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An updated classification scheme for mantle-derived garnet, for use by diamond explorers☆

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Abstract

Mantle-derived garnets recovered in diamond exploration programs show compositional variations in Cr, Ca, Mg, Fe and Ti that reflect the chemical, physical and lithological environments in which they occur, occasionally together with diamond. The association of diamond with mantle garnet has progressed through a number of geochemical advances, most notably those of Dawson and Stephens (1975) and Gurney (1984), which are integrated in this work with less well known petrological advances made primarily in xenolith and experimental petrology. A simple, robust garnet classification scheme is formulated which accommodates empirical garnet–diamond relationships for peridotitic (G10, G9, G12), megacrystic (G1), Ti-metasomatised (G11), pyroxenitic (G4, G5) and eclogitic (G3) lithologies in eight distinct garnet classes. The calcium-saturation characteristics of harzburgitic (G10), lherzolitic (G9) and wehrlitic (G12) garnets are described by a Ca-intercept projection that also shows promise as a relative barometer for garnet lherzolite (Grütter and Winter, 1997). Thermobarometric aspects of garnet–diamond associations are highlighted in the scheme through the use of the minor elements Mn and Na, though analysis by anything other than an electron microprobe is not required for classification. A "D" suffix is added to the G10, G4, G5 or G3 categories to indicate a strong compositional and pressure–temperature association with diamond. The scheme remains open to improvement, particularly with regard to delineation of pyroxenitic (or websteritic) diamond associations and to advances in Ca-in-garnet and Na-in-garnet thermobarometry.

Keywords: Diamond exploration; Pyrope; Ca-intercept; Peridotite; Megacryst; Eclogite; Pyroxenite; G10; G9; G1; G3

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1. Introduction

Exploration for potentially diamond-bearing intrusives worldwide usually involves a multi-disciplinary approach. One powerful approach is to trace mantle-derived garnet and related indicator minerals to their source. The pathfinder minerals are routinely analysed for major and minor elements by electron microprobe, in part to identify and differentiate them from visually

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similar minerals of non-mantle origin, but also to enable qualitative predictions to be made regarding the diamond potential of their source rock (e.g. Gurney et al., 1993). Garnet and chromite are the heavy minerals of choice in this application because they are very common amongst the mineral inclusions found in diamond and they usually survive dispersion and alteration at the Earth's surface substantially better than do mantle-derived olivine or pyroxene. Relative to common mantle-derived garnets, the peridotitic and eclogitic varieties found included in diamond have reasonably distinct compositions (e.g. Gurney, 1984) and simplified compositional screens based on bivariate scatterplots are commonly used to classify and prioritise mantle-derived garnets recovered during exploration programmes (e.g. Lee, 1993; Fipke et al., 1995). This methodology developed from the prior use of simple scatterplots to illustrate geochemical relationships of eclogitic and peridotitic garnet to diamond (Sobolev and Lavrent'ev, 1971; Gurney and Switzer, 1973) and to succinctly characterise mantle lithologies in terms of garnet composition (e.g. Sobolev et al., 1973a,b; Switzer, 1975; Schulze, 1995).

Multivariate statistical analysis involving five or more compositional attributes, particularly cluster analysis and derivatives thereof, has also been used to relate garnet xenocryst compositions to their parental mantle lithology (e.g. Dawson and Stephens, 1975; Danchin and Wyatt, 1979), to compare populations of grains within and between different kimberlite intrusions (Jago and Mitchell, 1989), and to characterise the compositional attributes of entire sections of mantle lithosphere (Griffin et al., 2002). Although not specifically concerned with the relationship of garnet to diamond, the diamond exploration industry has, through time and by common use, borrowed the cluster-based nomenclature of Dawson and Stephens (1975) to describe simplified garnet compositional categories. For peridotitic garnets the term "G10" is thus considered short-hand for "subcalcic", "Ca-undersaturated" or "harzburgitic", while "G9" represents "Ca-saturated" or "lherzolitic". The work reported on here continues this convenient practise whilst updating and formalising many of the simple classification thresholds. Additional constraints, based primarily on garnet phase-relations, the results of experimental petrology investigations and empirical observations on garnet concentrates are added to arrive at a simple, robust garnet classification scheme that is specifically tailored to the requirements of the diamond explorationist. The main features of the updated scheme are (i) reliance only on compositional data obtained by electron microprobe analysis, (ii) backward compatibility with previous work, concepts and nomenclature, (iii) internal consistency with known diamond associations, and (iv) ease and transparency of implementation.

