Available online at www.sciencedirect.com
SCIENCE DIRECT®

Lithos 71 (2003) 195–213

LITHOS

www.elsevier.com/locate/lithos

A classification scheme for mantle-derived garnets in kimberlite: a tool for investigating the mantle and exploring for diamonds

Daniel J. Schulze

Department of Geology, University of Toronto, Erindale College, 3359 Mississauga Road North, Mississauga, Ontario, Canada L5L 1C6

Abstract

A new empirical method has been devised for classification of mantle-derived garnets in kimberlite. Simple chemical screens have been developed to distinguish between garnets from different parageneses, based on Mg, Fe, Ca, Cr, Ti and Na values of published analyses of garnets from >2000 ultramafic xenoliths in kimberlite. Although crustal garnets are typically uncommon as xenocrysts in kimberlite, the first step in the classification is to screen these from the mantle population, using data from >600 garnet-bearing crustal rocks. Such a screen may also prove useful in evaluating the source (crust vs. mantle) of garnet in kimberlite exploration samples. Subsequent steps divide mantle garnets into eclogite, peridotite and Cr-poor megacryst groupings, and sub-groups of the peridotite (lherzolite, harzburgite, wehrlite) and eclogite (Groups I and II and A, B, C and grospydite) populations. Important features of this classification include the fact that it is based on distinctions between groups of fundamental geological significance (e.g., peridotite vs. eclogite) and it is based on a large, well-documented and well-understood xenolith database. As it utilizes oxide values and molar ratios of major and minor elements, the rationale for the screens is readily understood and it is simple to use.

Keywords: Garnet; Kimberlite; Upper mantle; Eclogite; Peridotite

1. Introduction

Our knowledge of the constitution of the inaccessible parts of the interior of Earth comes from a variety of sources, including cosmochemical modelling and geophysical studies. Direct study of actual samples of the deep interior of Earth, such as the upper mantle, is made possible by the occurrence of such material as tectonically emplaced slices in orogenic belts (e.g., Alpine peridotites) and as accidental inclusions of mantle material brought to the surface by some kimberlites and other alkaline volcanic rocks. Intact rocks (xenoliths) are ideal samples to study, but these are not as abundant as are single crystals (xenocrysts) derived by the disaggregation of mantle rocks during the typically violent transport to the surface in the host magmas. Great progress has been made in the study of the composition and structure of the upper mantle through xenocryst investigations, especially studies of xenocrystal garnet and chromite (e.g., Gurney and Switzer, 1973; Sobolev et al., 1973, 1975; Boyd and Gurney, 1982; Schulze, 1989b; Griffin et al., 1999; Grutter et al., 1999; Pokhilenko et al., 1999). Most attention has been turned towards garnet, as it occurs in a variety of rock types, such as eclogites and peridotites, rocks prevalent in most

---

E-mail address: dschulze@credit.erin.utoronto.ca (D.J. Schulze).

0024-4937/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0024-4937(03)00113-0

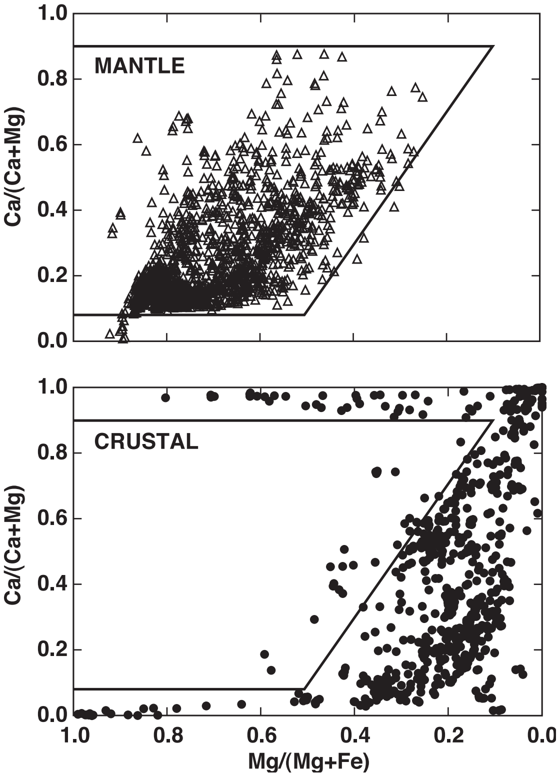

Fig. 1. Distinction between mantle-derived garnets and those from crustal rocks, in terms of Mg/(Mg + Fe) and Ca/(Ca + Mg). As discussed in the text, mantle-derived garnets are from peridotites (lherzolites and harzburgites), eclogites, alkremites and Cr-poor megacrysts. Crustal sources of garnets are dominantly amphibolite to granulite grade meta-pelites and meta-basites, in which garnets are rich in the almandine and spessartine components, but also included are less common garnets rich in the grossular, uvarovite, andradite and pyrope end members.

upper mantle xenolith suites in kimberlite and thus thought to dominate the upper mantle.

A serious drawback of dealing with xenocrysts is that, as they are single crystals, the nature of their parent rock prior to disaggregation is uncertain. One must make inferences about the characteristics of the intact parent rocks based on chemical, and to some extent physical, characteristics of the xenocrysts. To this end, a number of classification schemes have been devised to assist in deciphering more about the pre-disaggregation host of the xenocryst garnets.

Chemical screens have been proposed to help distinguish between garnets from various parageneses, although most workers have dealt with a restricted range of rock types. Sobolev et al. (1973), for example, outlined the field of compositions of garnets from lherzolites, relative to those from harzburgites and wehrlites, in terms of their CaO and Cr_2O_3 contents and Gurney (1984) proposed a screen to distinguish between garnets from lherzolites and low-Ca garnet harzburgites, also based on CaO and Cr_2O_3 contents. Jago and Mitchell (1989) devised a cluster analysis scheme to group garnets from individual kimberlites based on chemical similarities, although the linkage of the various groups with xenolith types was tenuous. Ramsay (1992) presented graphical screens to subdivide garnets from various rock types.

The most comprehensive and widely used classification scheme for mantle-derived garnets is the cluster analysis of Dawson and Stephens (1975), in which

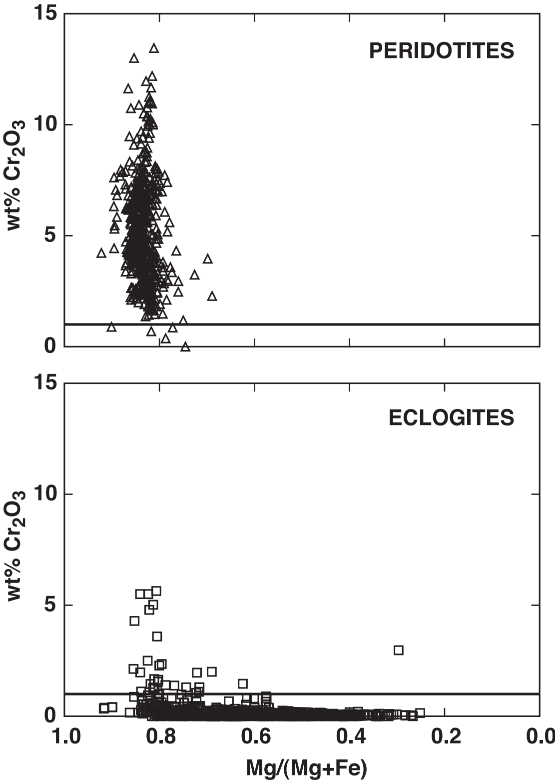

Fig. 2. Variation in Cr_2O_3 and Mg/(Mg + Fe) in garnets from eclogites and peridotites. A value of 1 wt.% Cr_2O_3 is used to discriminate between the two groups, with peridotite garnet values above this and those of eclogite garnets below.

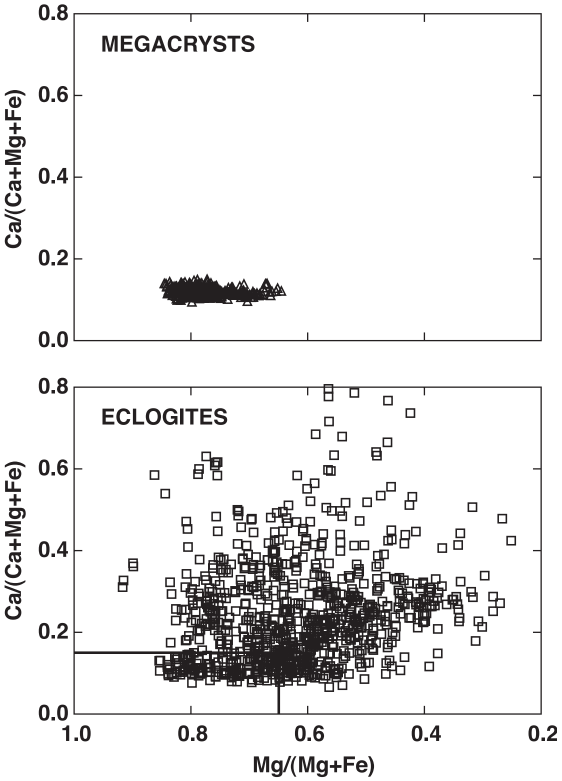

Fig. 3. Variation in Mg/(Mg + Fe) and Ca/(Ca + Mg + Fe) that assist in discrimination between garnets from the Cr-poor megacryst suite and those from eclogites. The solid lines enclose the range of eclogite garnet compositions that overlap with those of Cr-poor megacrysts. Eclogite garnets within this range are distinguished from megacrysts using Ti content in Fig. 4.

garnets from kimberlite are classified into 12 groups based on FeO, MgO, CaO, TiO_2 and Cr_2O_3 contents. Drawbacks of this scheme, however, include the facts that some groups contain garnets from more than one rock type, some rock types fall into two different groups (e.g., Cr-poor megacrysts can be classified into both Groups 1 and 2) and some garnets used to set up the classification are apparently of crustal derivation. Furthermore, the database was relatively small, utilizing only 136 xenoliths, and a substantial number of garnets (163) were single crystals of unknown, or at least uncertain, paragenesis. Danchin and Wyatt (1979) used a similar technique, although their method divided garnets into an unwieldy 52 groups.

A new classification scheme for mantle garnets is presented in this paper. It is based on chemical analyses of 2073 garnets in mantle xenoliths from kimberlite, together with analyses of 624 garnets from crustal rocks. Figs. 1–7 illustrate the chemical screens that allow distinction between garnets from different parageneses. Figs. 8–11 are flow charts outlining steps using the chemical screens, first to discriminate crustal from mantle garnets (Fig. 8), followed by subdivision of mantle garnets into groups representing those from peridotite, eclogite and the Cr-poor megacryst suite (Fig. 9). Figs. 10 and 11 illustrate subdivision of the eclogite and peridotite groups, respectively. By connecting to the University of Toronto web site at http://www.geology.utoronto.ca/faculty/schulze.html, an Excel macro that executes this classification can be downloaded.

The screens are based on Ca, Mg, Fe, Cr, Ti and Na contents of the garnets. Routine modern electron microprobe procedures should typically provide data of high enough quality that analytical accuracy should not be a concern in applying this classification to new garnet data. The one possible exception, however, is the quality of sodium analyses. If garnets classified as eclogite-derived are to be divided into Groups I and II on the basis of their Na_2O contents (as described in a later section), care must be taken to ensure that appropriate WDS microprobe methods have been

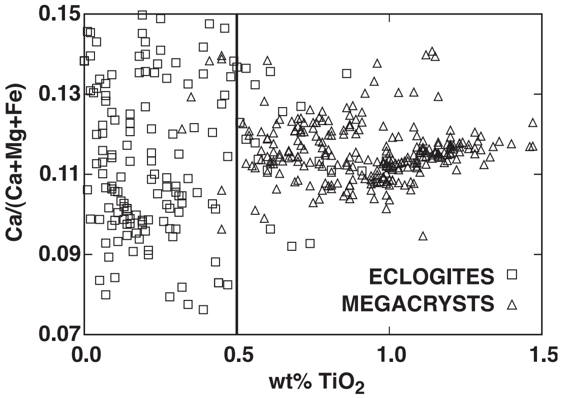

Fig. 4. Variation in TiO_2 and Ca/(Ca + Mg + Fe) in garnets from Cr-poor megacrysts with $Cr_2O_3 < 1$ wt.% and those from eclogites with Mg/(Mg + Fe)>0.65 and Ca/(Ca + Mg + Fe) < 0.15. A cut-off value of 0.5 wt.% TiO_2 is used to discriminate between the two groups. Most of the eclogite garnets with TiO_2>0.5 wt.% are from a single locality, the Kaalvallei kimberlite, as discussed in the text.

used to obtain low Na detection limits (e.g., ~ 0.01 wt.% Na_2O).

