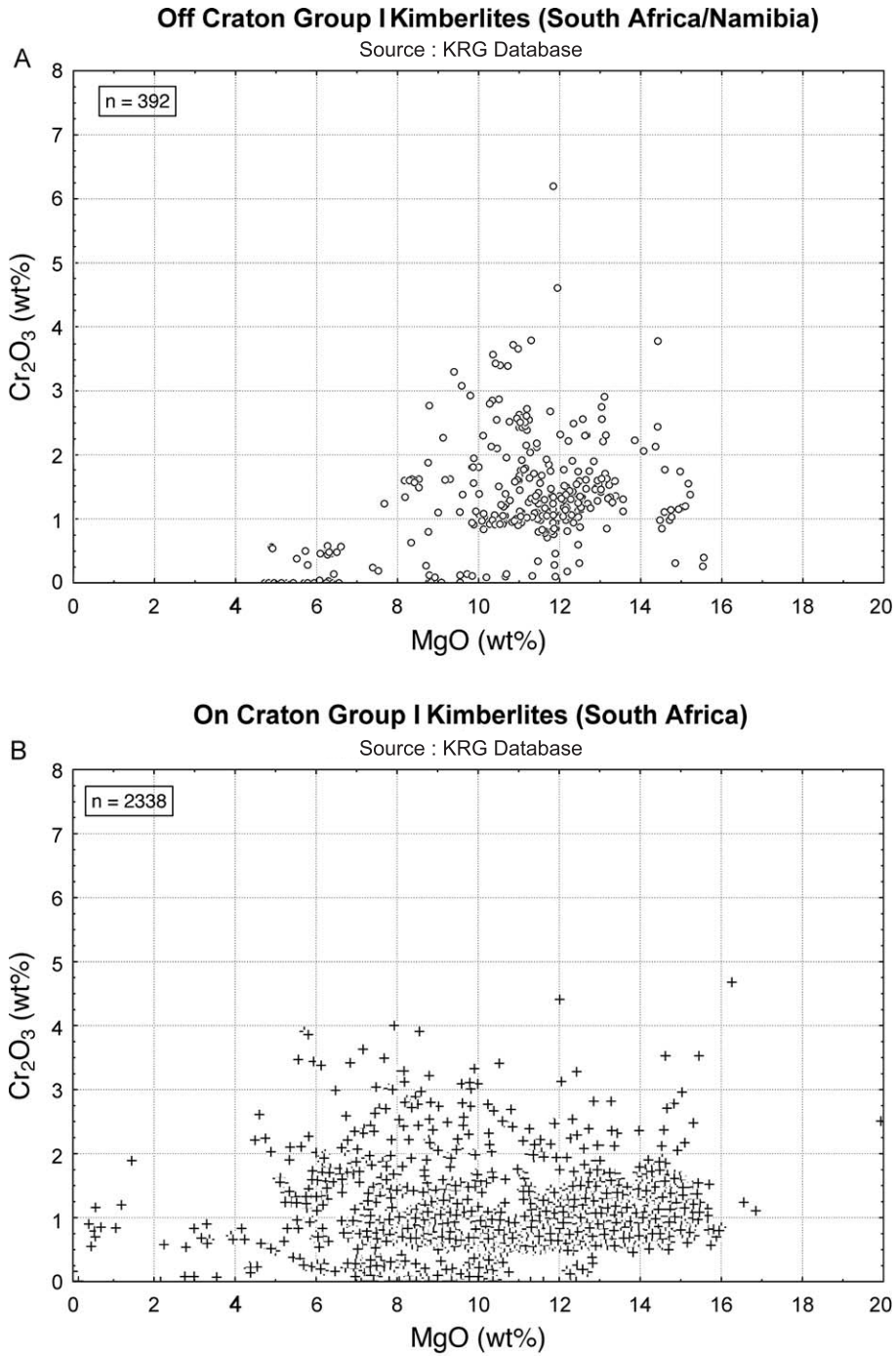


Fig. 2. Plot of MgO versus Cr₂O₃ for (A) off-craton group I kimberlites from South Africa and Namibia, and (B) on-craton group I kimberlites from South Africa.

reference line is well defined by the ilmenite compositions from both the off-craton and on-craton localities at MgO contents between 4 and 15 wt.% (Fig. 1). Below 8 wt.% MgO, the kimberlite compositional arc is defined by the following quadratic equation:

$$y = -51.9078 + 52.8316x - 11.5519x^2 + 1.2003x^3 - 0.0475x^4.$$

Above 8 wt.% MgO, the arc is defined by the following cubic equation:

$$y = 28.5188 + 4.7521x - 0.287x^2 + 0.0067x^3.$$

It is stressed that these equations are a convenient way to define a bounding or limiting reference curve applicable to kimberlites on a world wide basis. This bounding curve can be used as an aid in assessing the kimberlitic characteristics of individual ilmenite grains found in prospecting grains. However, as discussed further below, individual kimberlite localities comprising a population of ilmenites may define different but approximately parallel arcs. Grade categories for the kimberlites are given in Table 1. All the

off-craton kimberlites are barren or extremely low grade and most of the on-craton bodies have at least some diamonds, and based on these data, there is no obvious systematic relationship between grade and the MgO–TiO₂ relationships.

In order to assess the broader applicability of the kimberlitic ilmenite reference arc defined by Southern African sources, the MgO–TiO₂ relationships of ilmenite in mineral concentrates from selected North American, Siberian, Australian, and West Africa kimberlites (Table 1) are shown in Figs. 3–6, respectively. The compositional statistics are given in Table 2.

For the North America data, all but one of the 1071 available analyses fall to the MgO-rich side of the defined arc. The North America kimberlitic ilmenite compositions extend to lower MgO content than those from Southern Africa, and hence aid in defining the kimberlitic ilmenite field boundary at very low MgO contents (Fig. 3).

The Siberian data represented on Fig. 4 includes analyses from the Udachnaya and Mir kimberlites, and the vast majority of the data points plot well to the right of the kimberlitic ilmenite reference line. The Siberian data presented here could be used to define its own well-constrained line, but this would not be universally

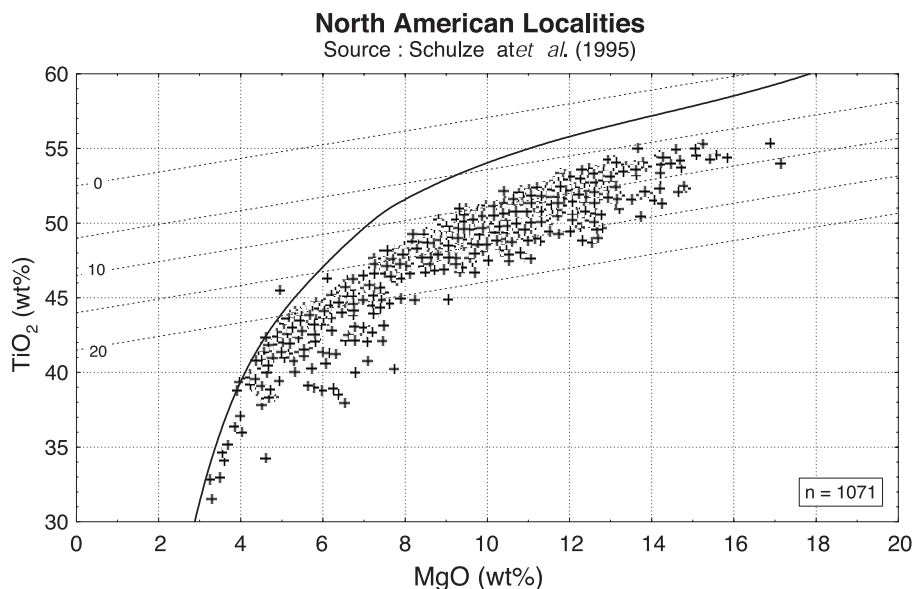


Fig. 3. Plot of MgO versus TiO₂ for ilmenite from North America kimberlites (data of Schulze *et al.*, 1995). Symbology as for Fig. 1.