2. Data and methods

2.1. Data sources

The compositions of garnet and associated minerals that occur in some 4500 mantle-derived or granulite-grade lower crustal xenoliths and microxenoliths and as inclusions in about 600 diamonds were compiled from a large number of published sources and selected unpublished theses (see Appendix A of this work, Appendix 1 of Grütter and Moore, 2003 and Appendix 1 of Grütter and Quadling, 1999). Additional data for minerals in xenoliths are derived from the compilations of Schulze (1995, 1996, 1997, 2003). The compositions of garnet inclusions in diamonds are from essentially the same sources as listed by Stachel et al. (2000, and references therein). Garnet compositions used in the multivariate statistical studies of Dawson and Stephens (1975), Danchin and Wyatt (1979) and Jago and Mitchell (1989) were kindly provided on request. Data for minerals occurring in concentrate derived from kimberlites and related rocks are those held by the Kimberlite Research Group at the University of Cape Town and De Beers Consolidated Mines. The compiled data set encompasses a variety of analytical conditions, standardizations and matrix correction procedures for electron microprobes, and in this regard matches the commercial data typically being used in modern-day exploration applications. The available analyses were checked to comply within ± 3% of ideal stoichiometry and were screened to eliminate rare non-mantle (i.e. crustal) compositions. Majoritic garnet analyses (>3.1 Si cations per 12 oxygens) were identified for a limited number of garnets occurring as inclusions in diamond; they are not represented elsewhere in the compiled data sets.

2.2. Diamond-facies nomenclature, geotherms and pressure–temperature data

Modern-day single-grain thermometry techniques are in principle capable of assigning individual peridotitic garnet grains recovered during diamond exploration to the stability field of graphite or diamond (e.g. Griffin and Ryan, 1993; Grütter et al., 1999), but doing so requires knowledge of the local geotherm. This is commonly an unknown in exploration programmes and we therefore make the simplifying assumption that a typical cratonic geotherm pertains to the area being explored. The updated classification scheme is thus calibrated by design for geotherms intersecting the graphite/diamond transition at temperatures in the range 920 to 1000 °C, this being equivalent to the 38 to 40 mW/m^2 model conductive geotherms of Pollack and Chapman (1977). Individual grains that have a strong compositional association with diamond and that also fall within the diamond stability field under these conditions are considered to be of “diamond-facies” and are labelled with the suffix “D” in the classification scheme. The general validity of this approach can be tested by comparing garnet compositions in concentrates from cratonic sources that are known to be diamondiferous or barren. The actual geotherm could also be verified by employing single-grain thermobarometers (Ryan et al., 1996; Nimis and Taylor, 2000; Grütter and Moore, 2003).

Current xenolith thermobarometry techniques are capable of discriminating pressure–temperature (P–T) conditions for naturally occurring mantle xenoliths to within approximately 3.0 kbar (Pearson et al., 1994; Table 2 of Taylor, 1998). Allowing for this error margin on either side of the diamond stability curve (P [kbar] $= 19.4 + 0.025*T$ [°C], Kennedy and Kennedy, 1976) permits assignment of mantle xenoliths to the stability fields of graphite ($P < 16.4 + 0.025*T$) or diamond ($P > 22.4 + 0.025*T$) with relatively high confidence. Such graphite- or diamond-stable assignments for mantle xenoliths are used below to validate temperature and pressure effects on garnet MnO content and Ca-intercept variations. The requisite pressures and temperatures were calculated for garnet-bearing xenoliths in our compiled data base using the orthopyroxene–garnet barometer of Nickel and Green (1985) in combination with a clinopyroxene–solvus thermometer (Nimis and Taylor, 2000) for lherzolites and pyroxenites, or the olivine–garnet thermometer (O’Neill and Wood, 1979) for garnet harzburgites.