2. The database

The garnet data used in this study have been taken primarily from the published literature and theses,

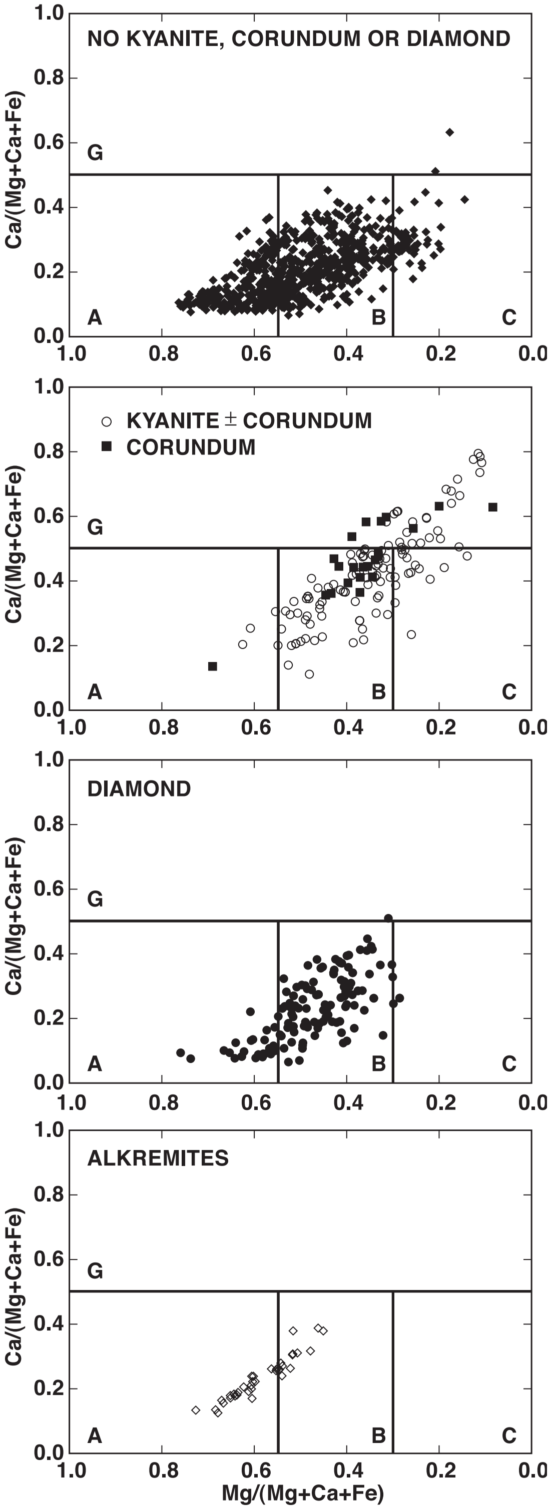

Fig. 5. Variation in Mg/(Mg + Ca + Fe) and Ca/(Ca + Mg + Fe) used to subdivide eclogite garnet compositions. “Grospydite” garnets (field G) have Ca/(Ca + Mg + Fe)>0.50, and those with lower calcium contents are subdivided into groups “A”, “B” and “C” at Mg/(Mg + Ca + Fe) values of 0.55 and 0.30, as discussed in the text. Figure is subdivided into garnets from eclogites lacking diamond or the aluminous phase kyanite or corundum, those with kyanite (with or without corundum) and those with corundum (but lacking kyanite), and those containing diamond. The compositional range of garnets from alkremites is also shown.

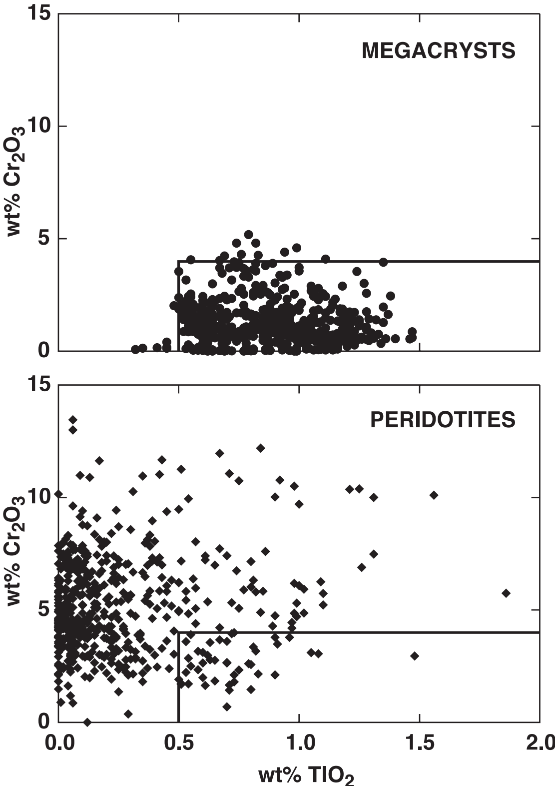

Fig. 6. Variation in Ti and Cr contents of garnets from the Cr-poor megacryst suite and peridotites. In the classification, Cr-poor megacryst garnets are defined as those with TiO_2>0.5 wt.% and Cr_2O_3 < 4.0 wt.%, and peridotite garnets have values outside these ranges.

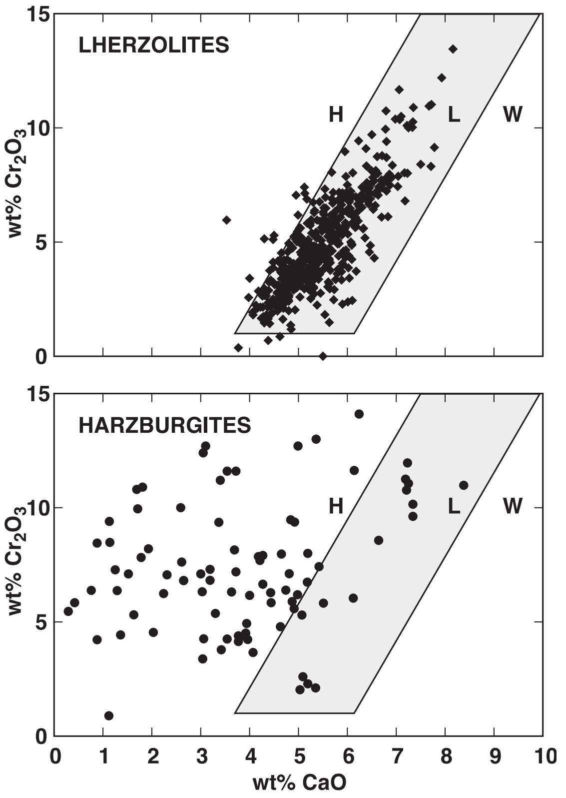

Fig. 7. Variation in CaO and Cr_2O_3 in garnets from lherzolites and harzburgites. Garnets from lherzolites are dominantly in the shaded area within the solid lines, with the points at CaO values significantly below the lower lherzolite limit likely not to be in equilibrium with both clinopyroxene and orthopyroxene. Garnets from harzburgites (lacking modal clinopyroxene) fall both within the lherzolite field, indicating equilibration with clinopyroxene, and at CaO values below the lherzolite field. The latter are typical of peridotite–suite garnets in diamonds. Garnets from wehrlites, not in equilibrium with orthopyroxene, will plot at CaO values above those of the lherzolite field. Fields defined in this classification are harzburgite (H), lherzolite (L, shaded field) and wehrlite (W).

and some previously unpublished microprobe analyses have also been used. These new WDS data (obtained at the University of Toronto) consist of analyses of 56 eclogite garnets from Kaalvallei and Bobbejaan and 94 lherzolite garnets from Kimberley dumps, Hamilton Branch and Liqhobong. By connecting to the University of Toronto web site at http://www.geology.utoronto.ca/faculty/schulze.html, these new data can be downloaded. Although some published analyses included calculated Fe_2O_3 values, all iron values used in this study have been recalculated to total Fe as FeO, the typical method used to report electron microprobe data.

2.1. Crustal garnets

The most common occurrence of garnet in crustal rocks is in medium to high-grade meta-pelites and meta-basites. These garnets are rich in the almandine end-member, $Fe_3Al_2Si_3O_{12}$, and can have significant Mn contents (spessartine end-member, $Mn_3Al_2Si_3O_{12}$). Such garnets dominate the crustal component of the database as they are readily obtainable from the published literature. A specific search was also made for less common compositions of crustal garnets, including those rich in the grossular ($Ca_3Al_2Si_3O_{12}$), andradite ($Ca_3Fe_2Si_3O_{12}$), uvarovite ($Ca_3Cr_2Si_3O_{12}$), and pyrope ($Mg_3Al_2Si_3O_{12}$) end-members. Crustal garnet compositions in the database are from Dunn (1978), Nixon (1979), Percival (1981), Pattison et al. (1982), Chopin (1984), Cortesogno and Lucchetti (1986), von Knorring et al. (1986), Chopin et al. (1991), Gordon et al. (1991, 1994), Pattison (1991), Bégin and Pattison (1994), Fitzsimons and Harley (1994), Pattison and Bégin (1994), Nyman et al. (1995), Santos de Lima et al. (1995), Fitzsimons (1996), Guiraud et al. (1996), Hartel and Pattison (1996), Knudsen (1996), Kryza et al. (1996), Shaw and Arima (1996), Thöni and Miller (1996), Whitney et al. (1996, 2001), Azor and Ballèvre (1997), Cartwright et al. (1997), Simon et al. (1997), Willner et al. (1997), Rosenberg et al. (1998), Vance and Mahar (1998), Parthasarathy et al. (1999), Abd El-Naby et al. (2000), Bose et al. (2000), Clarke et al. (2000), Cooke et al. (2000), Fraser et al. (2000), Gayk and Kleinschrodt (2000), Gupta et al. (2000), Jones and Strachan (2000), Moraes and Fuck (2000), Parkinson (2000), Zhao et al. (2000), Bruno et al. (2001), Compagnoni and Hirajima (2001), Garcia-Casco et al. (2001), Habler and Thoni (2001), Harangi et al. (2001), Lang and Gilotti (2001), Pita and de Waal (2001), Rolland et al. (2001), Rotzler and Romer (2001), Satish-Kumar et al. (2001), Schmadicke et al. (2001), Scrimegour et al. (2001), Stowell et al. (2001), White et al. (2001) and Zeh and Millar (2001).

2.2. Mantle-derived garnets

All of the garnets in this category are from ultramafic xenoliths from kimberlites, specifically lherzo-

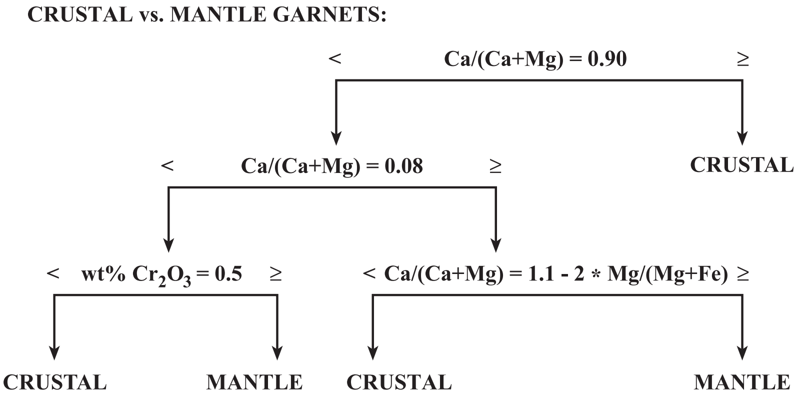

Fig. 8. Flow chart illustrating the steps used to distinguish between garnets derived from crustal rocks and those of mantle origin.

lites, harzburgites, eclogites, and Cr-poor megacrysts. Garnet inclusions in diamonds were not included as in some instances their compositions are well outside of the range of compositions of minerals from ultramafic xenoliths (e.g., Gurney et al., 1984; Schulze, 1997). Table 1 lists the regional distribution of the kimberlite sources of the 2073 mantle xenoliths in the database. Approximately half of the samples are from kimberlites on the Kaapvaal Craton. Specific locations can be obtained from the references cited.