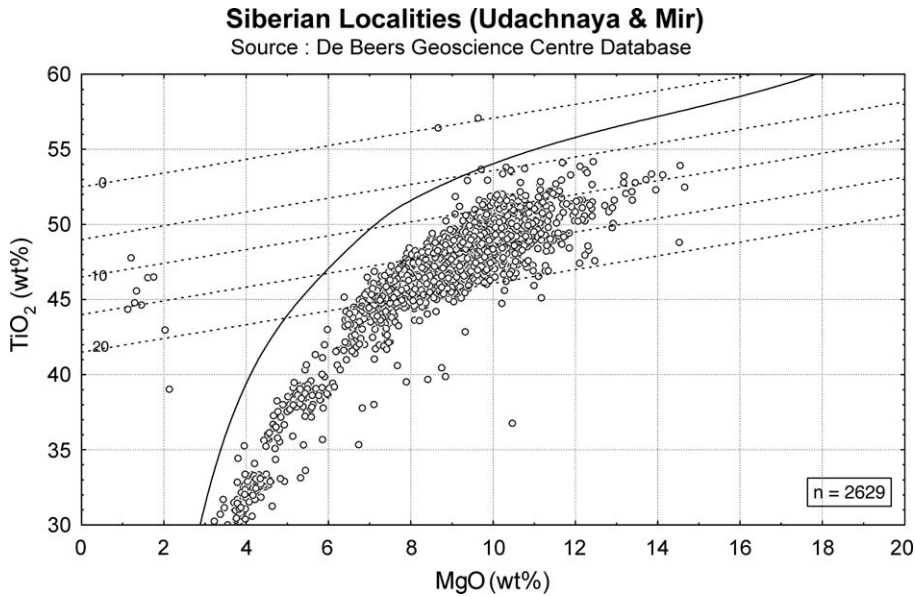


Fig. 4. Plot of MgO versus TiO₂ for ilmenite from Siberia kimberlites. Symbology as for Fig. 1.

applicable because much of the Southern African data would fall to the low-Mg side of such a line.

The Australian data includes ilmenite analyses from the Cleve-1 and Skerring kimberlites located in South and North Australia, respectively (Fig. 5). As

with the North America localities, over 90% of the data points plot to the MgO-rich side of the kimberlitic ilmenite reference line. These data actually show a very similar compositional trend to the kimberlites from Southern Africa.

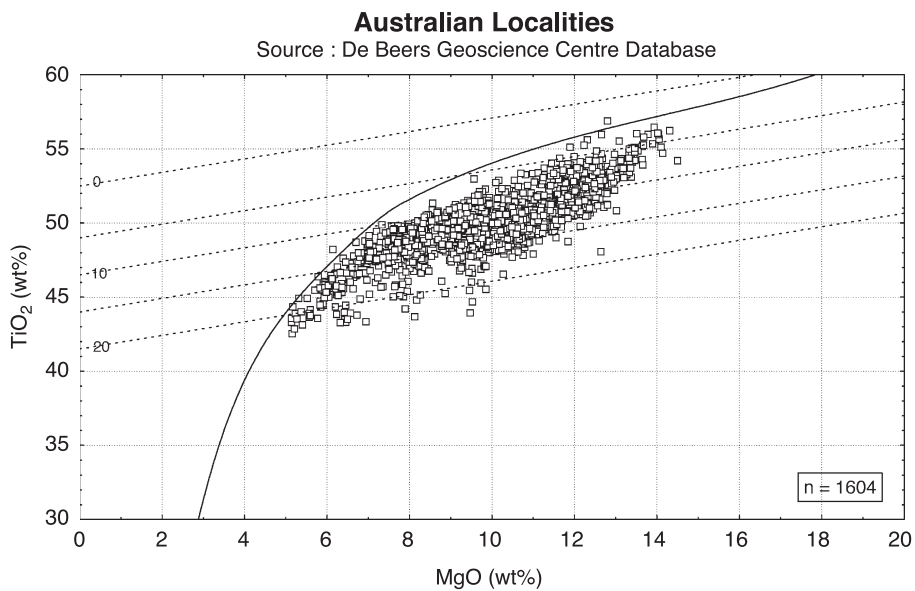


Fig. 5. Plot of MgO versus TiO₂ for ilmenite from Australia kimberlites. Symbology as for Fig. 1.

The West African ilmenites (Fig. 6) are divided into various ilmenite types according to the divisions listed in the UMASS ilmenite database. It is evident in Fig. 6 that a significant proportion of the ilmenites fall to the low-Mg side of kimberlitic reference line, and while these mostly relate to groundmass ilmenites, there are a number of discrete ilmenite nodules and bimineralic associations that also fall in this area. Most of the discrete nodules in the non-kimberlitic field are from the Liberian data, while most of the groundmass ilmenites in the non-kimberlitic field are from Sierra Leone. These ilmenites all contain elevated MnO contents, with the proportion of MnO to MgO increasing to lower MgO contents. A high proportion of these have slightly elevated or elevated Cr_2O_3 (more than approximately 0.25 and 0.5 wt.%, respectively) which approach typical kimberlitic values. Elevated MnO in ilmenites from Koidu, Sierra Leone (Haggerty and Tompkins, 1984; Tompkins and Haggerty, 1985) and MnO enrichment trends evident in some Monastery ilmenites (Haggerty et al., 1979) were attributed to late-stage carbonate and $\text{CO}-\text{CO}_2$ reactions in the kimberlite. In a practical sense, most groundmass

ilmenites would not report to heavy mineral concentrates in exploration samples, most being less than approximately 0.3 mm in diameter. The relatively few data compiled for the group I kimberlites that fall to the low-MgO side of the kimberlite reference line (Fig. 1b) could be similar late-stage ilmenites, or possibly spurious non-kimberlitic ilmenites incorporated into the kimberlite from disaggregated country rock xenoliths.

It is noted that carbonatites can contain high-MnO ilmenites, often also associated with high-MgO contents (see, e.g., Haggerty, 1976, table Hg-16(3) and Hg-20(9); Haggerty, 1991). Such ilmenites, however, seldom contain high- Cr_2O_3 contents (rarely more than approximately 0.3 wt.%).

Ilmenites from various Southern African, North American, and Russia localities extracted from the UMASS database (Table 1), which were not used in defining the kimberlitic reference line discussed above, are shown in Fig. 7. These data represent an independent confirmation of the applicability of the reference line. While a few of the data clearly fall on the non-kimberlitic side of the reference line, the majority are within the kimberlitic field.

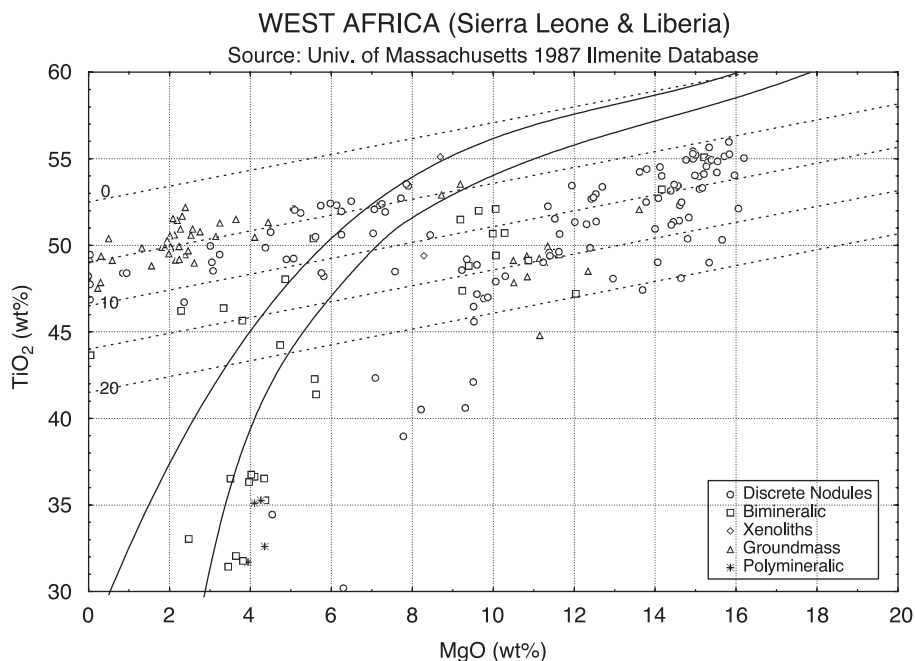


Fig. 6. Plot of MgO versus TiO_2 for ilmenite from West Africa kimberlites. Symbology as for Fig. 1.

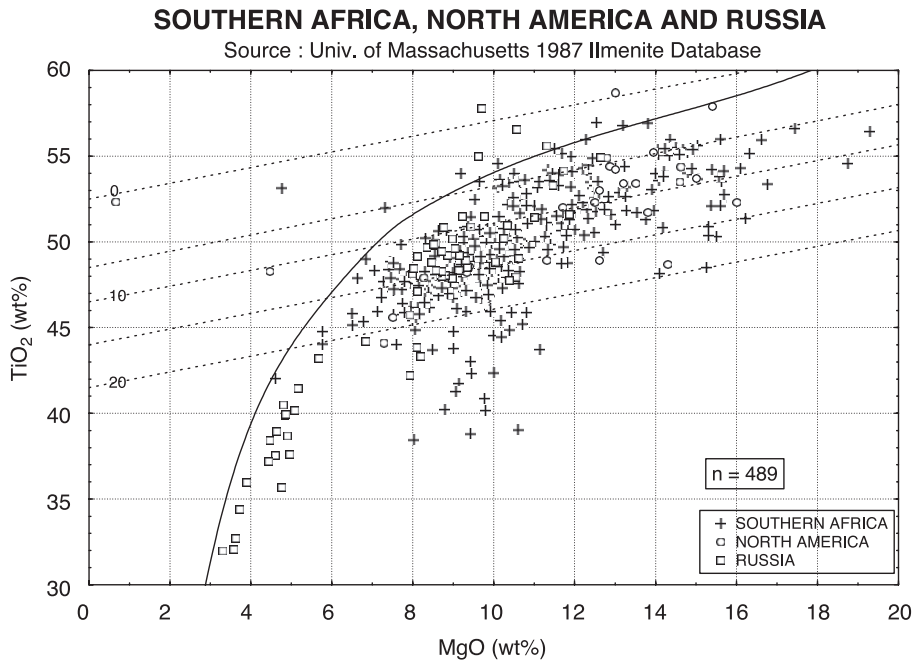


Fig. 7. Plot of MgO versus TiO₂ for ilmenite from Southern Africa, North America, and Russia. Symbology as for Fig. 1.