3. Petrological constraints

3.1. Garnet–chromite–carbon relations in peridotite

Compositional and phase-relations between Cr-pyrope garnet, chromite and carbon in model peridotite systems are illustrated for typically cratonic geothermal conditions in Fig. 1. The Cr/(Cr + Al) ratios of Ca-free harzburgitic garnet, Ca-saturated lherzolitic garnet and coexisting chromite increase with pressure and respectively attain values of J, K and L at the graphite/diamond transition. For the fixed geothermal conditions illustrated, this implies that any Cr-pyrope garnet with Cr/(Cr + Al) greater than line segment J–K must derive from inside the diamond stability field. The line segment J–K has been constrained to the simple

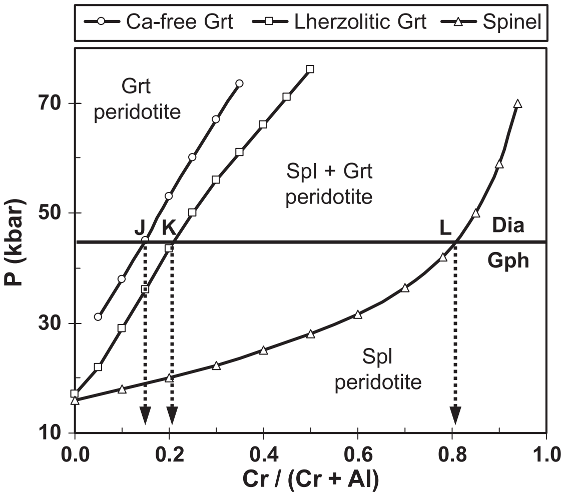

Fig. 1. Partly schematic pressure–composition section illustrating the influence of Cr/(Cr+Al) ratio on spinel–garnet (Spl–Grt) assemblage relations in peridotite (modified after Webb and Wood, 1986). The graphite/diamond (Gph/Dia) transition occurs at fixed pressure for a fixed geotherm and hence specifies garnet and coexisting chromite compositions J, K and L in peridotite assemblages. Line segment J–K represents a compositional tie line which corresponds to the graphite–diamond constraint illustrated in Fig. 3.

relationship $Cr_2O_3 = 5.0 + 0.94{*}CaO$ (in wt.%) for low-Ca Cr-pyrope garnet compositions by inspection of experimental (Malinovsky and Doroshev, 1977) and natural assemblage relations in chromite-saturated, carbon-bearing garnet harzburgite xenoliths derived from cratonic kimberlites (Pokhilenko et al., 1991, 1993; Grütter, 1994; Grütter and Sweeney, 2000; Menzies, 2001, see Fig. 3). The relationship is designated as the graphite–diamond constraint (the GDC) and we accordingly use $Cr_2O_3 \geq 5.0 + 0.94{*}CaO$ (wt.%) in the updated classification scheme as a petrologically defined limit that aids in differentiating diamond-facies low-Ca garnet compositions (“D” suffix).

The relations shown in Fig. 1 illustrate that pyrope garnets with Cr/(Cr + Al) less than line segment J–K may also occur inside the diamond stability field, but only when they occur in chromite-free peridotite assemblages. Thus about 46% of the 348 peridotitic Cr-pyrope inclusions in diamond in our database have Cr_2O_3 contents lower than the GDC (i.e. $1.0 < Cr_2O_3 < 5.0 + 0.94{*}CaO$, see also Fig. 5 of Gurney et al., 1993). An additional constraint is required to correctly identify these Cr-pyrope garnets as being of diamond-facies, and we use their MnO content for this purpose.

3.2. MnO in pyrope garnet

Detailed empirical work on upper mantle xenoliths has documented an inverse relationship between the MnO content of peridotitic garnet and xenolith equilibration temperature (Delaney et al., 1979; Fig. 13 of MacGregor, 1979; Smith et al., 1991). Our thermobarometric categorization of 751 garnet harzburgite and lherzolite xenoliths derived from cratonic, diamond-bearing kimberlites shows a value of MnO < 0.36 wt.% (± 0.1 at 1σ) to be characteristic of peridotitic garnets that occur inside the diamond stability field (Fig. 2). The threshold has a large error (~ 30%) and should be used with care, but since it correctly classifies 268 of 336 peridotitic garnets included in diamond (i.e. 80% of those analysed for MnO), it may be employed to good effect in the updated scheme to differentiate diamond-facies low-Ca garnet compositions (Fig. 2).