Eclogite garnet data are from Sobolev et al. (1968, 1994), Meyer and Brookins (1971), Chinner and Cornell (1974), Reid et al. (1976), Smyth and Hatton (1977), Shee (1978), Shee and Gurney (1979), Boyd and Danchin (1980), Ater (1982), Tollo (1982), McGee and Hearn (1984), Robinson et al. (1984), Smyth and Caporuscio (1984), Spetsius et al. (1984), Hall (1985), MacGregor and Manton (1986), McCandless and Gurney (1986), Ford (1987), Schulze and Helmstaedt (1988), Sommerville (1988), de Bruin (1989), Hills and Haggerty (1989), Smith et al. (1989), Taylor and Neal (1989), Schulze (1992, 1997), Jerde et al. (1993a,b), Jacob et al. (1994), Viljoen (1994, 1995), Fung and Haggerty (1995), Beard et al. (1996), Schulze et al. (1996, 1997, 2000), Taylor et al. (1996), Viljoen et al. (1996),

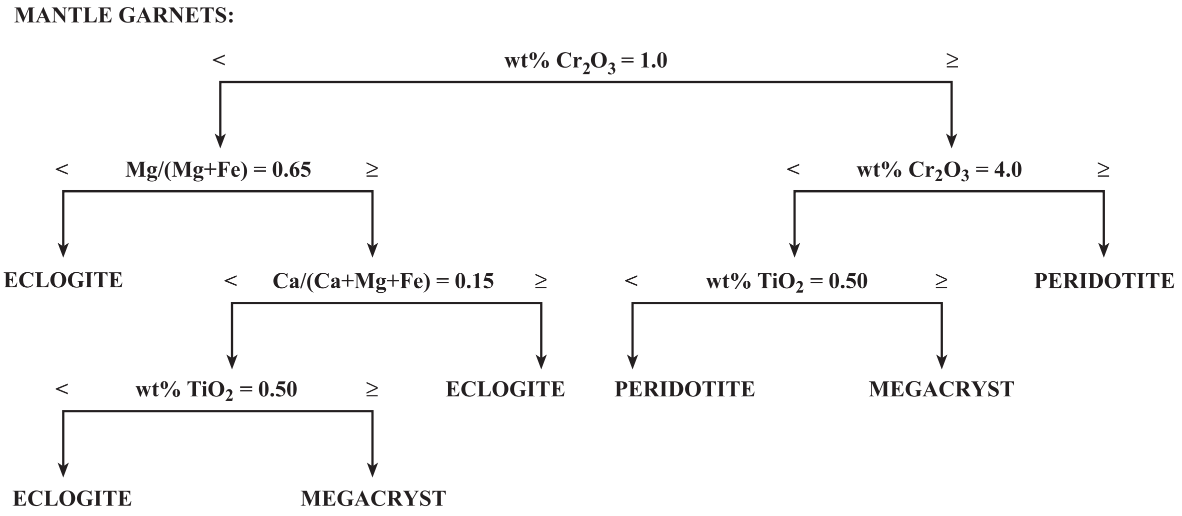

Fig. 9. Flow chart illustrating the steps used to subdivide mantle garnets into groups representing those from eclogites, peridotites and Cr-poor megacrysts.

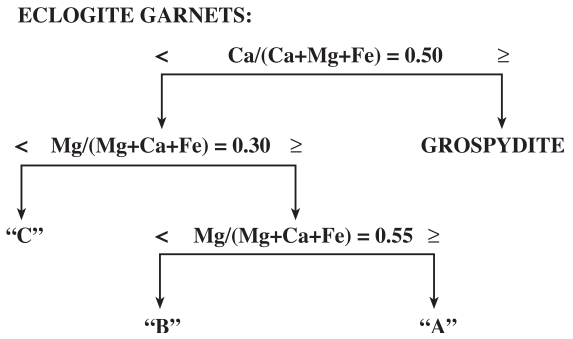

Fig. 10. Flow chart illustrating the steps used to subdivide eclogite garnets. Eclogite garnets are further subdivided into Groups I and II using sodium content, if reliable values for Na_2O values are available. See text for discussion.

Snyder et al. (1997), El Fadili and Demaiffe (1999), Kopylova et al. (1999) and this paper. Alkremite garnets, used for comparison with other rock types but not specifically used to define the chemical screens, are from Nixon et al. (1978), Shee (1978), Exley et al. (1983), Mazzone and Haggerty (1989a,b), and Viljoen (1994).

Harzburgite garnet data were taken from Pokhilenko et al. (1977, 1991, 1993), Dawson et al. (1978), Sobolev et al. (1984) Nixon et al. (1987), Boyd and Nixon (1988), Hops (1989), Skinner (1989), Viljoen et al. (1992), Boyd et al. (1993), Schulze (1995), Pearson et al. (1994, 1999), Schulze et al. (1997) and Burgess and Harte (1999). Lherzolite garnet data are from Boyd (1973), Cox et al. (1973), Nixon and Boyd (1973b), Hearn and Boyd (1975), Boyd et al. (1976), Danchin and Boyd (1976), Pokhilenko et al. (1977, 1991), Smith (1977), Sobolev (1977), Bishop et al. (1978), Boyd and Nixon (1978), Carswell et al. (1979), MacGregor (1979), Boyd and Danchin (1980), Robey (1981), Shee et al. (1982), Hearn and McGee (1984), Mitchell (1984), Sobolev et al. (1984), Eggler et al. (1987), Hops (1989), Nehru and Reddy (1989), Skinner (1989), Hall (1991), Pearson et al. (1994, 1999), Viljoen et al. (1994), Vicker (1997), Burgess and Harte (1999), Kopylova et al. (1999) and this paper.

Analyses of garnets belonging to the Cr-poor megacryst suite are from Nixon and Boyd (1973a), Jakob (1977), Robey (1981), Hops (1989), de Bruin (1991) and Schulze (1997).

3. Distinction between crustal and mantle garnets

As kimberlites pass through both the uppermost upper mantle and the entire thickness of the continental crust on their rise to Earth's surface, they are likely to contain garnets derived from both mantle and crustal regions. In most kimberlites, mantle-derived xenoliths appear to be far more abundant than xenoliths that belong to the crustal portion of the crystalline basement, although locally garnet-bearing (and other) crystalline crustal rocks may be relatively abundant (e.g., Dawson and Smith, 1987). In studies of garnet xenocrysts from 32 kimberlites from South Africa and North America (4500 garnets), Schulze (1993, 1994) found that 2/3 of the kimberlites contained some crustal garnets and 3% of all the garnet xenocrysts in these kimberlites were derived from crustal rocks (using an earlier formulation of this classification scheme). Approximately one-quarter of the garnet xenocrysts in the Lace kimberlite are crustal (Schulze, 1994). Thus, it is important to be able to

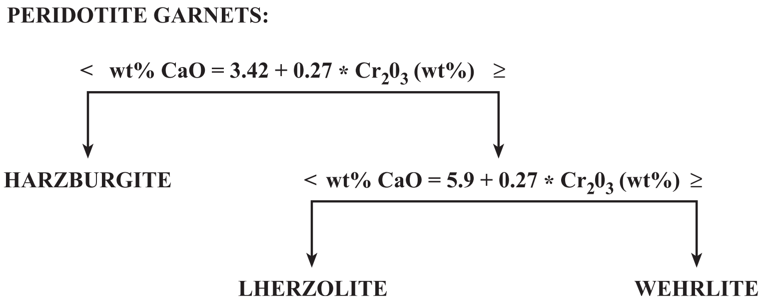

Fig. 11. Flow chart illustrating the steps used to subdivide peridotite garnets into harzburgite, lherzolite and wehrlite subgroups.

Table 1
Geographic–tectonic distribution of samples in database

	Lherzolite	Harzburgite	Megacryst	Eclogite
Kaapvaal Craton	208	55	422	458
Kaapvaal margin	14		27	
Zimbabwe Craton				117
West African Craton				87
Congo Craton	12			16
Tanzanian Craton	3			
Namaqua Belt	55			
Siberian Platform	18	29		116
Dharwar Craton	6			
Slave Craton	26	5		28
Superior Craton	82			9
Grenville Province	43			
Canadian Cordillera	2			
Wyoming Craton	15			
Yavapai-Mazatzal Belt, USA	14		98	96
Adeladian Belt, Australia			12	
Total	498	89	559	927

screen out crustal garnets from kimberlite xenocryst populations in order to interpret properly the mantle population. Furthermore, in kimberlite and diamond exploration work, in which most garnets from sediment samples are likely to be derived from exposed crustal rocks, it is essential to be able to screen out the crustal garnet population in the search for the kimberlite-derived (i.e., mantle) garnets.

Garnets from crustal and mantle sources are compared in Fig. 1, in terms of Ca/(Ca + Mg) and Mg/(Mg + Fe) values (mole proportions). In general, crustal garnets are characterized by lower Mg/(Mg + Fe) values relative to those from mantle rocks, but many crustal garnets with very high or low values of Ca/(Ca + Mg) overlap mantle garnets in terms of Mg/(Mg + Fe).

With the exception of some Ca-poor Cr-pyropes from harzburgites, mantle garnets do not extend to the very low Ca/(Ca + Mg) values of some of the pyrope-rich garnets in high-grade quartzites and whiteschists, such as those described from coesite-bearing rocks in the Alps (e.g., Chopin, 1984) and a cut-off of Ca/(Ca + Mg) = 0.08 discriminates between the Mg-rich, Ca-poor crustal garnets and most of the Mg-rich mantle garnets that have higher values of Ca/(Ca + Mg). The crustal Ca-poor pyropes are essentially Cr-free, however, whereas similarly magnesian and Ca-poor mantle garnets (such as diamond-bearing low-Ca garnet harzburgites) are Cr-rich. Mantle garnets with $Ca/(Ca+Mg) < 0.08$ have Cr_2O_3 contents above 0.5 wt.%, and this cutoff is used in addition to distinguish between Ca-poor, Mg-rich garnets from the crust and those from the mantle (Fig. 1). The upper limit of Ca/(Ca + Mg) values for mantle garnets is 0.90.

For garnets of intermediate Ca/(Ca + Mg) values ($0.08 < Ca/(Ca+Mg) < 0.90$), the two garnet groups are divided at $Ca/(Ca+Mg) = 1.1 - 2Mg/(Mg+Fe)$, with mantle garnets having Mg/(Mg + Fe) values above this and those from crustal rocks below (Fig. 1). Five mantle garnets, all from eclogites, and 27 crustal garnets fall outside of the defined boundaries for these rock types, representing < 1% and 4% of the database for each rock type, respectively (Table 2). The discriminant line has been chosen to favour correct classification of mantle garnets, as few crustal garnets are expected to occur in most kimberlites and the classification is primarily intended for use with garnets in kimberlite. If this discriminant is used for garnets from exploration samples, some Mg-rich crustal garnets could be incorrectly classified as mantle-derived (specifically eclogitic). In the absence of a significantly larger number of additional clearly mantle-derived garnets in such an exploration sample (e.g., Cr-pyropes and Cr-poor megacryst garnets), as predicted by garnet populations from known kimberlites (Schulze, 1997), such a result should be viewed with suspicion.

Table 2
Comparison of garnet classifications: classification proposed in this paper vs. rock name given in the literature for garnets in the database

Name in proposed classification	Literature rock name				
	Crustal (624)[a]	Lherzolite (498)	Harzburgite (89)	Megacryst (559)	Eclogite (927)
Crustal	597	0	0	0	5
Wehrlite	0	0	1	0	2
Lherzolite	0	438	15	12	22
Harzburgite	0	12	72	0	4
Megacryst	0	45	0	541	21
Eclogite	27	3	1	6	873
% Agreement	96	88	81	97	94

[a] Number in parentheses indicates number of garnets from that rock type in the database.