In summary, we have chosen the arc defined by the Southern African sources as the kimberlitic ilmenite reference line as it would correctly classify kimberlitic ilmenites from a variety of kimberlite sources.

For comparative purposes, the ilmenite data from North America, Siberia, and Australia are also shown in MgO–Cr₂O₃ compositional space in Figs. 8–10. These data reinforce the notion that a high proportion of kimberlitic ilmenites have elevated Cr₂O₃, some of which also display a parabolic MgO–Cr₂O₃ relationship (Haggerty, 1975, 1976, 1991). However, it is noted that while this ‘parabolic’ relationship is relatively common, it is by no means universal. Often only the right hand limb is present, and both base and position of the limb vary in MgO–Cr₂O₃ space (see, e.g., Smith, 1977; Egglar et al., 1979; Apter et al., 1984; Schulze, 1984; Moore, 1987; Wyatt et al., 1994; Orr, 1998; Graham et al., 1999).

3.2. Non-kimberlitic ilmenites

A variety of sources were used to define a compositional reference line for non-kimberlitic ilmenites. These included abundant ilmenite compo-

sitions from gabbros and picrites that form part of the Mount Ayliff Intrusion (Insizwa Complex), ilmenites from Karoo Basalts in the Bobonong area of Botswana, and groundmass ilmenites in gabbroic phases of the Okenyanya Igneous Complex in Namibia (Table 1). The major element MgO versus TiO₂ compositions for the Insizwa and Okenyanya non-kimberlitic ilmenites are presented in Fig. 11, and the Bobonong ilmenites is given in Fig. 12. The non-kimberlitic ilmenites (Table 1) have lower MgO contents at equivalent TiO₂ values than ilmenites derived from kimberlites (Figs. 1, Figs. 3 Figs. 4 Figs. 5). Note that this non-kimberlitic reference line is a measure of the likely maximum MgO limit, at a given TiO₂ value, for non-kimberlitic ilmenites, irrespective of the fact that the trend within individual data sets is often subparallel to the Fe₂O₃ contours and oblique to the reference line. Thus, most non-kimberlitic ilmenites will plot to the left of the non-kimberlitic arc, and kimberlitic ilmenites to the right of the kimberlitic arc. The area between these arcs, therefore, represents an area of uncertainty that will require additional information, such as Cr₂O₃ and/or MnO

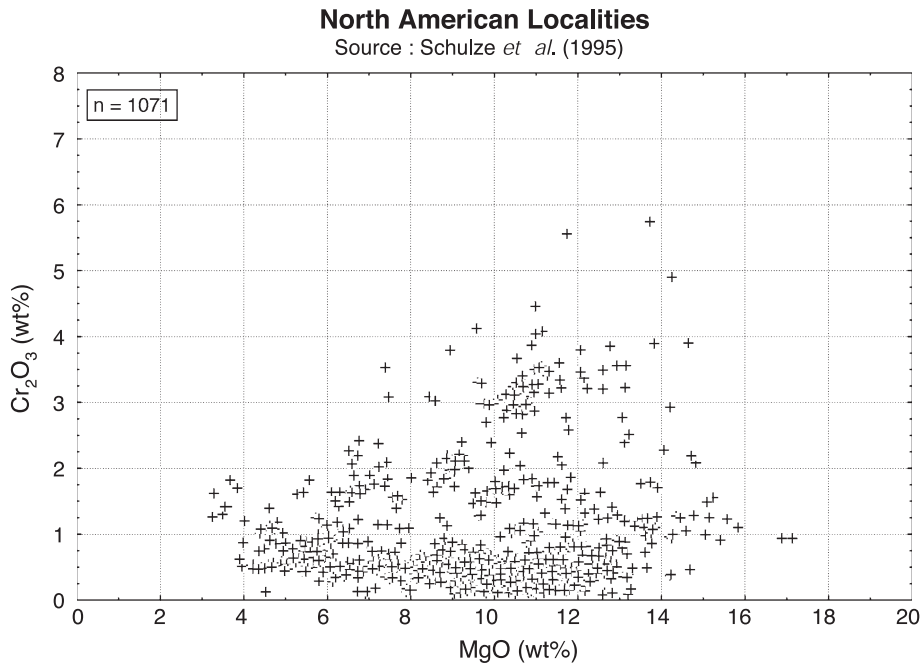


Fig. 8. Plot of MgO versus Cr₂O₃ for ilmenite from North American kimberlites.

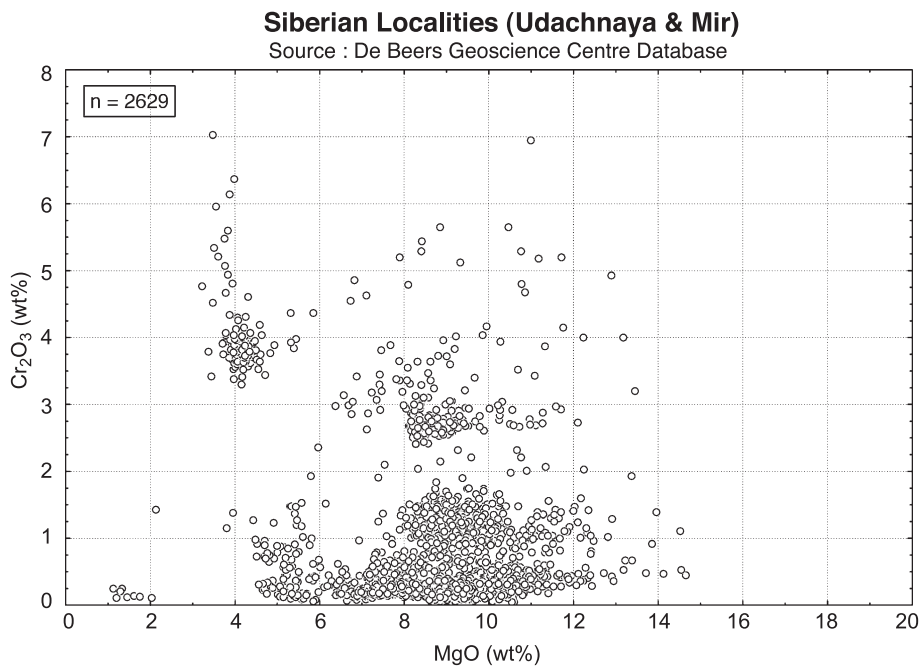


Fig. 9. Plot of MgO versus Cr₂O₃ for ilmenite from Siberian kimberlites.

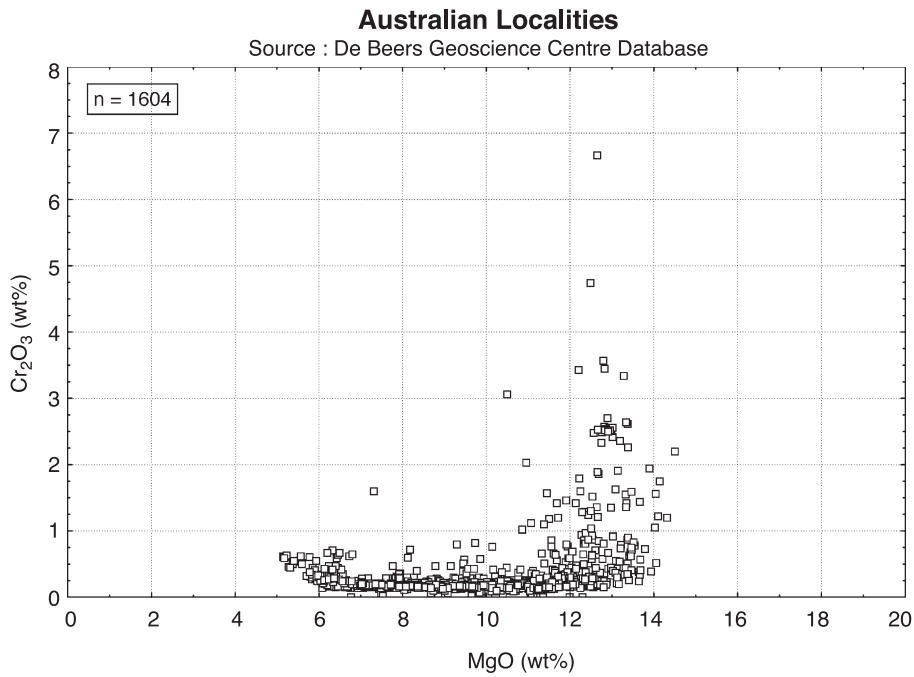


Fig. 10. Plot of MgO versus Cr₂O₃ for ilmenite from Australian kimberlites.