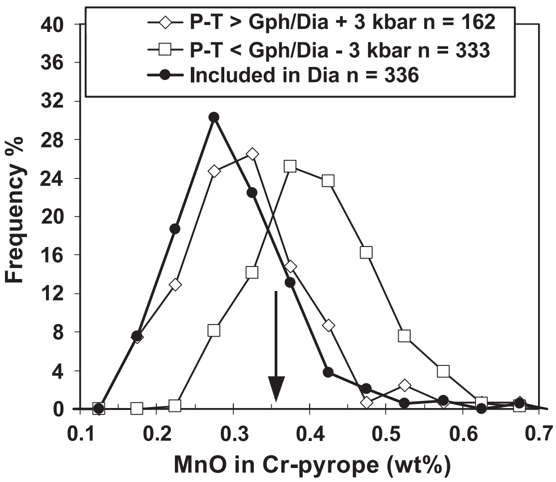

Fig. 2. Frequency histogram of MnO content in garnet for diamond- or graphite-facies peridotite xenoliths from cratonic kimberlites. The diamond- or graphite-facies designation is based on conventional thermobarometry, subject to an error of ± 3 kbar (see Section 2). Garnet MnO contents overlap within the range 0.25 to 0.45 wt.% MnO, but we adopt a graphite/diamond division at 0.36 wt.% MnO (arrow) for the purposes of the classification scheme. This choice correctly classifies as diamond-facies some 268 of 336 peridotitic garnets included in diamond.

It is instructive to note that 52 of the 68 incorrectly classified Cr-pyrope inclusions in diamonds have relatively high Cr_2O_3 contents (8 to 15 wt.% Cr_2O_3), and it is possible that their MnO contents have been artificially inflated by as much as 0.20 wt.% during electron microprobe analysis as a result of a Cr-Kβ peak (at 5.947 keV) overlapping that of the Mn-Kα peak (at 5.985 keV). This analytical artifact is particularly noticeable for high-Cr_2O_3 garnet compositions reported as inclusions in Chinese diamonds (Wang et al., 2000), but it appears to also be present in a few other data sets investigated in the course of this work. The peak overlap is normally readily resolved during wavelength-dispersive analysis of Mn at low concentrations by selection of a LiF rather than a PET crystal.

3.3. Garnet Ca-intercept variations

The close association of diamond with Ca-undersaturated garnet compositions in preference to Ca-saturated compositions (Gurney and Switzer, 1973; Gurney, 1984) suggests that the G10/G9 divide (Fig. 3) may be empirically correlated with pressure–temperature conditions falling just inside the diamond stability field. Pressure values of 45 to 50 kbar are considered appropriate for cratonic geotherms by

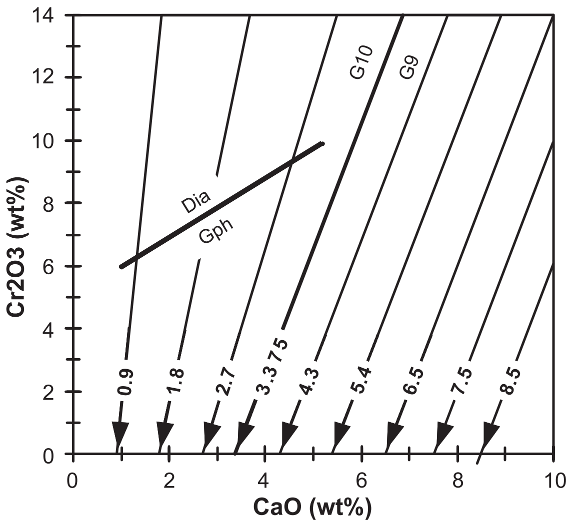

Fig. 3. Conventional garnet Cr_2O_3 vs. CaO diagram showing the 85% line of Gurney (1984) (commonly known as the G10/G9 divide) and the graphite–diamond constraint of Grütter and Sweeney (2000). The downward-pointing arrows with CA_INT values illustrate the geometric effect of the calcium-intercept projection discussed in this work (modified after Grütter and Winter, 1997).

Gurney et al. (1993, p. 2430) and Gurney and Zweistra (1995, p. 297). Prior observations on garnet concentrates from off-craton kimberlites illustrated that, at fixed Cr_2O_3 content, the CaO content of lherzolitic garnet populations increases by ~ 12% relative to cratonic conditions (Boyd and Gurney, 1982), the implication being that the CaO variation may be an effect of decreased pressure. Garnet CaO variations of similar magnitude are well known from high-pressure experimental results in model and natural lherzolitic or pyroxenitic assemblages, where they are found to be non-linear with respect to pressure, dependent on temperature and the Na_2O content of coexisting clinopyroxene, and most useful for relative thermobarometry at pressures inside the graphite stability field (Kushiro et al., 1967; Boyd, 1970; Akella, 1976; Brey et al., 1986, 1990; Brenker and Brey, 1997). These circumstances indicate that the G10/G9 divide may be utilized as an appropriately situated static reference from which to measure the Ca-saturation characteristics of harzburgitic as well as lherzolitic garnets. Given the G10/G9 divide occurs at $CaO = 3.375 + 0.25*Cr_2O_3$ (in wt.%), a calcium-intercept (CA_INT) projection to 0 wt.% Cr_2O_3, adapted from that given in Grütter and Winter (1997), is formulated as (in wt.%):

IF $CaO \leq 3.375 + 0.25*Cr_2O_3$

THEN $CA\_INT = 13.5*CaO/(Cr_2O_3 + 13.5)$
ELSE $CA\_INT = CaO - 0.25*Cr_2O_3$.