4. Subdivision of mantle garnets

4.1. Eclogite vs. peridotite

The three general categories of mantle garnets considered in this paper are eclogite, peridotite, and Cr-poor megacryst. Eclogites are essentially bimineralic garnet–clinopyroxene rocks that may contain a variety of accessory minerals, such as rutile, kyanite, diamond, graphite and coesite. With few exceptions, the silicates in rocks termed "eclogite" have low Cr_2O_3 contents, and cut-off values at modest levels of Cr_2O_3 (0.5–4.0 wt.%; e.g., Gurney, 1984; Schulze, 1989b) have been proposed to distinguish eclogite-derived garnets from those from peridotites. A cut-off of 1.0 wt.% Cr_2O_3 is used in this classification. In the database, garnets from 29 of 927 rocks described as eclogite have Cr_2O_3>1.0 wt.% (3% of eclogite garnets) and only 5 of 541 peridotitic garnets have $Cr_2O_3 < 1.0$ wt.% (less than 1% of peridotitic garnets) (Fig. 2).

4.2. Pyroxenites

One group that is not distinguished in this classification is "pyroxenite". Rocks rich in pyroxene and poor in, or free of, olivine are common, though typically not abundant, in many xenolith suites in kimberlites. They undoubtedly have a variety of origins. The Cr-rich eclogites in the database would be called garnet clinopyroxenites by many workers, and some garnet pyroxenites, especially those containing primary spinel (e.g., Eggler et al., 1987), are probably more closely related to peridotites than to eclogites. Two-pyroxene garnet websterites may be also be modal variants of peridotites (e.g., Cox et al., 1973) and others may be closely related to eclogites (e.g., Hatton, 1978). Some Ti-rich pyroxenites may be cumulates related to the Cr-poor megacryst suite (e.g., Kopylova et al., 1999). In the classification scheme proposed here, such garnets will be classified as the variety of peridotite, eclogite or Cr-poor megacryst that they would most closely resemble chemically.

4.3. Eclogite vs. Cr-poor megacryst

Although peridotite garnets are distinct from eclogite garnets in terms of Cr_2O_3, the other important type of garnet from the mantle, from the Cr-poor megacryst suite (e.g., Eggler et al., 1979; Gurney et al., 1979; Schulze, 1987) overlaps both eclogitic and peridotitic garnets in Cr_2O_3 content. Unlike the large variation in Ca/(Ca + Mg + Fe) and Mg/(Mg + Fe) exhibited by eclogite garnets, however, Cr-poor megacryst garnets show only a small range in these values, illustrated in Fig. 3. Compositions of only two megacryst garnets of 559 in the database (< 1%) are outside of the ranges $0.09 < Ca/(Ca + Mg + Fe) < 0.15$ and $Mg/(Mg + Fe) > 0.65$. Cr-poor megacryst garnets typically have elevated Ti contents relative to eclogite garnets, however, and the two groups can be effectively separated on the basis of TiO_2, Mg/(Mg + Fe) and Ca/(Ca + Mg). Only 150 eclogite garnets in the database overlap Cr-poor megacryst garnets in terms of Ca/(Ca + Mg) and Mg/(Mg + Fe). Comparison of Ti contents of these two groups (megacrysts with $Cr_2O_3 < 1.0$ wt.% and the sub-set of 150 eclogitic garnets) in Fig. 4 shows little overlap, and a distinction between the two groups is made at 0.5 wt.% TiO_2. Seven of the 265 Cr-poor megacryst garnets with Cr_2O_3 below 1.0 wt.% have less than 0.5 wt.% TiO_2 (3% of this megacryst sub-group and 1% of the whole megacryst suite). Eighteen eclogite garnets have TiO_2>0.5 wt.%, which would cause them to be mis-classified as garnets belonging to the Cr-poor megacryst suite. Fourteen of those are from the Kaalvallei kimberlite, however, which is anomalous in the Ti-rich eclogites that occur there (Viljoen, 1994). Aside from the Kaalvallei Ti-rich eclogite garnets, only four other eclogite garnets have TiO_2 values corresponding to the Cr-poor megacryst field (less than 1% of the 927 eclogites in the database). Even including the Kaalvallei Ti-rich eclogites, only 2% of the eclogites overlap garnets from the Cr-poor megacryst suite (Table 2).

4.4. Subdivision of eclogite garnets

Although mantle eclogites contain a wide variety of primary accessory minerals (e.g., rutile, kyanite, corundum, diamond, graphite, coesite, sanidine, orthopyroxene, ilmenite, apatite, zircon, phlogopite, titanite, spinel, amphibole, sulphides), and their garnets and clinopyroxenes range widely in composition, there are few paragenetic or chemical screens that allow meaningful subdivision of this group. One classification that has gained wide acceptance, however, is based on the Na_2O content of eclogitic garnet. Many eclogite suites have garnets with bimodal distribution of Na contents, which has been especially well documented in samples from the Roberts Victor Mine (e.g., MacGregor and Carter, 1970; Hatton, 1978; McCandless and Gurney, 1989; Schulze et al., 2000). Based on Roberts Victor and other eclogite suites (e.g., Gurney, 1984), eclogite garnets are divided into two groups at 0.07 wt.% Na_2O. Group II eclogite garnets have < 0.07 wt.% Na_2O and those from Group I have ≥ 0.07 wt.% Na_2O.

The high sodium content of Group I eclogite garnets has been proposed as a diamond exploration tool, as the garnets in most diamond-bearing eclogites have $Na_2O > 0.07$ wt.% and are classified as Group I. Of the 145 diamond-bearing eclogites in the database, only seven have $Na_2O < 0.07$ wt.%. Group I eclogite garnets are not completely correlative with diamonds, however, as garnets from many graphite-bearing eclogites have $Na_2O > 0.07$ wt.% (e.g., Grutter and Quadling, 1999), and most Group I eclogites do not contain any carbon polymorph.

Not all published eclogite garnet data have reliable sodium values. Sodium is typically not reported for analyses obtained using energy dispersive microprobe methods, and some older wavelength dispersive microprobe data are imprecise. In this classification scheme, sub-division into Groups I and II based on sodium content of garnet is applied at the end of the routine in appropriate cases, modifying the other eclogite sub-groupings suggested below.

Kyanite-bearing eclogites are well known and fairly common and corundum-bearing examples also occur, but are less abundant. Kyanite eclogites with high Ca garnets ($Ca/(Ca+Mg+Fe) > 0.50$) are referred to as grospydites (e.g., Sobolev et al., 1968). In Fig. 5, eclogites containing kyanite and/or corundum are compared with eclogites lacking these aluminous minerals, and it is clear that most eclogites in which garnets have $Ca/(Ca+Mg+Fe) > 0.50$ also contain kyanite and/or corundum. Thus, garnets with $Ca/(Ca+Mg+Fe) > 0.50$ are classified as G-type (for grospydite), although not all such garnets necessarily represent disaggregated kyanite eclogites, which is part of the true definition of grospydite. Some garnets with $Ca/(Ca+Mg+Fe) > 0.50$ are from kyanite-free, corundum-bearing eclogites and a few contain neither corundum nor kyanite (Fig. 5). Furthermore, it is clear from the wide variation in $Ca/(Ca+Mg+Fe)$ contents of garnets from corundum/kyanite eclogites that the presence of these aluminous minerals is not restricted to eclogites with high calcium garnets.

Eclogitic garnets with $Ca/(Ca+Mg+Fe) < 0.50$ have been subdivided into three groups, based on their $Mg/(Mg+Ca+Fe)$ values (Fig. 5). These three groups, termed A, B and C have ranges of $Mg/(Mg+Ca+Fe)$ as illustrated in Fig. 5, corresponding to the compositional breaks suggested by Coleman et al. (1965) in their study of eclogites from a variety of geologic settings. The original three Groups A, B and C were established in order to "subdivide the various types [of eclogite] into geologically similar occurrences" (Coleman et al., 1965, p. 485) and it was *not* their intention to use these groupings to classify eclogites based on garnet composition. [At that time, the mineral chemical database for mantle eclogites was so small that all mantle eclogite garnets were thought to be pyropic and correspond to Group A. It has since been shown that mantle eclogites have an extremely wide compositional range (e.g., MacGregor and Carter, 1970; Hatton, 1978; Ater, 1982; Fung and Haggerty, 1995). The A, B and C designations are used here solely to divide the large compositional range into smaller, but arbitrary, fields (with no particular petrologic significance), to facilitate discussion of various eclogite populations. For example, diamond-bearing eclogites (Fig. 5) can be described as primarily belonging to Group B, with Group A examples being less abundant, and Group C and grospydite varieties being extremely rare. The compositional ranges and A, B, C designations have been chosen for historical purposes, consistent with continued use of the Coleman et al. (1965) terminology (e.g., Fung and Haggerty, 1995; Snyder et al., 1997).

Also illustrated in Fig. 5 are compositions of garnets from alkremites (Ponomarenko, 1975), which are garnet–spinel rocks, some of which contain corundum (e.g., Nixon et al., 1978). Ponomarenko (1975) considered alkremites to belong to an "ultramafic" paragenesis. They are much less abundant and less widely distributed than are either peridotites or eclogites. Although their mineral assemblage is distinct from eclogites (alkremites lack clinopyroxene and primary spinel is extremely rare in mantle eclogites; Viljoen, 1994), and they have only a small range in composition, in terms of Ca/Mg/Fe values (Fig. 5), as well as Ti, Cr and Mn contents, their garnets are similar in composition to some in eclogites. In garnet composition, alkremites form a sub-group of the eclogites and thus in the classification scheme alkremite garnets are grouped with those from eclogites.

4.5. Cr-poor megacryst vs. peridotite

As noted above, eclogites with Cr_2O_3>1.0 wt.% are uncommon, and most garnets with Cr_2O_3>1.0 wt.% are from peridotites and the Cr-poor megacryst suite. As the name implies, Cr-poor megacryst garnets do not have very high Cr_2O_3 contents, and those with $Cr_2O_3 < 1.0$ wt.% were distinguished from eclogites above. Garnets from most Cr-poor megacryst suites have $Cr_2O_3 < 2–3$ wt.%, especially those from Group I kimberlites in southern Africa (e.g., Nixon and Boyd, 1973a,b; Gurney et al., 1979), although those from North America (e.g., Eggler et al., 1979; Schulze, 1997), and from Group II kimberlites in southern Africa (e.g., Moore and Gurney, 1991), can reach Cr_2O_3 values above 4 wt.% (Fig. 6).

Garnets in most peridotites are considerably richer in Cr_2O_3. Cr_2O_3 values above 5 wt.% are typical and those above 10 wt.% are not uncommon (Fig. 6).

Titanium contents are also useful in distinguishing between garnets that belong to the Cr-poor megacryst suite and those from peridotites. Megacryst garnets are mostly above 0.5 wt.% TiO_2 whereas those from peridotites, though occupying a large range, have TiO_2 contents primarily below that value. The smallest overlap between these two groups occurs by defining megacryst garnets as having TiO_2>0.50 wt.% and $Cr_2O_3 < 4.0$ wt.%, and peridotite garnets having compositions outside this range, as illustrated in Fig. 6. Using these values as screens, 12 of 559 Cr-poor megacryst garnets and 45 of 587 peridotites are incorrectly classified, 5% of the summed populations of the two groups. Within some individual kimberlite populations, there is no overlap between garnets from the megacryst suite and those from "sheared" peridotites, such as at Jagersfontein (Hops, 1989).

Most of the peridotite garnets that correspond in composition to Cr-poor megacrysts occur in the population of high-temperature, deformed ("sheared") peridotites (e.g., Nixon and Boyd, 1973a,b). This is not surprising, as many workers have concluded that the parent magma of the megacrysts has infiltrated the sheared peridotites and metasomatised them (e.g., Gurney and Harte, 1980) and so the similarities in composition between the two groups reflect genetic links. As many of the Ti-rich garnets in the high-temperature peridotites are zoned (e.g., Smith and Boyd, 1992), whereas garnet megacrysts are typically homogeneous, a test for homogeneity in suspect garnets might assist in distinguishing one type of Ti-rich, Cr-poor garnet from the other.