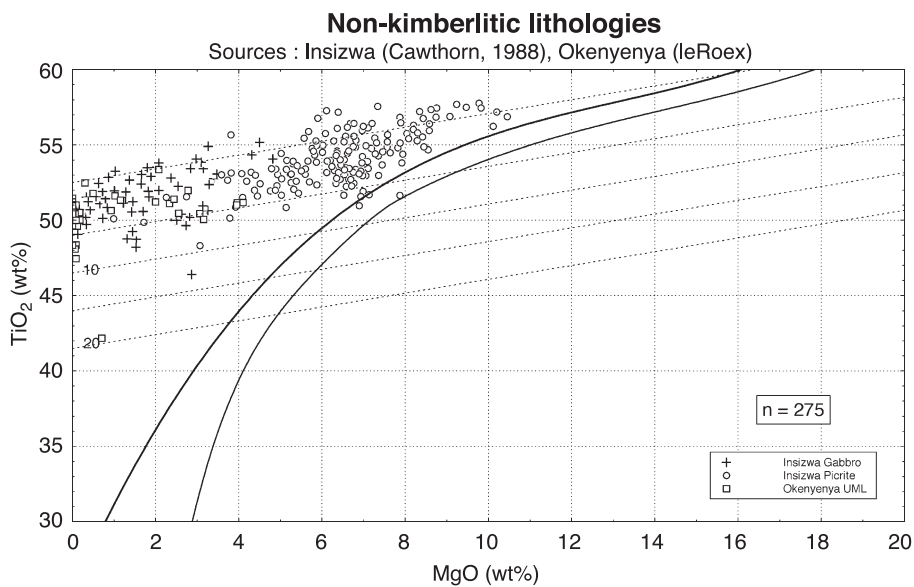


Fig. 11. Plot of MgO versus TiO₂ for non-kimberlitic rocks from Insiwa and Okenyenya (data from Cawthorn et al., 1988, and le Roex, pers. comm.). Percentage Fe₂O₃ contours (from Fig. 1) are shown as the dashed light-grey lines. The black line at lower MgO represents the chosen bounding reference line of the non-kimberlitic ilmenite field. The black line at higher MgO represents the bounding reference line of kimberlitic ilmenite compositions defined localities in South Africa and Namibia (Fig. 1).

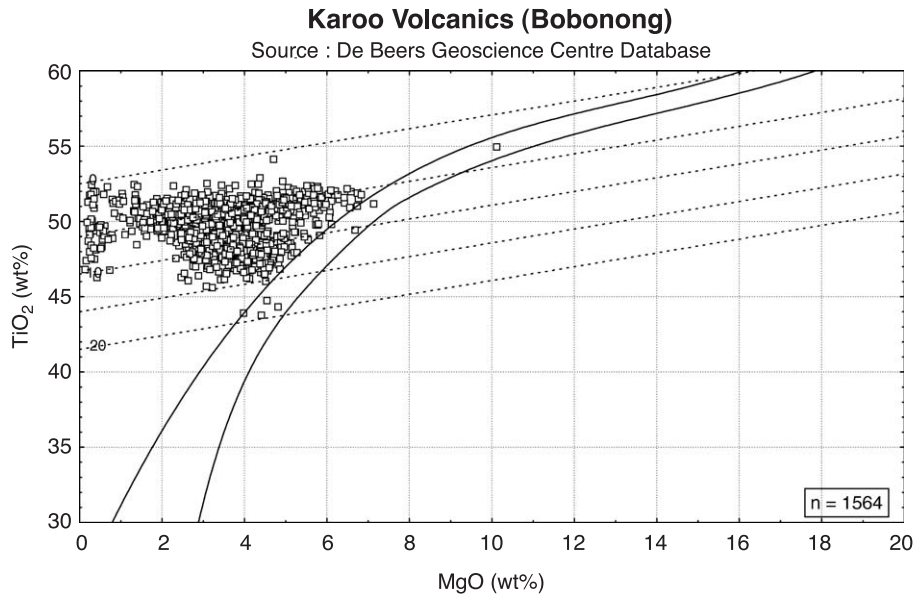


Fig. 12. Plot of MgO versus TiO₂ for non-kimberlitic Karoo volcanics from the Bobonong Area in Botswana. Symbology as for Fig. 11.

contents, before a paragenesis can be attributed. Non-kimberlitic ilmenites also usually have less than 1.0 wt.% Cr₂O₃ and, with few exceptions, have less than 0.5 wt.% Cr₂O₃. This is well illustrated in the major element statistics presented for the Insizwa and Karoo Data in Table 2. Note that several data points, especially those from Insizwa, fall just above the 0 wt.% Fe₂O₃ line in the MgO–TiO₂ plot, and these data should be viewed as suspicious (perhaps due to rutile or pseudobrookite intergrowths in the ilmenite?). The data set as a whole is nevertheless very useful in defining a nonkimberlitic reference line.

The maximum MgO contents of non-kimberlitic ilmenites were used to estimate a compositional field for these ilmenite varieties. The cubic equation defining the non-kimberlitic bounding reference line is as follows (Figs. 11 and 12):

$$y = 25.4062 + 6.1433x - 0.4187x^2 + 0.0106x^3$$

3.3. Ilmenites from other kimberlite-related rock types (melnoites)

In the previous sections, we have attempted to establish the compositional fields for kimberlitic and

non-kimberlitic ilmenites in terms of TiO₂ and MgO. The next step was to evaluate where ilmenites from kimberlite related rock types fall into the classification scheme. These include ultramafic lamprophyres (e.g., alnoites, mellilitites, etc.) and alkali basalts, and are referred to by the term “melnoite” for the purpose of this review (Table 1). Melnoites are known to host phenocrystic and groundmass ilmenites, as well as megacrystic and xenocrystic ilmenite derived from mafic lower crustal or upper mantle lithologies.

Fig. 13 shows the MgO and TiO₂ compositional range of ilmenites present in the Malaita alnoites, as well as ilmenite megacrysts found in the Okenyena ultramafic lamprophyre (UML) breccia. The ilmenites from Malaita show a trend of slightly decreasing TiO₂ contents with decreasing MgO content, and these ilmenite compositions transect the kimberlitic and non-kimberlitic reference lines. The Okenyena ilmenite megacrysts plot just to the left of the non-kimberlitic reference line at low MgO content. As with the Malaita data, ilmenites from the Entilombo Melnoite, from the Kwazulu Natal province of South Africa, show a linear trend of decreasing TiO₂ with decreasing MgO contents (Fig. 14). Although the data transect the kimberlitic ilmenite reference line, only 3 of the 1417 analyses plot on the low-MgO side of the non-kimberlitic line.

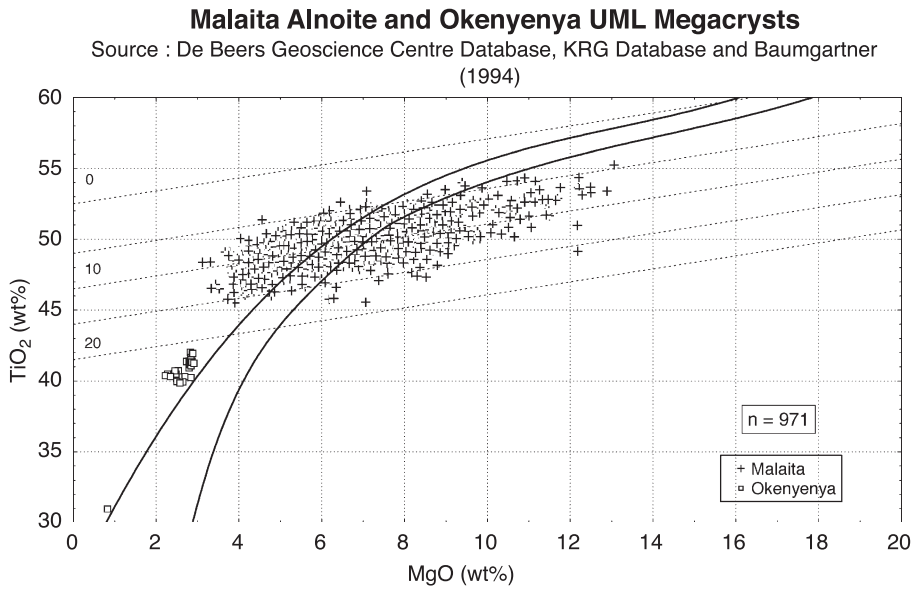


Fig. 13. Plot of MgO versus TiO₂ for ilmenites from the Malaita Alnoite and Okenyenya ultramafic lamprophyre. Symbology as for Fig. 11.