Fig. 3 illustrates that the projection contains geometric elements of the J-score developed by Gurney for harzburgitic garnets (as quoted in Lee, 1993), and also of the "reduced CaO values" calculated and used by Hatton and Gurney (1987, their Fig. 237c) to represent Ca-content relationships amongst eclogitic, websteritic and lherzolitic garnets. The current formulation follows that of Grütter and Winter (1997) in that it sweeps smoothly from a CA_INT value of 0.0 across the G10 field to 3.375 at the G10/G9 divide and continuously extends to substantially higher values (Fig. 3).

Typical CA_INT values calculated for Cr-pyrope garnets from cratonic, peri-cratonic and off-craton settings are shown in histogram format in Fig. 4A to 4C. A general decrease of CA_INT values for lherzolitic garnet populations is observed for these three settings, in agreement with the pressure effects noted by previous workers and summarised above. A notional divide at CA_INT ~ 4.3 partially separates diamond-bearing kimberlite settings (central Slave, central Kaapvaal and Somerset Island) from settings that are barren (Gibeon, Karoo, East Griqualand, The Thumb), but there is substantial overlap of CA_INT values. It follows that CA_INT values for individual lherzolitic garnets cannot be assigned unambiguously to any one of the three cratonic settings considered, nor, by inference, to diamond-stable conditions (Fig. 4A to C). Further work is necessary to improve the accuracy of the Ca-in-garnet thermobarometer and to incorporate additional compositional factors not accounted for by the simple Ca-intercept projection employed here (see also Brenker and Brey, 1997). However, the observed overlap and consequent lack of barometric constraint does not affect the utility of Ca-intercept values in classifying garnet compositions. For instance, it is apparent from Fig. 4 that CA_INT values for lherzolitic garnets range upward from 3.375 and show a natural upper limit at a value of ~ 5.4. We hence regard the latter value as the maximum for lherzolitic garnets derived from the