4.6. Subdivision of peridotite garnets

Pyroxene-bearing peridotites (i.e., not dunites) are subdivided into lherzolite, harzburgite and wehrlite, based on the presence or absence of modal orthopyroxene and clinopyroxene. Harzburgites contain orthopyroxene and lack clinopyroxene, wehrlites contain clinopyroxene but lack orthopyroxene and lherzolites contain both clinopyroxene and orthopyroxene. Sobolev et al. (1973) showed that Ca and Cr correlate positively in garnets from lherzolites, and the field of garnets from lherzolites in the database is shown in terms of wt.% CaO and wt.% Cr_2O_3 (Fig. 7). Garnets that plot within the field defined by the lherzolite garnets are classified as lherzolite, those with CaO values above the lherzolite field are termed wehrlite, and those with CaO values below the lherzolite field are termed harzburgite. The lower limit of the lherzolite field in this figure ($CaO = 3.42 + 0.27Cr_2O_3$, with oxide values in weight percent) is taken from Fig. 3 of Gurney (1984), dividing the garnets termed G9 and G10 in his study of peridotite–suite garnets included in diamonds. Garnets termed G9 correspond to those from lherzolites and those termed G10 correspond to harzburgite garnets. The upper CaO limit of the lherzolite field in Fig. 7 is drawn to enclose the lherzolite garnets in the database, and be parallel to the lower CaO limit. Four lherzolite garnets have Cr_2O_3 contents below 1.0 wt.%, and 12 plot below the lower CaO limit. Of the latter, two significantly within the harzburgite field are in a zoned garnet from Jagersfontein described by Burgess and Harte (1999). The composition of the core of this garnet is so far into the harzburgite field that it is probably not in equilibrium with the clinopyroxene in the rock and thus is not considered in defining the lherzolite field (also see Pokhilenko et al., 1999). A similar situation was documented in a lherzolite from the Roberts Victor mine by Viljoen et al. (1994), who concluded that a low-CaO garnet in a lherzolite was out of equilibrium with the clinopyroxene in the peridotite, which probably represented late, metasomatic introduction of clinopyroxene into a low-Ca garnet harzburgite.

Fig. 7 also illustrates compositions of garnets from rocks described as in the literature as harzburgites. As this type of garnet does not have much influence on the screens used for classification, only a few sources were used for data, simply to illustrate how harzburgite garnets might be classified. A significant proportion (~ 17%) of these garnets plot in the lherzolite field. This suggests that the minerals in these rocks are in equilibrium with clinopyroxene, though it does not appear in the mode of the rock. Such garnets would be classified as lherzolite-derived, and are common in harzburgites (Schulze, 1995).

Most peridotite–suite garnets that occur as inclusions in diamonds correspond to compositions in the harzburgite field (the G10 garnets of Gurney, 1984), and this chemical characteristic has proven to be one of the most valuable features of garnets used in diamond exploration. Further subdivisions of the harzburgite field have been used by Gurney (1980) to give "scores" to garnet xenocryst populations, "scores" used in ranking the diamond potential of individual kimberlites. Versions of these harzburgite subdivisions have been illustrated by Hill (1989), Griffin et al. (1992), and Lee (1993), but are not utilized in this classification scheme.

Garnets that plot above the lherzolite field, in the wehrlite field, are not common in kimberlites. Some true garnet wehrlites have been described (e.g., Sobolev et al., 1973; Schulze, 1989a) and garnets from rocks referred to as Cr-rich eclogites also fall within the wehrlite field. Most of the unusual green garnet xenocrysts, rich in the uvarovite component, such as those described by Sobolev et al. (1973), Clarke and Carswell (1977) and Schulze (1989) correspond to wehrlite garnets.

5. Evaluation of the classification scheme

Table 2 is cross-tabulation comparing original rock names in the literature for garnets in the database with names that would be assigned to them using the new classification. The original name is returned in over 93% of the cases.

Three suites of mantle garnets not included in the database have also been used to independently evaluate the new classification. They are garnets from peridotites from Letseng-la-Terae, Lesotho (new data from Moore and Lock, 2001), garnet megacrysts from Orapa, Botswana (Shee, 1978) and garnets from eclogites from the Jagersfontein kimberlite in South Africa (Dawson and Smith, 1986; Pyle and Haggerty, 1998). Garnets from these populations have been classified using the new scheme in this paper, and results are compared with the names given to the rocks in the original studies.

Of the 17 clinopyroxene-bearing peridotites from Letseng, all are classified as peridotite. Garnets from 16 of these are classified as lherzolite and one as harzburgite (though very near the lherzolite field). All 20 of the Orapa garnet megacrysts are classified as megacrysts by the new classification scheme. Of the 76 eclogites from Jagersfontein, one Cr-rich ($Cr_2O_3 = 1.59$ wt.%) garnet would be classified as a lherzolite garnet. One Ti-rich eclogite garnet (0.90 wt.% TiO_2) would be classified as derived from the Cr-poor megacryst suite. As the clinopyroxene with which this garnet coexists (Pyle and Haggerty, 1998) is anomalous relative to other eclogite clinopyroxenes at Jagersfontein, but similar to Cr-poor clinopyroxene megacrysts from this location (Hops, 1989), it is likely that the sample was originally mis-classified, but is correctly classified in the new scheme. The remaining 74 Jagersfontein eclogite garnets are classified as eclogite-derived. Eclogites with Na_2O values of both Groups I and II occur, although there is not a clear separation between the two groups at $Na_2O = 0.07$ wt.%. In terms of Mg/(Mg + Ca + Fe) values, Group C eclogites are absent and the ratio of Group B to Group A is about 2:1.

Thus, the new classification scheme yields satisfactory results in classifying garnets from mantle xenoliths of known paragenesis for the three suites used here, and for the original data in the database.

6. Concluding remarks

The mantle garnet classification scheme proposed in this paper is thought to represent a significant improvement over those currently available in the published literature. It is based on a large body of published data of garnets from mantle xenoliths in kimberlites worldwide. The chemical screens utilized to distinguish between populations typically only "mis-classify" a few percent of garnets from any given rock type, giving a high degree of confidence in their general applicability to garnets from unknown sources.

Although the primary intention of the classification is to understand better garnets from the upper mantle, to aid in furthering our knowledge of the constitution of this inaccessible part of Earth, several features of the scheme have direct applicability to the more practical pursuit of exploration for kimberlites and diamonds. With this scheme, garnets from crustal sources can be screened out from exploration samples, and in a single sequence of steps those that have a high probability of indicating the presence of diamonds (e.g., Group I eclogites and low-Ca garnet harzburgites) can be identified.

Acknowledgements

I thank Claudio Cermignani and Kimberley Scully for assistance with electron microprobe analysis, and Mike Kolcun for producing the classification macro. Reviews by Nick Pokhilenko, Bruce Wyatt and Herman Grutter improved the manuscript, and I also benefited from discussions with Herman and Bruce. Alison Dias and Jennifer Storer-Folt are thanked for their assistance with figure and manuscript preparation. Financial assistance was provided by N.S.E.R.C.

References

Abd El-Naby, H., Frisch, W., Hegner, E., 2000. Evolution of the Pan-African Wadi Haimur metamorphic sole, Eastern Desert, Egypt. J. Metamorph. Geol. 18, 639–651.

Ater, P.C., 1982. Petrology and geochemistry of mantle eclogite xenoliths from Colorado–Wyoming kimberlites, MS thesis, Colorado State University.

Azor, A., Ballèvre, M., 1997. Low-pressure metamorphism in the Sierra Albarrana Area (Variscan Belt, Iberian Massif). J. Petrol. 38, 35–64.

Beard, B.L., Fraracci, K.N., Taylor, L.A., Snyder, G.A., Clayton, R.A., Mayeda, T.K., Sobolev, N.V., 1996. Petrography and geochemistry of eclogites from the Mir kimberlite, Yakutia, Russia. Contrib. Mineral. Petrol. 125, 293–310.

Bégin, N.J., Pattison, D.R.M., 1994. Metamorphic evolution of granulites in the Minto Block, northern Québec: extraction of peak $P-T$ conditions taking account of late Fe–Mg exchange. J. Metamorph. Geol. 12, 411–428.

Bishop, F.C., Smith, J.V., Dawson, J.B., 1978. Na, K, P and Ti in garnet, pyroxene and olivine from peridotite and eclogite xenoliths from African kimberlites. Lithos 11, 153–173.

Bose, A., Fukuoka, M., Sengupta, P., Dasgupta, S., 2000. Evolution of high-Mg–Al granulites from Sunkarametta, eastern Ghats, India: evidence for a lower crustal heating-cooling trajectory. J. Metamorph. Geol. 18, 223–240.

Boyd, F.R., 1973. Appendix of mineral analyses. In: Nixon, P.H. (Ed.), Lesotho Kimberlites. Lesotho National Development, Maseru, pp. 33–36.

Boyd, F.R., Danchin, R.V., 1980. Lherzolites, eclogites and megacrysts from some kimberlites of Angola. Am. J. Sci. 280-A, 528–549.

Boyd, F.R., Gurney, J.J., 1982. Low calcium garnets: keys to craton structure and diamond crystallization. Carnegie Inst. Wash. Yrbk. 81, 261–267.

Boyd, F.R., Nixon, P.H., 1978. Ultramafic nodules from the Kimberley pipes. Geochim. Cosmochim. Acta 42, 1267–1282 (Appendix).

Boyd, F.R., Nixon, P.H., 1988. Low-Ca garnet harzburgites: origin and role in craton structure. Annu. Rep. Dir. Geophys. Lab. 2102, 8–13.

Boyd, F.R., Fujii, T., Danchin, R.V., 1976. A noninflected geotherm for the Udachnaya kimberlite pipe, USSR. Carnegie Inst. Wash. Yrbk. 75, 523–531.

Boyd, F.R., Pearson, D.G., Nixon, P.H., Mertzman, S.A., 1993. Low-calcium garnet harzburgites from southern Africa: their relations to craton structure and diamond crystallization. Contrib. Mineral. Petrol. 113, 352–366.

Bruno, M., Compagnoni, R., Rubbo, M., 2001. The ultra-high pressure coronitic and pseudomorphous reactions in a metagranodiorite from the Brossasco-Isasca Unit, Dora-Maira Massif, western Italian Alps: a petrographic study and equilibrium thermodynamic modeling. J. Metamorph. Geol. 19, 33–43.

Burgess, S.R., Harte, B., 1999. Tracing lithosphere evolution through the analysis of heterogeneous G9/G10 garnets in peridotite xenoliths: I. Major element chemistry. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), Proceedings of the VIIth International Kimberlite Conference, vol. 1. Red Roof Design, Cape Town, pp. 66–79.

Carswell, D.A., Clarke, D.B., Mitchell, R.H., 1979. The petrology and geochemistry of ultramafic nodules from Pipe 200, northern Lesotho. In: Boyd, F.R., Meyer, H.O.A. (Eds.), The Mantle Sample: Inclusions in Kimberlites and Other Volcanics. Amer. Geophys. Union, Washington, pp. 127–144.

Cartwright, I., Buick, I.S., Maas, R., 1997. Fluid flow in marbles at Jervois, central Australia: oxygen isotope disequilibrium and zoning produced by decoupling of mineralogical and isotopic resetting. Contrib. Mineral. Petrol. 128, 335–351.

Chinner, G.A., Cornell, D.H., 1974. Evidence of kimberlite–grospydite reaction. Contrib. Mineral. Petrol. 45, 153–160.

Chopin, C., 1984. Coesite and pure pyrope in high-grade blueschists of the Western Alps: a first record and some consequences. Contrib. Mineral. Petrol. 86, 107–118.

Chopin, C., Henry, C., Michard, A., 1991. Geology and petrology of the coesite-bearing terrain, Dora Maira massif, Western Alps. Eur. J. Mineral. 3, 263–291.

Clarke, D.B., Carswell, D.A., 1977. Green garnets from the Newlands kimberlite, Cape Province, South Africa. Earth Planet. Sci. Lett. 34, 30–38.

Clarke, G.L., Klepeis, A., Daczko, N.R., 2000. Cretaceous high-*P* granulites at Milford Sound, New Zealand: metamorphic history and emplacement in a convergent margin setting. J. Metamorph. Geol. 18, 359–374.

Coleman, R.G., Lee, D.E., Beatty, L.B., Brannock, W.W., 1965. Eclogites and eclogites: their similarities and differences. Geol. Soc. Amer. Bull. 76, 483–508.

Compagnoni, R., Hirajima, T., 2001. Superzoned garnets in the coesite-bearing Brossasco-Isasca Unit, Dora-Maira massif, Western Alps, and the origin of the whiteschists. Lithos 57, 219–236.

Cooke, R.A., O'Brien, P.J., Carswell, D.A., 2000. Garnet zoning and the identification of equilibrium mineral compositions in high-pressure–temperature granulites from the Moldanubian Zone, Austria. J. Metamorph. Geol. 18, 551–569.