Fig. 15 is a plot of MgO versus TiO₂ for ilmenites from the Selco alkaline intrusions, Canada, which are described in detail by Janse et al. (1986), and classified petrogenetically as alnoites. These ilmenite data also transect the kimberlitic and non-kimberlitic boundaries. Ilmenites from the Lake Bullenmerri

basanite intrusion, Australia, a ‘kimberlite related rock’ which also comprises abundant upper mantle garnets, are presented in Fig. 16. The majority of the data fall to the low-Mg side of the non-kimberlitic reference line with only two data points within the kimberlitic ilmenite field.

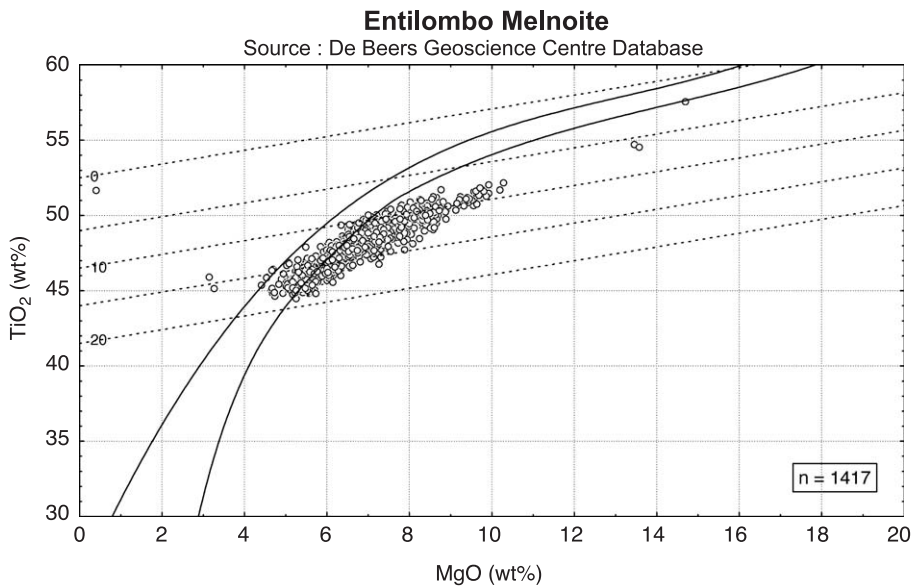


Fig. 14. Plot of MgO versus TiO₂ for ilmenites from the Entilombo Melnoite, Kwazulu Natal province, South Africa. Symbology as for Fig. 11.

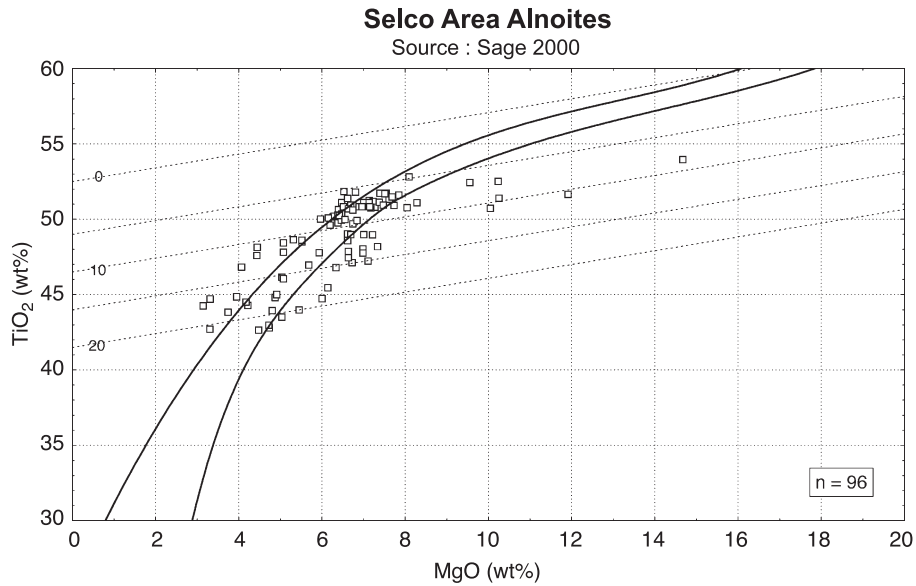


Fig. 15. Plot of MgO versus TiO₂ for the North America, Selco Alnoite. Symbology as for Fig. 11.

The observation that these kimberlite ‘related rock’ ilmenite compositions straddle the kimberlite reference line is consistent with the fact that is no sharp petrological boundary line between them and genuine kimberlites. While it may be difficult to differentiate single isolated ‘related rock’ ilmenites found in ex-

ploration samples from kimberlitic ilmenites on the basis of TiO₂–MgO relationships alone, the former are normally low in Cr₂O₃ (less than approximately 0.3 wt.% Cr₂O₃; see Table 2). If a population of ilmenites is present, a related rock paragenesis is also suggested if they define a trend at a shallow angle to

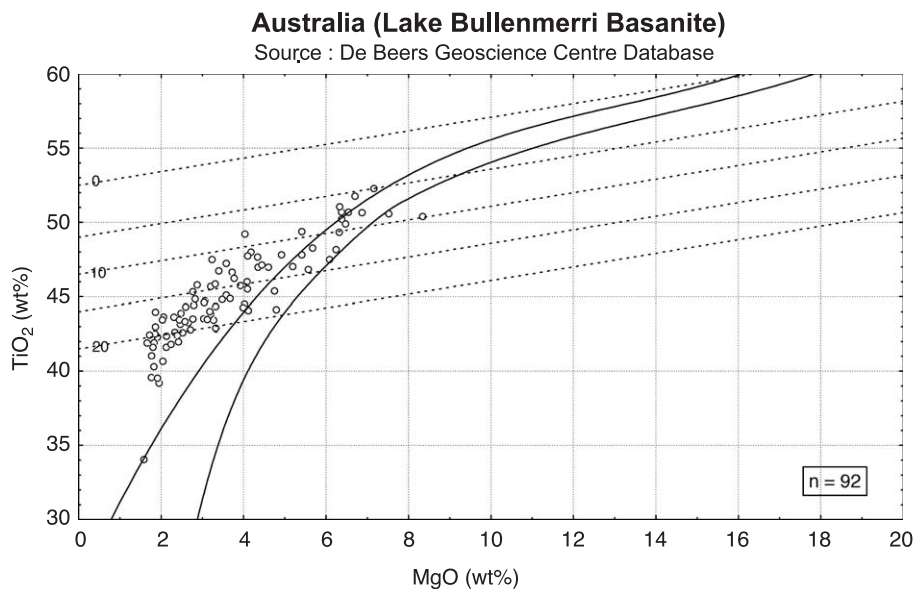


Fig. 16. Plot of MgO versus TiO₂ for the Australia, Lake Bullenmerri Basanite. Symbology as for Fig. 11.

the kimberlite reference line (and in some cases, subparallel to the Fe_2O_3 contours).

3.4. Ilmenites from exploration programs

Some exploration data sets are used to illustrate the application of the classification scheme to distinguish kimberlitic from non-kimberlitic ilmenites. Fig. 17 shows the MgO versus TiO_2 contents for a population of ilmenites visually identified as potentially kimberlitic by the Mineral Sorters at Mineral Services diamond laboratory. The majority of the ilmenites are classified as non-kimberlitic in this plot. Importantly, however, four of the 142 grains are in fact classified as kimberlitic. These samples would therefore warrant additional follow-up because these are highly likely to derive from a kimberlite.

The MgO and TiO_2 compositions of the ilmenites in the KIMC exploration database for the Slave craton in Canada (Table 1) are shown in Fig. 18. Clearly several of these analyses plot above the 0 wt.% Fe_2O_3 reference line and are poor analyses, or perhaps could be other high- TiO_2 bearing minerals that have been incorrectly designated as ilmenites in the database. This plot further highlights the apparent difficulties in visually distinguishing kimberlitic from non-kimberlitic ilmenites. The majority of the ilmenites shown in this plot are

clearly kimberlitic, but the data set also contains a large population of non-kimberlitic grains. Any follow-up work conducted over these recoveries prior to mineral analysis may have resulted in misdirected exploration. For comparative purposes, the KIMC ilmenites are also shown in MgO– Cr_2O_3 compositional space in Fig. 19. The majority of these data display a parabolic kimberlite relationship noted by Haggerty (1975, 1976, 1991), but the lower-Mg, low-Cr data clearly fall into a separate population.