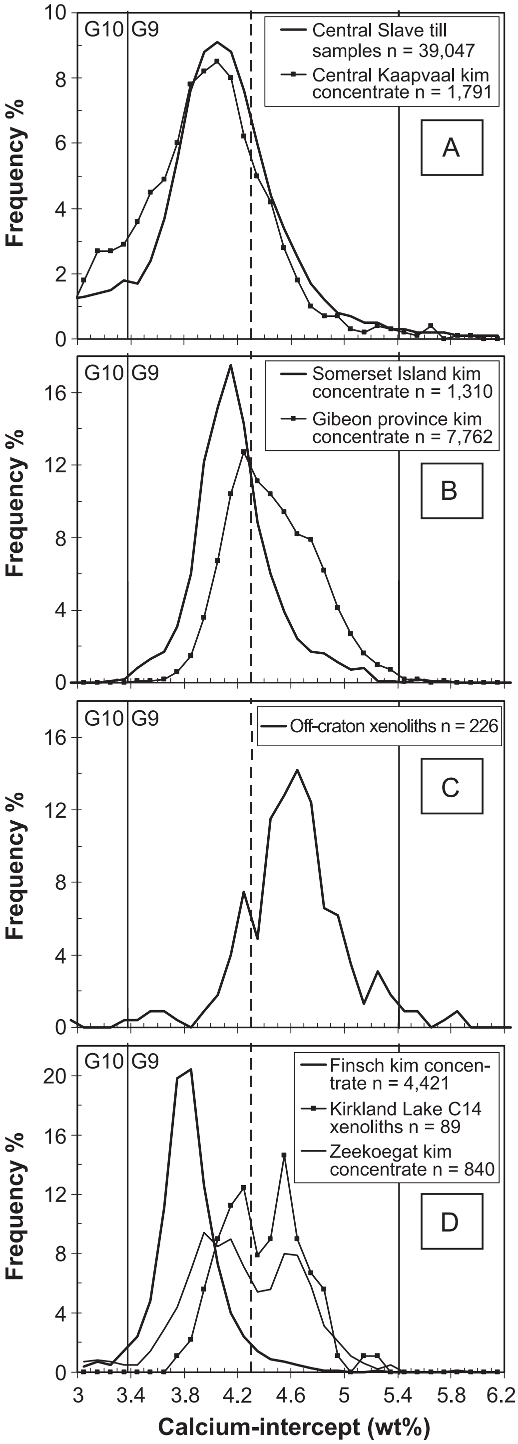

Fig. 4. (A–D) Histograms of CA_INT values for peridotitic garnets with Cr_2O_3>1.0 wt.% from cratonic settings (A), peri-cratonic settings (B), off-craton settings (C), and from individual kimberlites (D). See text for discussion of thresholds indicated at CA_INT values of 3.375, 4.3 and 5.4. Central Slave data from Armstrong (2001), central Kaapvaal from the UCT KRG database, Somerset Island from Jago and Mitchell (1989), Gibeon province, Finsch and Zeekoegat from the De Beers database. Off-craton xenolith data are from The Thumb (Ehrenberg, 1978), Karoo kimberlites (Robey, 1981; Nowicki, 1990), East Griqualand kimberlites (Boyd and Nixon, 1979) and alkali basalt vents at Vitim, Eastern Siberia (Ionov et al., 1993; Glaser et al., 1999). The Zeekoegat kimberlite occurs off-craton in the East Griqualand province, southeast of the Kaapvaal craton. Garnet compositions for most of the southern African localities mentioned here were originally described in Boyd and Gurney (1982), which also includes a locality map.

wide variety of settings that are likely to occur in diamond exploration applications.

Bulk-tested kimberlites in the Kirkland Lake and Somerset Island provinces are known to have very low diamond contents (0 to 0.02 ct/ton, Kjarsgaard and Levinson, 2002) while kimberlites in the Gibeon province are not known to contain diamond. The combination of this information with the results illustrated in Fig. 4 suggests that *average* CA_INT values of less than 4.3 for large populations of lherzolitic garnets may be useful to discriminate diamond-stable from graphite-stable conditions in cratonic upper mantle lithospheres. This application of Ca-intercept thermobarometry to populations of lherzolitic garnets should be approached with care because population variances are comparatively high (typically ± 0.3 at 1σ). Since prominent CA_INT modes for lherzolitic garnet populations from individual kimberlites may fall either side of the 4.3 threshold, particularly for small data sets (Fig. 4D), it is considered advisable to closely inspect the data set and to calculate average CA_INT values only for data sets that contain 500 or more lherzolitic garnets.

4. Garnet classifications

4.1. Harzburgitic (G10)

Gurney (1984) correlated 85% of peridotitic garnet inclusions in diamonds from global sources with the Ca-poor, Cr-rich harzburgitic pyrope cluster 10 of Dawson and Stephens (1975) and in doing so “branded" the G10 garnet standard with which the diamond potential of exploration projects is often judged (Fig. 3). The association made with diamond in this case is primarily geochemical and statistical in nature. The presence of graphite in garnet harzburgite xenoliths (Nixon et al., 1987; Viljoen et al., 1994) implies an association of both polymorphs of carbon with low-Ca G10 garnet compositions. The Cr-saturation characteristics of G10 garnets (Figs. 1 and 3) and/or their MnO content (Fig. 2) may be used to specifically highlight diamond-facies G10 garnets. G10 garnets in our classification scheme are thus compositionally characterised by:

Cr_2O_3 [wt.%]: ≥ 1.0 to < 22.0
CA_INT [wt.%]: 0 to < 3.375
MGNUM: ≥ 0.75 to < 0.95

where MGNUM=(MgO/40.3)/(MgO/40.3 + FeOt/71.85) [oxides in wt.%]. G10D diamond-facies garnets additionally have (in wt.%):

$Cr_2O_3 \geq 5.0 + 0.94{*}CaO$, or
$Cr_2O_3 < 5.0 + 0.94{*}CaO$ *and* $MnO < 0.36$.