Cortesogno, L., Lucchetti, G., 1986. Andradites and chromian andradites from Northern Apennine ophiolites (Italy). Neues Jahrb. Mineral. Abh. 155, 165–184.

Cox, K.G., Gurney, J.J., Harte, B., 1973. Xenoliths from the Matsoku Pipe. In: Nixon, P.H. (Ed.), Lesotho Kimberlites. Lesotho National Development, Maseru, pp. 76–92. Plus Appendix.

Danchin, R.V., Boyd, F.R., 1976. Ultramafic nodules from the Premier kimberlite pipe, South Africa. Carnegie Inst. Wash. Yrbk. 75, 531–538.

Danchin, R.V., Wyatt, B.A., 1979. Statistical Cluster Analysis of Garnets from Kimberlites and Their Xenoliths. Kimberlite Symposium II, Cambridge.

Dawson, J.B., Smith, J.V., 1986. Relationship between eclogites and certain megacrysts from the Jagersfontein kimberlite, South Africa. Lithos 19, 325–330.

Dawson, J.B., Smith, J.V., 1987. Reduced sapphirine granulite xenoliths from the Lace kimberlite, South Africa: implications for the deep structure of the Kaapvaal Craton. Contrib. Mineral. Petrol. 95, 376–383.

Dawson, J.B., Stephens, W.E., 1975. Statistical classification of garnets from kimberlites and associated xenoliths. J. Geol. 83, 589–607.

Dawson, J.B., Smith, J.V., Delaney, J.S., 1978. Multiple spinel-garnet peridotite transitions in upper mantle: evidence from a garnet harzburgite xenolith. Nature 273, 741–743.

de Bruin, D., 1989. Mantle eclogites from the Schuller kimberlite, Transvaal, South Africa. S. Afr. J. Geol. 92, 134–145.

de Bruin, D., 1999. The megacryst suite from the Schuller kimberlite, South Africa. PhD thesis, University of Cape Town.

Dunn, P.J., 1978. On the composition of some Canadian green garnets. Can. Mineral. 16, 205–206.

Eggler, D.H., McCallum, M.E., Smith, C.B., 1979. Megacryst assemblages in kimberlites from northern Colorado and southern Wyoming. In: Boyd, F.R., Meyer, H.O.A. (Eds.), The Mantle Sample: Inclusions in Kimberlites and Other Volcanics. AGU, Washington, pp. 213–226.

Eggler, D.H., McCallum, M.E., Kirkley, M.B., 1987. Kimberlite-transported nodules from Colorado–Wyoming: a record of enrichment of shallow portions of an infertile lithosphere. In: Morris, E.M., Pasteris, J.D. (Eds.), Mantle Metasomatism and Alkaline Magmatism. Geol. Soc. Amer. Spec. Paper, vol. 215, pp. 77–90.

El Fadili, S., Demaiffe, D., 1999. Petrology of eclogite and granulite nodules from the Mbuji Mayi kimberlites (Kasai, Congo): significance of kyanite–omphacite intergrowths. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), Proceedings of the VIIth International Kimberlite Conference, vol. 1. Red Roof Design, Cape Town, pp. 205–213.

Exley, R.A., Smith, J.V., Dawson, J.B., 1983. Alkremite, garnetite and eclogite xenoliths from Bellsbank and Jagersfontein. Am. Mineral. 68, 512–516.

Fitzsimons, I.C.W., 1996. Metapelitic migmatites from Brattstrand Bluffs, East Antarctica—metamorphism, melting and exhumation of the mid crust. J. Petrol. 37, 395–414.

Fitzsimons, I.C.W., Harley, S.L., 1994. The influence of retrograde cation exchange on granulite $P-T$ estimates and a convergence technique for the recovery of peak metamorphic conditions. J. Petrol. 35, 543–576.

Ford, F.D., 1987. Petrology and geochemistry of xenoliths from the Blaauwbosch kimberlite pipe. R.S.A. BSc thesis, Queen's University.

Fraser, G., Worley, B., Sandiford, M., 2000. High-precision geothermobarometry across the High Himalayan metamorphic sequence, Langtang Valley, Nepal. J. Metamorph. Geol. 18, 665–681.

Fung, A., Haggerty, S.E., 1995. Petrography and mineral compositions of eclogites from the Koidu kimberlite complex, Sierra Leone. J. Geophys. Res. 100, 20451–20473.

Garcia-Casco, A., Torres-Roldan, R.L., Millan, G., Monie, P., Haissen, F., 2001. High-grade metamorphism and hydrous melting of metapelites in the Pinos terrane (W Cuba): evidence for crustal thickening and extension in the northern Caribbean collisional belt. J. Metamorph. Geol. 19, 699–715.

Gayk, T., Kleinschrodt, R., 2000. Hot contacts of garnet peridotites in middle/upper crustal level: new constraints on the nature of the late Variscan high-*T*/low-*P* event in the Moldanubian (central Voges/NE France). J. Metamorph. Geol. 18, 293–305.

Gordon, T.M., Ghent, E.D., Stout, M.Z., 1991. Algebraic analysis of the biotite–sillimanite isograd in the File Lake area, Manitoba. Can. Mineral. 29, 673–686.

Gordon, T.M., Aranovich, L.Ya., Fed'kin, V.V., 1994. Exploratory data analysis in thermobarometry: an example from the Kisseynew Sedimentary Gneiss Belt, Manitoba, Canada. Am. Mineral. 79, 973–982.

Griffin, W.L., Gurney, J.J., Ryan, C.G., 1992. Variations in trapping temperatures and trace elements in peridotite–suite inclusions from African diamonds: evidence for two inclusion suites, and implications for lithosphere stratigraphy. Contrib. Mineral. Petrol. 110, 1–15.

Griffin, W.L., Fisher, N.I., Friedman, J., Ryan, C.G., O'Reilly, S.Y., 1999. Cr-pyrope garnets in the lithospheric mantle: I. Compositional systematics and relations to tectonic setting. J. Petrol. 40, 679–704.

Grutter, H.S., Quadling, K.E., 1999. Can sodium in garnet be used to monitor eclogitic diamond potential? In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), Proceedings of the VIIth International Kimberlite Conference, vol. 1. Red Roof Design, Cape Town, pp. 314–320.

Grutter, H.S., Apter, D.B., Kong, J., 1999. Crust–mantle coupling: evidence from mantle-derived xenocrystic garnets. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), Proceedings of the VIIth International Kimberlite Conference, vol. 1. Red Roof Design, Cape Town, pp. 307–313.

Guiraud, M., Powell, R., Cottin, J.-Y., 1996. Hydration of orthopyroxene-cordierite-bearing assemblages at Laouni, Central Hoggar, Algeria. J. Metamorph. Geol. 14, 467–476.

Gupta, S., Bhattacharya, A., Raith, M., Nanda, J.K., 2000. Contrasting pressure–temperature–deformation history across a vestigal craton mobile belt boundary: the western margin of the Eastern Ghats Belt at Deobhog, India. J. Metamorph. Geol. 18, 683–697.

Gurney, J.J., 1980. Variations in garnet, chromite and ilmenite chemistry and in diamond and micro diamond content from some well characterised kimberlites: An orientation survey. Report published by Mineral Services.

Gurney, J.J., 1984. A correlation between garnets and diamonds. In: Glover, J.E., Harris, P.G. (Eds.), Kimberlite Occurrence and Origin: A Basis for Conceptual Models in Exploration. University of Western Australia Publication, vol. 8, pp. 376–383.

Gurney, J.J., Harte, B., 1980. Chemical variations in upper mantle nodules from southern African kimberlites. Philos. Trans. R. Soc. Lond., A 297, 273–293.

Gurney, J.J., Switzer, G.S., 1973. The discovery of garnets closely related to diamonds in the Finsch pipe, South Africa. Contrib. Mineral. Petrol. 39, 103–116.

Gurney, J.J., Jakob, W.R.O., Dawson, J.B., 1979. Megacrysts from the Monastery kimberlite pipe, South Africa. In: Boyd, F.R., Meyer, H.O.A. (Eds.), The Mantle Sample: Inclusions in Kimberlites and Other Volcanics. Amer. Geophys. Union, Washington, pp. 227–243.

Gurney, J.J., Harris, J.W., Rickard, R.S., 1984. Minerals associated with diamonds from the Roberts Victor Mine. In: Kornprobst, J. (Ed.), Kimberlites I: Kimberlites and Related Rocks. Elsevier, Amsterdam, pp. 25–32.

Habler, G., Thoni, M., 2001. Preservation of Permo Triassic low pressure assemblages in the Cretaceous high pressure metamorphic Saualpe crystalline basement (Eastern Alps, Austria). J. Metamorph. Geol. 19, 679–697.

Hall, D.C., 1985. The petrology of xenoliths from the Orapa AK1 kimberlite pipe, Botswana. MSc thesis, Queen's University.

Hall, D.C., 1991. A petrological investigation of the Cross kimberlite occurrence, southeastern British Columbia, Canada. PhD Thesis, Queen's University.

Harangi, S.Z., Downes, H., Kosa, L., Szabo, C.S., Thirwall, M.F., Mason, P.R.D., Mattey, D., 2001. Almandine garnet in calc alkaline volcanic rocks of the northern Pannonian basin (Eastern Central Europe): geochemistry, petrogenesis and geodynamic considerations. J. Petrol. 42, 1813–1843.

Hartel, T.H.D., Pattison, D.R.M., 1996. Genesis of the Kapuskasing (Ontario) migmatitic mafic granulites by dehydration melting of amphibolite: the importance of quartz to reaction progress. J. Metamorph. Geol. 14, 591–611.

Hatton, C.J., 1978. The geochemistry and origin of xenoliths from the Roberts Victor mine. PhD thesis, University of Cape Town.

Hearn Jr., B.C., Boyd, F.R., 1975. Garnet peridotite xenoliths in a Montana, U.S.A. kimberlite. Phys. Chem. Earth 9, 247–255.

Hearn Jr., B.C., McGee, E.S., 1984. Garnet peridotites from Williams kimberlites, north central Montana, U.S.A. In: Kornprobst, J. (Ed.), Kimberlites II: The Mantle and Crust–Mantle Relationships. Elsevier, Amsterdam, pp. 57–70.

Hill, S.J., 1989. A study of the diamonds and xenoliths from the Star kimberlite, Orange Free State, South Africa, MSc Thesis, University of Cape Town.

Hills, D.V., Haggerty, S.E., 1989. Petrochemistry of eclogites from the Koidu kimberlite complex, Sierra Leone. Contrib. Mineral. Petrol. 103, 397–422.

Hops, J.J., 1989. Some aspects of the geochemistry of high-temperature peridotites and megacrysts from the Jagersfontein kimberlite pipe. South Africa, PhD Thesis, University of Cape Town.

Jacob, D., Jagoutz, E., Lowry, D., Mattey, D., Kudrjavtseva, G., 1994. Diamondiferous eclogites from Siberia: Remnants of Archean oceanic crust. Geochim. Cosmochim. Acta 58, 5191–5207.

Jago, B.C., Mitchell, R.H., 1989. A new garnet classification technique: divisive cluster analysis applied to garnet populations from Somerset Island kimberlites. In: Ross, J. (Ed.), Kimberlites and Related Rocks, vol. 1: Their Composition, Occurrence, Origin and Emplacement. Geol. Soc. Austr. Spec. Pub., vol. 14, pp. 298–310.

Jakob, W.R.O., 1977. Geochemical aspects of the megacryst suite from the Monastery kimberlite pipe. MSc Thesis, University of Cape Town.

Jerde, E.A., Taylor, L.A., Crozaz, G., Sobolev, N.V., Sobolev, V.N., 1993a. Diamondiferous eclogites from Yakutia, Siberia: evidence for a diversity of protoliths. Contrib. Mineral. Petrol. 114, 189–202.

Jerde, E.A., Taylor, L.A., Crozaz, G., Sobolev, N.V., 1993b. Exsolution of garnet within clinopyroxene of mantle eclogites: major- and trace-element chemistry. Contrib. Mineral. Petrol. 114, 148–159.

Jones, K.A., Strachan, R.A., 2000. Crustal thickening and ductile extension in the NE Greenland Caledonides: a metamorphic record from anatectic pelites. J. Metamorph. Geol. 18, 719–735.