3.5. Zoning of ilmenite: implications for the classification scheme

Schulze et al. (1995) demonstrated for several ilmenite populations from North America kimberlites that core and rim compositions might show significant chemical variation. Indeed it appears as though compositional zoning in ilmenite megacrysts and macrocrysts may be fairly common worldwide. Schulze et al. (1995) and O'Brien and Tyni (1999) note that, at most localities where chemical zonation is present, this is represented by increased MgO and/or Cr_2O_3 contents in the outer 100 to 500 μm of the grain. This compositionally distinct rim is different to the perovskite mantle commonly seen on kimberlitic ilmenites derived directly from kimberlite concentrate or recov-

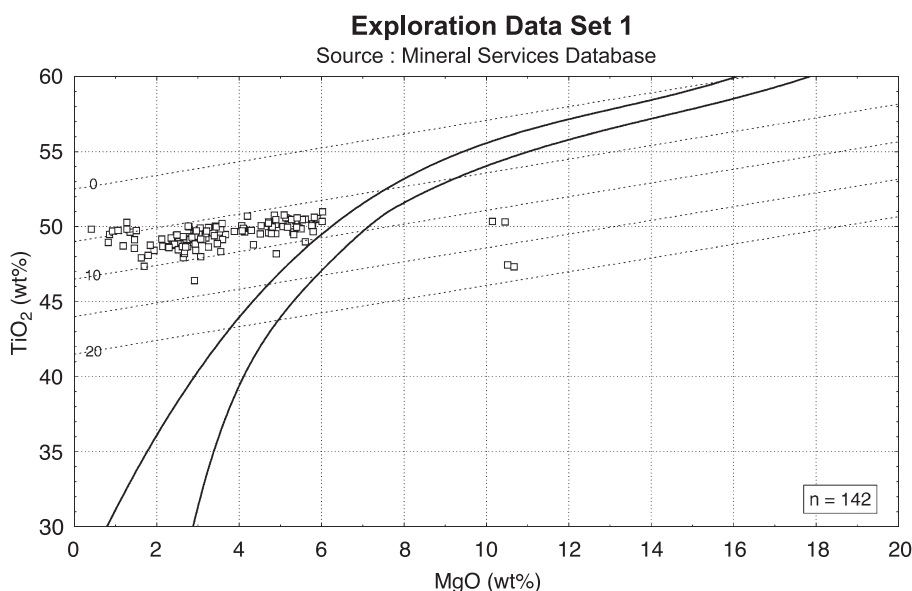


Fig. 17. Plot of MgO versus TiO_2 for an exploration data set. Symbology as for Fig. 11.

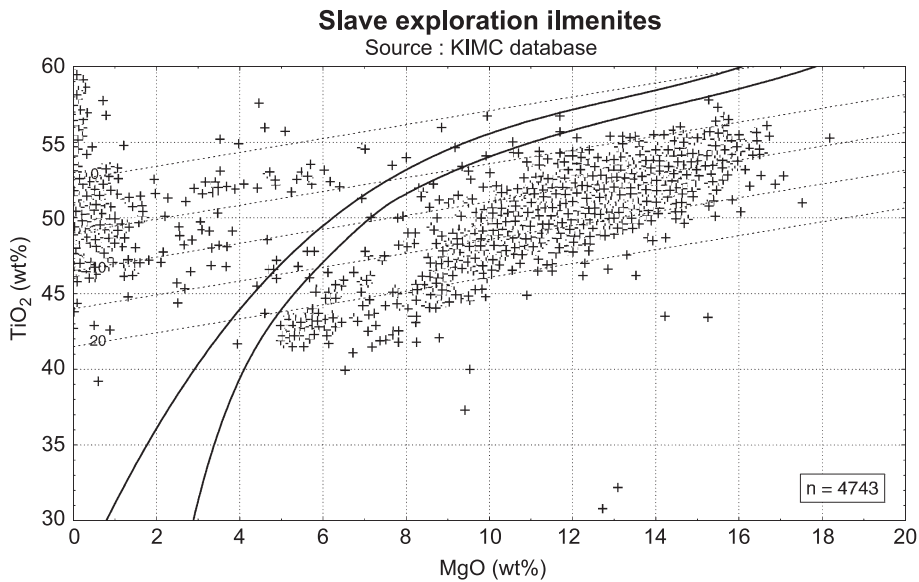


Fig. 18. Plot of MgO versus TiO₂ for ilmenites from the Canadian Slave exploration KIMC database. Symbology as for Fig. 11.

ered close to the kimberlite source rock. Schulze et al. (1995) furthermore concur with the conclusions of previous investigations into ilmenite zoning that the rims of elevated MgO and Cr₂O₃ are a result of late

stage magmatic overgrowth of new ilmenite on pre-existing cores or partial re-equilibration of the ilmenite rims with the host magma. O'Brien and Tyni (1999) suggest that magma mixing may also play an

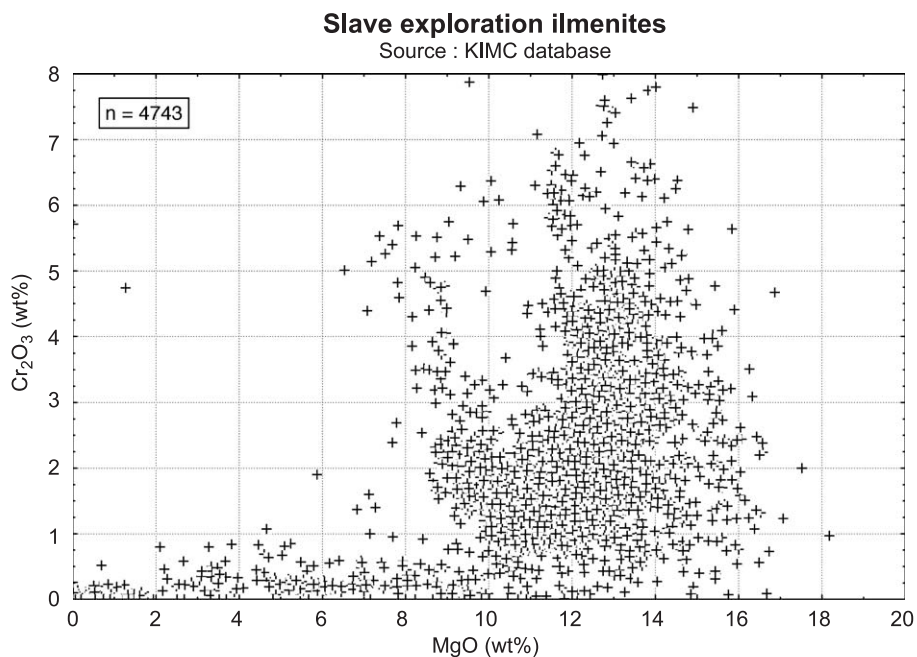


Fig. 19. Plot of MgO versus Cr₂O₃ for ilmenites from the Canadian Slave exploration KIMC data set.

important role in generating high-MgO ilmenite rims. Certain localities studied by Schulze et al. (1995), and work conducted by O'Brien and Tyni (1999), however, show examples of ilmenite rims with elevated MgO contents and no corresponding Cr₂O₃ increase. The inferred models for these ilmenites are, either that the magma transporting the grains to surface is a more primitive MgO rich variety that had not yet precipitated significant Cr-rich mineral phases, or that magnetite which would have accompanied the ilmenite macrocrysts to surface would have decomposed in the magma resulting in a sudden increase in MgO content of the magma (Schulze et al., 1995).

In addition to the primary chemical zonation seen in kimberlitic ilmenites, alteration of kimberlitic ilmenites in the secondary environment may also be a factor in certain climatic environments. Such secondary alteration is however markedly different from that described above, and is manifested in a distinct increase in MnO and lower MgO contents (e.g., Wyatt, 1979; Agata, 1998; Jiang et al., 1996). Ilmenites showing these features are present in the Premier kimberlite, and were reported at the Second Cambridge Kimberlite Symposium in 1979 (Wyatt, 1979). The data presented in this study, and reproduced in Table 3, have been plotted in MgO–TiO₂ space in Fig. 20. Most of the core and intermediate zone analyses fall within the kimberlite field, while the rim analyses fall well within the non-kimberlitic field. Wyatt (1979) interprets the MnO enrichment at Premier as either a late-stage nonmagmatic phenomenon postdating kimberlite consolidation, or being due to low-temperature metasomatism of the grains by cir-

culating Mn-bearing groundwater in a reducing environment below the water table. A characteristic of the individual zoned ilmenites is that they retain their characteristic 'kimberlitic' high-Cr₂O₃ contents (+0.6 wt.%) from core to rim. This example illustrates that, when attempting to classify ilmenites extracted from exploration samples, and these turn out to be enriched in MnO (at the possible expense of MgO), and consequently fall on the low-MgO side of the kimberlite reference line (Fig. 1), it would be prudent to scrutinise for high-Cr₂O₃ (more than approximately 0.5 wt.%). Such grains could represent altered kimberlitic ilmenites, or may be kimberlitic but affected by late stage carbonate reactions as described by Haggerty et al. (1979), Haggerty and Tompkins (1984) and Tompkins and Haggerty (1985).