4.2. Lherzolitic (G9)

Cr-pyrope garnets derived from lherzolites are by far the most abundant garnet type recovered in diamond exploration applications. Their statistical association with diamond is weak (15% of peridotitic inclusions in diamond, Gurney, 1984), particularly given their high relative abundance as xenocrysts in diamondiferous kimberlites (e.g. Gurney and Switzer, 1973, also Fig. 4). Dawson and Stephens (1975) classified lherzolitic garnets in cluster 9, and in our scheme G9 garnets have the following compositions:

Cr_2O_3 [wt.%]: ≥ 1.0 to < 20.0
CA_INT [wt.%]: ≥ 3.375 to < 5.4
MGNUM: ≥ 0.70 to < 0.90

4.3. Wehrlitic (G12)

Mantle-derived garnets with high CaO and Cr_2O_3 content are only very rarely described as inclusions in diamonds (Sobolev et al., 1970), but are known to occur in xenolith and microxenolith fragments where their green or grey–green colour is often distinctive. Wehrlitic garnets classify predominantly in cluster groups 7 and 12 of Dawson and Stephens (1975), with minor occurrences in their cluster group 11. Here we follow the data compilations of Sobolev et al. (1973a,b) and Schulze (1993, 2003) to establish compositional limits for an updated and simplified wehrlitic garnet category labelled G12, as follows:

Cr_2O_3 [wt.%]: ≥ 1.0 to < 20.0
CA_INT [wt.%]: >5.4
CaO [wt.%]: < 28.0
MgO [wt.%]: >5.0

It is noted that crustal uvarovitic garnets commonly have extremely high CaO contents, generally well over 28 wt.% CaO (Schulze, 1993).

4.4. Low-Cr megacrysts (G1)

Garnets belonging to the low-Cr suite of megacryst minerals may occur in high relative abundance in certain kimberlites (e.g. Monastery), but Schulze (1987) notes their occurrence also in other mantle-derived magma types like alnoites (e.g. Solomon Islands) and in certain alkali basalts (e.g. Vitim, see Litasov, 2000). Megacrystic garnets are typically coarse-grained (2–10 cm) and significantly fractured, and due to their relatively Fe-rich and Ti-rich nature generally endure chemical weathering better than several other mantle-derived garnet types. Disaggregation of megacrysts in the secondary environment can hence release disproportionately abundant pathfinder minerals derived from kimberlite or kimberlite-like intrusives. Their isolation as a specific compositional group is therefore important from an exploration perspective, even though megacrystic garnets have no established association with diamond. Garnet megacrysts correspond very closely to cluster group 1 of Dawson and Stephens (1975) and have Cr, Ca and Mg-number characteristics overlapping those of garnets in pyroxenite and websterite xenoliths. However, the latter are generally less titaniferous at any given Mg-number (Fig. 5). Based predominantly on the compilations of megacryst data in Jakob (1977), Bell and Rossman (1992)

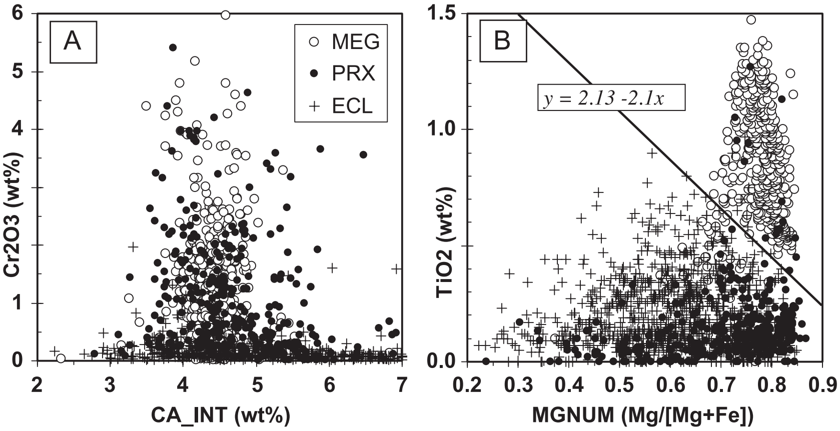

Fig. 5. (A, B) Diagrammatic summary of Cr, Ca, Ti, Mg and Fe compositional characteristics of garnets with moderate to low Cr_2O_3 content derived predominantly from kimberlite sources, but also including occurrences recorded in related rocks and alkali basalts. At any given Mg-number, megacrystic garnets (MEG, $n = 515$) generally have higher Ti content than garnets in eclogite xenoliths (ECL, $n = 1113$) and pyroxenite xenoliths (PRX, $n = 391$). The pyroxenite category includes 139 data for garnet websterite xenoliths.

and Schulze (1997, 2003), we characterise megacryst compositions as follows (see Fig. 5):

Cr_2O_3 [wt.%]: 0 to <4.0
CA_INT [wt.%]: ≥ 3.375 to <6.0
MGNUM: ≥ 0.65 to <0.85
TiO_2 [wt.%]: $\geq 2.13 - 2.1*$MGNUM
TiO_2 [wt.%]: <4.0