Knudsen, T.-L., 1996. Petrology and geothermobarometry of granulite facies metapelites from the Hisøy-Torungen area, south Norway: new data on the Sveconorvegian $P–T–t$ path of the Bamble sector. J. Metamorph. Geol. 14, 267–287.

Kopylova, M.G., Russell, J.K., Cookenboo, H., 1999. Petrology of peridotite and pyroxenite xenoliths from the Jericho kimberlite: implications for the thermal state of the mantle beneath the slave Craton, northern Canada. J. Petrol. 40, 79–104.

Kryza, R., Pin, C., Vielzeuf, D., 1996. High-pressure granulites from the Sudetes (south-west Poland): evidence of crustal subduction and collisional thickening in the Variscan Belt. J. Metamorph. Geol. 14, 531–546.

Lang, H.M., Gilotti, J.A., 2001. Plagioclase replacement textures in partially eclogitised gabbros from the Sanddal mafic-ultramafic complex, Greenland Caledonides. J. Metamorph. Geol. 19, 497–517.

Lee, J.E., 1993. Indicator mineral techniques in a diamond exploration program at Kokong, Botswana. Diamonds: Exploration, Sampling and Evaluation, Short Course Proceedings, Pros. Dev. Assoc. Can., pp. 213–235.

MacGregor, I.D., 1979. Mafic and ultramafic xenoliths from the Kao kimberlite pipe. In: Boyd, F.R., Meyer, H.O.A. (Eds.), The Mantle Sample: Inclusions in Kimberlites and Other Volcanics. Amer. Geophys. Union, Washington, pp. 156–172.

MacGregor, I.D., Carter, J.L., 1970. The chemistry of clinopyroxenes and garnets of eclogite and peridotite xenoliths from the Roberts Victor Mine, South Africa. Phys. Earth Planet. Inter. 1, 391–397.

MacGregor, I.D., Manton, W.I., 1986. Roberts Victor eclogites: ancient oceanic crust. J. Geophys. Res. 91, 14063–14079.

Mazzone, P., Haggerty, S.E., 1989a. Corganites and corgaspinites: two new types of aluminous assemblages from the Jagersfontein pipe. In: Ross, J. (Ed.), Kimberlites and Related Rocks: vol. 2. Their Mantle/Crust Setting, Diamonds and Diamond Exploration. Geol. Soc. Austr. Spec. Pub., vol. 14. Blackwell, Carlton, pp. 795–808.

Mazzone, P., Haggerty, S.E., 1989b. Peraluminous xenoliths in kimberlite: metamorphosed restites produced by partial melting of pelites. Geochim. Cosmochim. Acta 53, 1551–1561.

McCandless, T.E., Gurney, J.J., 1986. Sodium in garnet and potassium in clinopyroxene: criteria for classifying mantle eclogites. Univ. Cape Town, Kimberlite Research Group, Data Appendix, Internal Report, vol. 10. 60 pp.

McCandless, T.E., Gurney, J.J., 1989. Sodium in garnet and potassium in clinopyroxene: criteria for classifying mantle eclogites. In: Ross, J. (Ed.), Kimberlites and Related rocks: vol. 2. Their Mantle/Crust Setting, Diamonds and Diamond Exploration. Blackwell, Carlton, Australia, pp. 827–832.

McGee, E.S., Hearn Jr., B.C., 1984. The Lake Ellen kimberlite, Michigan, U.S.A. In: Kornprobst, J. (Ed.), Kimberlites I: Kimberlites and Related Rocks. Elsevier, Amsterdam, pp. 143–154.

Meyer, H.O.A., Brookins, D.G., 1971. Eclogite xenoliths from Stockdale kimberlite, Kansas. Contrib. Mineral. Petrol. 34, 60–72.

Mitchell, R.H., 1984. Garnet lherzolites from the Hanaus-I and Lowrensia kimberlites of Namibia. Contrib. Mineral. Petrol. 86, 178–188.

Moore, R.O., Gurney, J.J., 1991. Garnet megacrysts from Group II kimberlites in southern Africa. Ext. Abstr. 5th Int. Kimb. Conf., Araxa, Brasil, 298–300.

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.

Moraes, R.D., Fuck, R.A., 2000. Ultra-high-temperature metamorphism in central Brazil: the Barro Alto complex. J. Metamorph. Geol. 18, 345–358.

Nehru, C.E., Reddy, A.K., 1989. Ultramafic xenoliths from Vajrakarur kimberlites, India. In: Ross, J. (Ed.), Kimberlites and Related Rocks: vol. 2. Their Mantle/Crust Setting, Diamonds and Diamond Exploration. Geol. Soc. Austr. Spec. Pub., vol. 14. Blackwell, Carlton, pp. 745–758.

Nixon, P.H., 1979. Chromium garnet, uvarovite, from eastern Papua New Guinea. Sci N. Guin. 6, 16–18.

Nixon, P.H., Boyd, F.R., 1973a. The discrete nodule (megacryst) association in kimberlites from northern Lesotho. In: Nixon, P.H. (Ed.), Lesotho Kimberlites. Lesotho National Development, Maseru, pp. 67–75.

Nixon, P.H., Boyd, F.R., 1973b. Petrogenesis of the granular and sheared ultrabasic nodule suite in kimberlites. In: Nixon, P.H. (Ed.), Lesotho Kimberlites. Lesotho National Development, Maseru, pp. 48–56.

Nixon, P.H., Chapman, N.A., Gurney, J.J., 1978. Pyrope-spinel (alkremite) xenoliths from kimberlite. Contrib. Mineral. Petrol. 65, 341–346.

Nixon, P.H., van Calsteren, P.W.C., Boyd, F.R., Hawkesworth, C.J., 1987. Harzburgites with garnets of diamond facies from southern African kimberlites. In: Nixon, P.H. (Ed.), Mantle Xenoliths. Wiley, New York, pp. 524–533.

Nyman, M.W., Pattison, D.R.M., Ghent, E.D., 1995. Melt extraction during formation of k-feldspar + sillimanite migmatites, west of Revelstoke, British Columbia. J. Petrol. 36, 351–372.

Parkinson, C.D., 2000. Coesite inclusions and prograde compositional zonation of garnet in whiteschist of the HP-UHPM Kokchetav massif, Kazakhstan: a record of progressive UHP metamorphism. Lithos 52, 215–233.

Parthasarathy, G., Balaram, V., Srinivasan, R., 1999. Characterization of green garnets from an Archean calc-silicate rock, Bandihalli, Karnatacka, India: evidence for a continuous solid solution between uvarovite and grandite. J. Asian Earth Sci. 17, 345–352.

Pattison, D.R.M., 1991. Infiltration-driven dehydration and anatexis in granulite facies metagabbro, Grenville Province, Ontario, Canada. J. Metamorph. Geol. 9, 315–332.

Pattison, D.R.M., Bégin, N.J., 1994. Zoning patterns in orthopyroxene and garnet in granulites: implications for geothermometry. J. Metamorph. Geol. 12, 387–410.

Pattison, D.R.M., Carmichael, D.M., St-Onge, M.R., 1982. Geothermometry and geobarometry applied to Early Proterozoic "S-type" granitoid plutons, Wopmay Orogen, Northwest Territories, Canada. Contrib. Mineral. Petrol. 79, 394–404.

Pearson, D.G., Boyd, F.R., Haggerty, S.E., Pasteris, J.D., Field, S.W., Nixon, P.H., Pokhilenko, N.P., 1994. The characterisation and origin of graphite in cratonic lithospheric mantle: a petrological carbon isotope and Raman spectroscopic study. Contrib. Mineral. Petrol. 115, 449–466.

Pearson, N.J., Griffin, W.L., Doyle, B.J., O'Reilly, S.Y., van Achterbergh, E., Kivi, K., 1999. Xenoliths from kimberlite pipes of the Lac de Gras area, Slave Craton, Canada. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), Proceedings of the VIIth International Kimberlite Conference, vol. 2. Red Roof Design, Cape Town, pp. 644–658.

Percival, J., 1981. Geological evolution of part of the central Superior Province based on relationships among the Abitibi and Wawa sub-provinces and the Kapuskasing Structural Zone. PhD thesis, Queen's University.

Pita, P., de Waal, S.A., 2001. High-temperature, low-pressure metamorphism and development of prograde symplectites, Marble Hall Fragment, Bushveld Complex (South Africa). J. Metamorph. Geol. 19, 311–315.

Pokhilenko, N.P., Sobolev, N.V., Lavrent'ev, Y.G., 1977. Xenoliths of diamondiferous ultramafic rocks from Yakutian kimberlites. Ext. Abstr. 2nd Kimb. Conf., Santa Fe, USA. unpaged.

Pokhilenko, N.P., Pearson, D.G., Boyd, F.R., Sobolev, N.V., 1991. Megacrystalline dunites: sources of Siberian diamonds. Ann. Rev. Dir. Geophys. Lab. Carneg. Inst. Wash. 90, 11–18.

Pokhilenko, N.P., Sobolev, N.V., Boyd, F.R., Pearson, D.G., Shimizu, N., 1993. Megacrystalline pyrope peridotites in the lithosphere of the Siberian Platform: mineralogy, geochemical features and the problem of their origin. Russ. J. Geol. Geophys. 34, 56–67.

Pokhilenko, N.P., Sobolev, N.V., Kuligin, S.S., Shimizu, N., 1999. Peculiarities of distribution of pyroxenite paragenesis garnets in Yakutian kimberlites and some aspects of evolution of Siberian Craton lithospheric mantle. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), Proceedings of the VIIth International Kimberlite Conference, vol. 2. Red Roof Design, Cape Town, pp. 689–698.

Ponomarenko, A.I., 1975. Alkremite, a new variety of aluminous ultramafic rock in xenoliths from the Udachnaya kimberlite pipe. Dokl. Earth Sci. 225, 155–157.

Pyle, J.M., Haggerty, S.E., 1998. Eclogites and the metasomatism of eclogites from the Jagersfontein kimberlite: punctuated transport and implications for alkali magmatism. Geochim. Cosmochim. Acta 62, 1207–1231.

Ramsay, R.R., 1992. Geochemistry of diamond indicator minerals. PhD Thesis, University of Western Australia.

Reid, A.M., Brown, R.W., Dawson, J.B., Whitfield, G.G., Siebert, J.C., 1976. Garnet and pyroxene compositions in some diamondiferous eclogites. Contrib. Mineral. Petrol. 58, 203–220.

Robey, J.v.A., 1981. Kimberlites of the central Cape Province, R.S.A. PhD thesis, University of Cape Town.

Robinson, D.N., Gurney, J.J., Shee, S.R., 1984. Diamond eclogite and graphite eclogite xenoliths from Orapa, Botswana. In: Kornprobst, J. (Ed.), Kimberlites II: Their Mantle and Crust–Mantle Relationships. Elsevier, Amsterdam, pp. 11–24.

Rolland, Y., Maheo, G., Guillot, S., Pecher, A., 2001. Tectonometamorphic evolution of the Karakorum metamorphic complex (Dassu-Askole area, NE Pakistan): exhumation of mid-crustal HT-MP gneisses in a convergent context. J. Metamorph. Geol. 19, 717–737.

Rosenberg, J.L., Spry, P.G., Jacobson, C.E., Cook, N.J., Vokes, F.M., 1998. Thermobarometry of the Bleikvassli Zn–Pb–(Cu) deposit, Nordland, Norway. Miner. Depos. 34, 19–34.

Rotzler, J., Romer, R.L., 2001. $P-T-t$ evolution of ultrahigh-temperature granulites from the Saxon granulite massif, Germany: Part I. Petrology. J. Petrol. 42, 1995–2013.

Santos de Lima, E., Vannucci, R., Bottazzi, P., Ottolini, L., 1995. Reconnaissance study of trace element zonation in garnet from the Central Structural Domain, Northeastern Brazil: an example of polymetamorphic growth. J. South Am. Earth Sci. 8, 315–324.

Satish-Kumar, M., Wada, H., Santosh, M., Yoshida, M., 2001. Fluid-rock history of granulite-facies humite-marbles from Ambasamudram, southern India. J. Metamorph. Geol. 19, 395–410.

Schmadicke, E., Okrusch, M., Schubert, W., Elwart, B., Gorke, U., 2001. Phase relations of calc-silicate assemblages in the Auerbach marble, Odenwald Crystalline Complex, Germany. Mineral. Petrol. 72, 77–111.