Several of the Cr-rich kimberlitic ilmenites from the Mwenezi kimberlite in Zimbabwe studied by Williams and Robey (1999) showed high MnO contents ranging from 4.5 to 5.4 wt.%, and near zero MgO contents. The authors suggest this may be due to MnO introduction/replacement of MgO in the ilmenites, presumably similar to the Premier case presented above. Indeed, many of these ilmenites have typical kimberlitic high-Cr₂O₃ (more 0.5 wt.%) contents. These Mwenezi ilmenites would plot within the non-kimberlitic field on a bivariate MgO versus TiO₂ plot. Our experience has shown that, in certain cases, the MgO content decreases to the extent that visually kimberlitic ilmenites plot to the low-MgO side of kimberlitic compositional field. It is important to recognise such grains in exploration data sets and to classify their paragenesis correctly.

Table 3

Composition of zoned ilmenites from the Premier Mine, South Africa (from Wyatt, 1979)

	BHS 204			BHS 215			BHS 207			BHS 209		
	Margin	Int	Core	Margin	Int	Core	Margin	Int	Core	Margin	Int	Core
TiO ₂	50.65	50.62	51.22	50.04	53.49	54.12	50.73	50.85	54.07	46.13	49.48	51.70
Al ₂ O ₃	0.52	0.34	0.29	0.51	0.48	0.49	0.45	0.24	0.26	0.78	0.99	0.94
Cr ₂ O ₃	1.25	1.21	1.22	1.19	1.23	1.27	0.69	0.63	0.65	5.70	6.35	6.49
FeOt	41.74	41.65	41.00	38.09	32.17	29.90	42.21	42.55	32.43	41.68	32.02	25.62
MnO	5.38	4.44	3.11	9.28	1.36	0.26	3.93	1.97	0.29	2.60	0.74	0.39
MgO	0.08	0.49	2.43	0.18	9.88	12.64	0.65	2.33	11.25	1.18	9.48	13.90
CaO	0.04	0.02	0.01	0.09	0.03	0.03	0.18	0.07	0.03	0.11	0.08	0.09
Total	99.66	98.77	99.28	99.38	98.64	98.71	98.84	98.64	98.98	98.18	99.14	99.13
FeO	39.90	40.12	38.56	35.16	29.64	25.83	40.25	39.49	28.23	36.71	26.74	21.20
Fe ₂ O ₃	2.04	1.70	2.71	3.26	3.44	4.52	2.18	3.40	4.66	5.52	5.87	4.91
Total	99.86	98.94	99.55	99.71	98.99	99.16	99.06	98.98	99.45	98.73	99.73	99.62

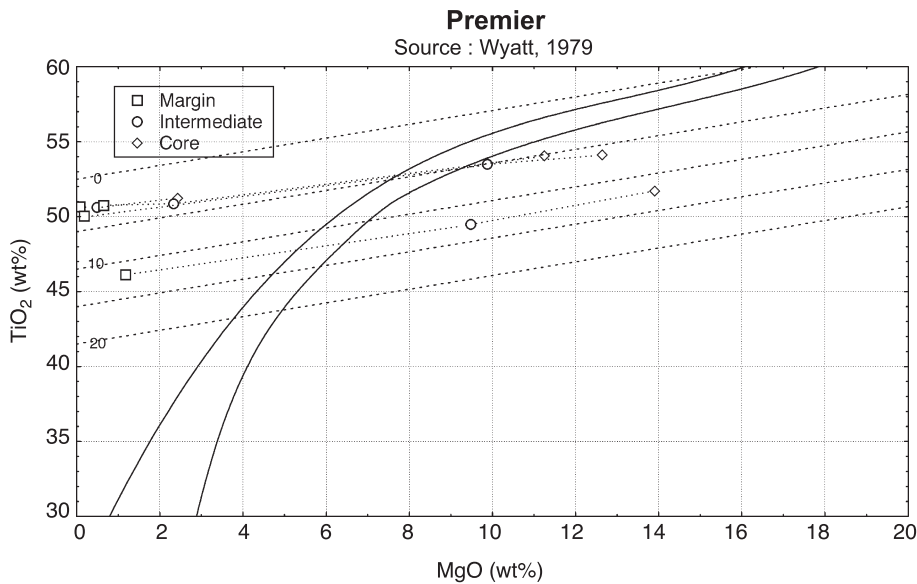


Fig. 20. Plot of MgO versus TiO₂ for zoned ilmenites from the Premier kimberlite. Percentage Fe₂O₃ lines are shown as the dashed light-grey lines. The black lines represent the non-kimberlitic and kimberlitic ilmenite reference lines, respectively.

In contrast to kimberlitic ilmenites, non-kimberlitic ilmenites seldom have zoned rims with increased MgO and/or Cr₂O₃ contents. A selection of the non-kimberlitic ilmenites from the Mineral Services exploration data set were analysed on their rims at distances of 10 and 20 μm from the grain margin, respectively, and the entire set of ilmenites was also examined using secondary electron backscatter imaging techniques on the in-house Mineral Services Scanning Electron microscope. Both the analytical data and the observations under backscatter confirmed the absence of ilmenite rims of differing composition to their cores.

The analysis of the rims of ilmenites that fall at or close to the compositional boundaries may aid in the interpretation of the paragenesis of these grains. The absence of a compositionally distinct rim does not necessarily mean that the grain is non-kimberlitic, but the presence of a rim with increased MgO or Cr₂O₃ contents may be significant.

4. Conclusions

The results of this study define a simple and practical classification scheme that can be used to compositionally discriminate ilmenites derived from

kimberlitic sources from those occurring in other sources. The key major elements used in this distinction are MgO and TiO₂. In addition, the Cr₂O₃ content of the ilmenites also needs to be considered because non-kimberlitic ilmenites typically contain very low to zero Cr₂O₃ contents (seldom above 0.5 wt.%). This is particularly relevant for assessing MnO-enriched ilmenites (more than approximately 1.0 wt.% MnO) that may be zoned or altered ilmenites.

The fact that both non-kimberlitic and kimberlitic ilmenites are recovered in exploration programs in several regions worldwide illustrates the need to be able to discriminate these effectively. The correct identification of the ilmenite source lithology, especially in areas where ilmenite is the key pathfinder mineral, will result in direct cost saving to exploration programs as false anomalies will be easily identified. In addition to this, the ilmenite classification scheme will also aid in finding kimberlitic rocks in areas that contain high background abundances of non-kimberlitic ilmenite.

Acknowledgements

Many of the original concepts presented in this paper were developed within the De Beers organisation

in the mid-1970s, the results of which were presented at several internal conferences, meetings, and training courses over approximately the last 25 years. This work benefited from discussions and input from many De Beers employees, but in particular, Dr. R.V. Danchin who first introduced the possibilities of using MgO–TiO₂ to one of authors (BAW) and De Beers. De Beers are gratefully thanked for allowing us to present this paper and for permission to use some of their data sets. The following other people and institutions are thanked for their contributions to the data sets that made this study possible. John Armstrong of the Diand–CS Lord Northern Geoscience Centre for providing the KIMC database, the Kimberlite Research Group at UCT for providing records from the KRG Database, Steve Haggerty and the University of Massachusetts (UMASS) for providing their 1987 Ilmenite Database to the KRG, Professor Anton le Roex for supplying the balance of the Okenyanya ilmenite data, Dan Shulze for supplying the data from the North American localities, Grant Cawthorn for providing the Insizwa data, and Mineral Services for supplying one of the exploration data sets. Linda Tompkins and Steve Haggerty are thanked for constructive reviews that improved the paper.

References

- Agata, T., 1998. Geochemistry of ilmenite from the Asama ultramafic layered igneous complex, Mikabu greestone belt, Sambagawa metamorphic terrane, central Japan. *Geochem. J.* 32, 231–241.
- Apter, D.B., Harper, F.J., Wyatt, B.A., Smith, B.H.S., 1984. The geology of the Mayeng sill complex, South Africa. In: Kornprobst, J. (Ed.), *Kimberlites I: Kimberlites and Related Rocks*. Proc. 3rd Int. Kimb. Conf. Elsevier, Amsterdam, pp. 43–57.
- Baumgartner, M.C., 1994. The xenoliths of the Okenyanya Volcanic breccia. Unpub. MSc thesis, Univ. Cape Town, South Africa.
- Boyd, F.R., Dawson, J.B., Smith, J.V., 1984. Granny Smith diopside megacrysts from the kimberlites of the Kimberley area and Jagersfontein, South Africa. *Geochim. Cosmochim. Acta* 48, 381–384.
- Bristow, J.W., 1980. The geochronology and geochemistry of Karoo Volcanics in the Lebombo and adjacent areas. Unpub. PhD Thesis, Univ. Cape Town, South Africa.
- Cawthorn, R.G., Maske, S., De Wet, M., Groves, D.I., Cassidy, K.F., 1988. Contrasting magma types in the Mount Ayliff Intrusion (Insizwa Complex), Transkei: evidence from ilmenite compositions. *Can. Mineral.* 26, 145–160.
- Dawson, J.B., Smith, J.V., 1977. The MARID (mica–amphibole–rutile–ilmenite–diopside) suit of xenoliths in kimberlite. *Geochim. Cosmochim. Acta* 41, 309–323.
- Dawson, J.B., Hill, P.G., Kinny, P.D., 2001. Mineral chemistry of a zircon-bearing, composite, veined and metasomatised upper-mantle peridotite xenolith from kimberlite. *Contrib. Mineral. Petrol.* 140, 720–733.
- Eggler, D.H., McCallum, M.E., Smith, C.B., 1979. Megacryst assemblages in kimberlite from northern Colorado and southern Wyoming: petrology, geothermometry–barometry, and areal distribution. In: Boyd, F.R., Meyer, H.O.A. (Eds.), *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics*. Proc. 2nd Int. Kimb. Conf., vol. 2. Amer. Geophys. Union, Washington, pp. 213–226.
- Finger, L.W., 1972. The uncertainty in the calculated ferric iron content of electron microprobe analysis. *Year B.–Carnegie Inst.* 71, 600–603.
- Graham, I., Burgess, J.L., Bryan, D., Ravenscroft, P.J., Thomas, E., Doyle, B.J., Hopkins, R., Armstrong, K.A., 1999. Exploration history and geology of the Diavik kimberlites, Lac de Gras, Northwest Territories, Canada. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), *Proc. VIIth Int. Kimb. Conf.*, vol. I. Red Roof Design, Cape Town, pp. 262–279.
- Haggerty, S.E., 1975. The chemistry and genesis of opaque minerals in kimberlite. In: Ahrens, L.H., Dawson, J.B., Duncan, A.R., Erlank, A.J. (Eds.), *Proc. 1st Int. Kimb. Conf.*, Physics Chem. Earth, vol. 9, pp. 195–307.
- Haggerty, S.E., 1976. Opaque mineral oxides in terrestrial igneous rocks. In: Rumble, D. (Ed.), *Oxide Minerals*. Mineral. Soc. Am. Short Course Notes, vol. 3, pp. Hg 101–Hg 300.
- Haggerty, S.E., 1989. Upper mantle opaque stratigraphy and the genesis of metasomites and alkali-rich melts. *Kimberlites and Related Rocks*, Proc. 4th Int. Kimberlite Conf., Vol. 2. Special Publication–GSA, vol. 14, pp. 687–699.
- Haggerty, S.E., 1991. Oxide mineralogy of the upper mantle. *Oxide Minerals*. Mineralogical Society of America Reviews in Mineralogy, vol. 25, pp. 355–416.
- Haggerty, S.E., Tompkins, L.A., 1984. Subsolidus reactions in kimberlitic ilmenites. In: Kornprobst, J. (Ed.), *Kimberlites I: Kimberlites and Related Rocks*. Proc. 3rd Int. Kimb. Conf., vol. 1. Elsevier, Amsterdam, pp. 335–357.
- Haggerty, S.E., Hardie, R.B., McMahon, B.M., 1979. The mineral chemistry of ilmenite nodule associations from the Monastery Daitreme. In: Boyd, F.R., Meyer, H.O.A. (Eds.), *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics*. Proc. 2nd Int. Kimb. Conf., vol. 2. Amer. Geophys. Union, Washington, pp. 249–256.
- Harte, B., 1987. Metasomatic events recorded in mantle xenoliths: an overview. In: Nixon, P.H. (Ed.), *Mantle Xenoliths*. Wiley, Chichester, pp. 625–640.
- Janse, A.J.E., Downie, I.F., Reed, L.E., Sinclair, I.G., 1986. Alkaline intrusions in the Hudson Bay lowlands, Canada: exploration methods, petrology and geochemistry. *Kimberlites and Related Rocks*, Proc. 4th Int. Kimb. Conf., Vol. 2. Special Publication–GSA, vol. 14, pp. 1192–1203.
- Jiang, S.-Y., Palmer, M.R., Slack, J.F., 1996. Mn-rich ilmenite from the Sullivan Pb–Zn–Ag deposit, British Columbia. *Can. Mineral.* 34, 29–36.

- Meyer, H.O.A., Svisero, D.P., 1975. Mineral inclusions in Brazilian diamonds. In: Ahrens, L.H., Dawson, J.B., Duncan, A.R., Erlank, A.J. (Eds.), *Proc. 1st Int. Kimb. Conf. Phys. Chem. Earth*, vol. 9, pp. 785–795.
- Mitchell, R.H., 1973. Magnesian ilmenite and its role in kimberlite petrogenesis. *J. Geol.* 81, 301–311.
- Mitchell, R.H., 1977. Geochemistry of magnesian ilmenites from kimberlites in South Africa and Lesotho. *Lithos* 10, 29–37.
- Mitchell, R.H., 1986. *Kimberlites: Mineralogy, Geochemistry and Petrology*. Plenum, New York. 442 pp.
- Moore, A.E., 1987. A model for the origin of ilmenite in kimberlite and diamond: implications for the genesis of the discrete nodule (megacryst) suite. *Contrib. Mineral. Petrol.* 95, 245–253.
- Moore, A.E., Lock, N.P., 2001. The origin of mantle-derived megacrysts and sheared peridotites—evidence from kimberlites in the northern Lesotho—Orange Free State (South Africa) and Botswana pipe clusters. *S. Afr. J. Geol.* 104, 23–38.
- O'Brien, H.E., Tyni, M., 1999. Mineralogy and geochemistry of kimberlites and related rocks from Finland. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), *Proc. VIIth Int. Kimb. Conf.*, vol. II. Red Roof Design, Cape Town, pp. 625–636.
- Orr, P., 1998. Geochemistry and petrology of the Yamba Lake kimberlites, Central Slave Province, Northwest Territories. Unpub. MsC thesis, University of Alberta, Edmonton, Alberta. 162 pp.
- Sage, R.P., 2000. MRD 60-Kimberlite Heavy Mineral Indicator Data, Attawapiskat Area, James Bay Lowlands, Northern Ontario. Data contained in Appendix A of Open File Report 6019. Ontario Geological Survey, Ontario, Canada.
- Schulze, D.J., 1984. Cr-poor megacrysts from the Hamilton Branch kimberlite, Elliot County, Kentucky. In: Kornprobst, J. (Ed.), *Kimberlites II: The Mantle and Crust—Mantle Relationships*. *Proc. 3rd Int. Kimb. Conf.* Elsevier, Amsterdam, pp. 97–108.
- Schulze, D.J., 1987. Megacrysts from alkalic volcanic rocks. In: Nixon, P.H. (Ed.), *Mantle Xenoliths*. Wiley, Chichester, pp. 434–451.
- Schulze, D.J., Anderson, P.F.N., Hearn, B.C., Hetman, C.M., 1995. Origin and significance of ilmenite megacrysts and macrocrysts from kimberlite. *Int. Geol. Rev.* 37, 780–812.
- Smith, C.B., 1977. Kimberlite and mantle derived xenoliths at Iron Mountain, Wyoming. Unpub. MsC thesis, Colorado State University, Fort Collins, Colorado. 218 pp.
- Sobolev, N.V., 1977. Deep-Seated Inclusions in Kimberlites and the Problem of the Composition of the Mantle. *Amer. Geophys. Union, Washington, DC*. 279 pp.
- Sobolev, N.V., Yefimova, E.S., 2000. Composition and petrogenesis of Ti-oxides associated with diamonds. *Int. Geol. Rev.* 42, 758–767.
- Tompkins, L.A., Haggerty, S.E., 1985. Groundmass oxide minerals in the Koidu kimberlite dykes, Sierra Leone, West Africa. *Contrib. Mineral. Petrol.* 91, 245–263.
- Williams, C.M., Robey, J.V.A., 1999. Petrography and mineral chemistry of the Mwenezi-01 kimberlite, Zimbabwe. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), *Proc. VIIth Int. Kimb. Conf.*, vol. 2. Red Roof Design, Cape Town, pp. 896–903.
- Wyatt, B.A., 1979. Manganoan ilmenite from the Premier kimberlite. *Proc. 2nd Kimb. Symposium, Cambridge*.
- Wyatt, B.A., Lawless, P.J., 1984. Ilmenite in polymict xenoliths from the Bultfontein and De Beers Mines, South Africa. In: Kornprobst, J. (Ed.), *Kimberlites II: Their Mantle and Crust/Mantle Relationships*. *Proc. 3rd Int. Kimb. Conf.* Elsevier, Amsterdam, pp. 43–56.
- Wyatt, B.A., Shee, S.R.S., Griffin, W.L., Zweistra, P., Robinson, H.R., 1994. The petrology of the Cleve kimberlite, Eyre Peninsula, South Australia. In: Meyer, H.O.A., Leonardos, O.H. (Eds.), *Kimberlites, Related Rocks and Xenoliths*. *Proc. 5th Int. Kimb. Conf.*, Rio de Janeiro. *Spec. Publ.-CPRM*, vol. 1/A (Jan/94), pp. 62–79.