Schulze, D.J., 1987. Megacrysts in alkaline volcanic rocks. In: Nixon, P.H. (Ed.), Mantle Xenoliths. Wylie, London, pp. 433–451.

Schulze, D.J., 1989a. Green garnets from South African kimberlites and their relationship to wehrlites and crustal uvarovites. In: Ross, J. (Ed.), Kimberlites and Related Rocks: vol. 2. Their Mantle/Crust Setting, Diamonds, and Diamond Exploration. Blackwell, Carlton, Australia, pp. 820–826.

Schulze, D.J., 1989b. Constraints on the abundance of eclogite in the upper mantle. J. Geophys. Res. 94, 4205–4212.

Schulze, D.J., 1992. Diamond eclogite from Sloan Ranch, Colorado, and its bearing on the diamond grade of the Sloan kimberlite. Econ. Geol. 87, 2175–2179.

Schulze, D.J., 1993. Garnet xenocryst populations in North American kimberlites. Diamonds: Exploration, Sampling and Evaluation, Short Course Proceedings, Pros. Dev. Assoc. Can., pp. 359–377.

Schulze, D.J., 1994. Abundance and distribution of low-Ca garnet harzburgites in the subcratonic lithosphere of southern Africa. In: Meyer, H.O.A., Leonardos, O. (Eds.), Vol. I: Kimberlites, Related Rocks, and Mantle Xenoliths. CPRM (Brasil) Spec. Pub., vol. 1-A/94, pp. 327–335.

Schulze, D.J., 1995. Low-Ca garnet harzburgites from Kimberley, South Africa: abundance and bearing on the structure and evolution of the lithosphere. J. Geophys. Res. 100, 12513–12526.

Schulze, D.J., 1997. The significance of eclogite and Cr-poor megacryst garnets in diamond exploration. Explor. Min. Geol. 6, 349–366.

Schulze, D.J., Helmstaedt, H., 1988. Coesite-sanidine eclogites from kimberlite: products of mantle fractionation or subduction? J. Geol. 96, 435–443.

Schulze, D.J., Wiese, D., Steude, J., 1996. Abundance and distribution of diamonds in eclogite revealed by volume visualization of CT x-ray scans. J. Geol. 104, 109–114.

Schulze, D.J., Valley, J.W., Viljoen, K.S., Stiefenhofer, J., Spicuzza, M., 1997. Carbon isotope composition of graphite in mantle eclogites. J. Geol. 105, 379–386.

Schulze, D.J., Valley, J.W., Spicuzza, M.J., 2000. Coesite eclogites from the Roberts Victor kimberlite, South Africa. Lithos 54, 23–32.

Scrimegour, I., Smith, J.B., Raith, J.G., 2001. Paleoproterozoic high-*T*, low-*P* metamorphism and dehydration melting in metapelites from the Mopunga Range, Arunta Inlier, central Australia. J. Metamorph. Geol. 19, 739–757.

Shaw, R.K., Arima, M., 1996. High-temperature metamorphic imprint on calc-silicate granulites on Rayagada, Eastern Ghats, India: implication for the isobaric cooling path. Contrib. Mineral. Petrol. 126, 169–180.

Shee, S.R., 1978. The mineral chemistry of xenoliths from the Orapa kimberlite pipe, Botswana. MSc thesis, University of Cape Town.

Shee, S.R., Gurney, J.J., 1979. The mineralogy of xenoliths from

Orapa, Botswana. In: Boyd, F.R., Meyer, H.O.A. (Eds.), The Mantle Sample: Inclusions in Kimberlites and Other Volcanics. A.G.U., Washington, pp. 37–49.

Shee, S.R., Gurney, J.J., Robinson, D.N., 1982. Two diamond-bearing peridotite xenoliths from the Finsch kimberlite, South Africa. Contrib. Mineral. Petrol. 81, 79–87.

Simon, G., Chopin, C., Schenk, V., 1997. Near-end-member magnesiochloritoid in prograde-zoned pyrope, Dora-Maira massif, western Alps. Lithos 41, 37–57.

Skinner, C.P., 1989. The petrology of peridotite xenoliths from the Finsch kimberlite, South Africa. S. Afr. J. Geol. 92, 197–206.

Smith, C.B., 1977. Kimberlite and mantle derived xenoliths at Iron Mountain, Wyoming. MS thesis, Colorado State University.

Smith, D., Boyd, F.R., 1992. Compositional zonation in garnets in peridotite xenoliths. Contrib. Mineral. Petrol. 112, 134–147.

Smith, C.B., Gurney, J.J., Harris, J.W., Robinson, D.N., Shee, S.R., Jagoutz, E., 1989. Sr and Nd isotope systematics of diamond-bearing eclogite xenoliths and eclogitic inclusions in diamond from southern Africa. In: Ross, J. (Ed.), Kimberlites and Related Rocks: vol. 2. Their Mantle/Crust Setting, Diamonds, and Diamond Exploration. Blackwell, Carlton, Australia, pp. 853–863.

Smyth, J.R., Caporuscio, F., 1984. Petrology of a suite of eclogite inclusions from the Bobbejaan kimberlite: II. Primary phase compositions and origin. In: Kornprobst, J. (Ed.), Kimberlites II: Their Mantle and Crust–Mantle Relationships. Elsevier, Amsterdam, pp. 121–131.

Smyth, J.R., Hatton, C.J., 1977. A coesite-sanidine grospydite xenolith from the Roberts Victor kimberlite. Earth Planet. Sci. Lett. 34, 284–290.

Snyder, G.A., Taylor, L.A., Crozaz, G., Halliday, A.N., Beard, B.L., Sobolev, V.N., Sobolev, N.V., 1997. The origins of Yakutian eclogite xenoliths. J. Petrol. 38, 85–113.

Sobolev, N.V., 1977. Deep-Seated Inclusions in Kimberlites and the Problem of the Composition of the Upper Mantle. AGU, Washington, DC.

Sobolev, N.V., Kuznetsova, I.K., Zyuzin, N.I., 1968. The petrology of grospydite xenoliths from the Zagodachnaya kimberlite pipe in Yakutia. J. Petrol. 9, 253–280.

Sobolev, N.V., Lavrent'ev, Y.G., Pokhilenko, N.P., Usova, L.V., 1973. Cr-rich garnets from kimberlites of Yakutia and their parageneses. Contrib. Mineral. Petrol. 40, 39–52.

Sobolev, N.V., Pokhilenko, N.P., Lavrent'ev, Y.G., Usova, L.V., 1975. Peculiarities of composition of chrome-spinels from diamonds and kimberlites of Yakutia. Geol. Geofiz. 11, 7–24.

Sobolev, N.V., Pokhilenko, N.P., Efimova, E.S., 1984. Diamond-bearing peridotite xenoliths in kimberlites and the problem of the origin of diamonds. Sov. Geol. Geophys. 25 (12), 62–76.

Sobolev, V.N., Taylor, L.A., Snyder, G.A., 1994. Diamondiferous eclogites from the Udachnaya kimberlite pipe, Yakutia. Int. Geol. Rev. 36, 42–64.

Sommerville, T.A., 1988. Petrography and geochemistry of xenoliths from Newlands kimberlite pipes. R.S.A., BSc Thesis, Queen's University.

Spetsius, Z.V., Nikishov, K.N., Makhotko, V.F., 1984. Kyanite eclogite with sanidine from the Udachnaya kimberlite pipe. Dokl. Earth Sci. Sect. 279, 138–141.

Stowell, H.H., Taylor, D.L., Tinkham, D.L., Goldberg, S.A., Ouderkirk, K.A., 2001. Contact metamorphic $P-T-t$ paths from Sm–Nd garnet ages, phase equilibria modelling and thermobarometry: garnet Ledge, south-eastern Alaska, USA. J. Metamorph. Geol. 19, 645–660.

Taylor, L.A., Neal, C.R., 1989. Eclogites with oceanic crustal and mantle signatures from the Bellsbank kimberlite, South Africa: Part I. Mineralogy, petrography and whole rock chemistry. J. Geol. 97, 551–567.

Taylor, L.A., Snyder, G.A., Crozaz, G., Sobolev, V.N., Yefimova, E.S., Sobolev, N.V., 1996. Eclogitic inclusions in diamonds: evidence of complex mantle processes over time. Earth Planet Sci. Lett. 142, 535–551.

Thöni, M., Miller, Ch., 1996. Garnet Sm–Nd data from the Saualpe and the Koralpe (Eastern Alps, Austria): chronological and $P-T$ constraints on the thermal and tectonic history. J. Metamorph. Geol. 14, 453–466.

Tollo, R.P., 1982. Petrography and mineral chemistry of ultramafic and related inclusions from the Orapa A/K-1 kimberlite pipe, Botswana. PhD thesis, University of Massachusetts.

Vance, D., Mahar, E., 1998. Pressure–temperature paths from $P-T$ pseudosections and zoned garnets: potential, limitations and examples from the Zanskar Himalaya, NW India. Contrib. Mineral. Petrol. 132, 225–245.

Vicker, P.A., 1997. Garnet peridotite xenoliths from kimberlites near Kirkland Lake, Canada. MSc Thesis, University of Toronto.

Viljoen, K.S., 1994. The petrology and geochemistry of a suite of mantle-derived eclogite xenoliths from the Kaalvallei kimberlite, South Africa. PhD thesis, University of Witwatersrand.

Viljoen, K.S., 1995. Graphite- and diamond-bearing eclogite xenoliths from the Bellsbank kimberlites, Northern Cape, South Africa. Contrib. Mineral. Petrol. 121, 414–423.

Viljoen, K.S., Swash, P.M., Otter, M.L., Schulze, D.J., Lawless, P.J., 1992. Diamondiferous garnet harzburgites from the Finsch kimberlite, Northern Cape, South Africa. Contrib. Mineral. Petrol. 110, 133–138.

Viljoen, K.S., Robinson, D.R., Swash, P.M., Griffin, W.L., Otter, M.L., Ryan, C.G., Win, T.T., 1994. Diamond- and graphite-bearing peridotite xenoliths from the Roberts Victor kimberlite, South Africa. In: Meyer, H.O.A., Leonardos, O. (Eds.), Kimberlites, Related Rocks and Mantle Xenoliths. C.P.R.M. Special Publication 1/A, Rio de Janeiro, pp. 285–303.

Viljoen, K.S., Smith, C.B., Sharp, Z.D., 1996. Stable and radiogenic isotope study of eclogite xenoliths from the Orapa kimberlite, Botswana. Chem. Geol. 131, 235–255.

von Knorring, O., Condliffe, E., Tong, Y.L., 1986. Some mineralogical and geochemical aspects of chromium-bearing skarn minerals from northern Karelia, Finland. Bull. Geol. Soc. Finl. 58, 277–292.

White, C.E., Barr, S.M., Jamieson, R.A., Reynolds, P.H., 2001. Neoproterozoic high-pressure/low-temperature metamorphic rocks in the Avalon terrane, southern New Brunswick, Canada. J. Metamorph. Geol. 19, 519–530.

Whitney, D.L., Mechum, T.A., Huehner, S.M., Dilek, Y.R., 1996. Progressive metamorphism of pelitic rocks from protolith to granulite facies, Dutchess County, New York, USA: constraints on the timing of fluid infiltration during regional metamorphism. J. Metamorph. Geol. 14, 163–181.

Whitney, D.L., Teyssier, C., Dilek, Y., Fayon, A.K., 2001. Metamorphism of the central Anatolian Crystalline Complex, Turkey: influence of orogen-normal collision vs. wrench-dominated tectonics on $P-T-t$ paths. J. Metamorph. Geol. 19, 411–432.

Willner, A.P., Rötzler, K., Maresch, W.V., 1997. Pressure–temperature and fluid evolution of quartzo-feldspathic metamorphic rocks with a relic high-pressure, granulite-facies history from the Central Erzgebirge (Saxony, Germany). J. Petrol. 38, 307–336.

Zeh, A., Millar, I.L., 2001. Metamorphic evolution of garnet–epidote–biotite gneiss from the Moine Supergroups, Scotland, and geotectonic implications. J. Petrol. 42, 529–554.

Zhao, G.C., Wilde, S.A., Cawood, P.A., Lu, L.Z., 2000. Petrology and $P-T$ path of the Fuping mafic granulites: implications for tectonic evolution of the central zone of the North China craton. J. Metamorph. Geol. 18, 375–391.