Many investigators have shown that Ca–Fe–Ti melt-metasomatism drives garnet compositions in high-temperature mantle peridotites toward those of megacrystic garnets (e.g. Burgess and Harte, 1999 and references therein). A compositional overlap between megacrystic garnets and certain lower-Cr_2O_3, high-TiO_2 peridotitic garnets may thus occur, but we make no discrimination in our classification scheme because neither diamond nor graphite is associated with melt-metasomatic assemblages in peridotites. McCammon et al. (2001) have indicated that the absence of carbon may be a consequence of progressive oxidation during melt-metasomatism.

4.5. High-TiO_2 peridotitic (G11)

Classification runs conducted by Dawson and Stephens (1975, pp. 601–602) on high-TiO_2 garnets derived from "sheared" peridotites returned instances in their cluster groups 1, 2, 9, 10 and mostly 11, depending slightly on the classification method used. We have adopted their group 11 as representative of high-TiO_2 peridotitic garnet compositions and describe them as follows.

Unlike G1 (i.e. G1 grains should be identified first and excluded as possible G11's):
Cr_2O_3 [wt.%]: ≥ 1.0 to <20.0
CA_INT [wt.%]: ≥ 3.0
CaO [wt.%]: <28.0
MGNUM: ≥ 0.65 to <0.90
TiO_2 [wt.%]: $\geq 2.13 - 2.1*$MGNUM
TiO_2 [wt.%]: $<4.$

4.6. Pyroxenitic, websteritic and eclogitic ("G4" and "G5")

Dawson and Stephens (1975) did not classify garnets that occur in pyroxenite (and websterite) mantle xenoliths into a specific group, but included them within their G9 (dominantly lherzolitic) and G3 (dominantly eclogitic) categories. Pyroxenitic garnets were also left undifferentiated in a recent garnet classification scheme (Schulze, 2003). These moderate- to low-Cr garnets are important to diamond explorers due to a distinct association with diamond (e.g. Gurney et al., 1984; Aulbach et al., 2002), and as possible indicators of lithosphere destruction (see Pokhilenko et al., 1999). Pyroxenitic/websteritic garnets are easily differentiated from megacrysts by Mg-number and TiO_2 content (Fig. 5), but, like previous investigators, we also found significant compositional overlaps to occur with low-Cr peridotitic and eclogitic garnets. A suitable compromise was found by allowing two categories of pyroxenitic garnets.

Pyroxenitic garnets similar to, but richer in Fe than moderate- to low-Cr G9 garnets are designated "G5" in the updated scheme, although the original term referred to an Fe-rich eclogitic category. The updated G5 garnet category is defined by:

TiO_2 [wt.%]: $< 2.13 - 2.1*\mathrm{MGNUM}$
Cr_2O_3 [wt.%]: ≥ 1 to < 4.0
CA_INT [wt.%]: ≥ 3.375 to < 5.4
MGNUM: ≥ 0.3 to < 0.7.

Pyroxenitic garnets lower in Cr than G9 garnets, but with compositions overlapping low-Ca eclogitic garnets are designated as group "G4". It is recognized that this group contains eclogitic, pyroxenitic and websteritic garnets and that the adopted nomenclature departs somewhat from the titaniferous ferroan eclogitic garnet category originally envisioned by Dawson and Stephens (1975). The updated G4 category is defined by:

TiO_2 [wt.%]: $< 2.13 - 2.1*\mathrm{MGNUM}$
Cr_2O_3 [wt.%]: < 1.0
CaO [wt.%]: ≥ 2.0 to < 6.0
MGNUM: ≥ 0.3 to < 0.90.

4.7. Eclogitic (G3)

Small diamond-bearing eclogite xenoliths are known to have in-situ grades equivalent to 650 to 20,000 ct/ton (see Helmstaedt, 1993), and for this reason alone eclogitic garnets represent extremely important pathfinder minerals for diamond explorers. Eclogitic garnets are aluminous and show large variations in FeO, MgO and CaO, to the extent that Dawson and Stephens (1975) required five separate cluster groups to describe their compositional variation (their groups 3, 4, 5, 6 and 8). A compilation of garnet compositions in carbon-free and carbonaceous eclogites shows that carbon is not preferentially associated with eclogitic garnets of particular Fe–Mg–Ca compositions (Fig. 6). This implies that subdivision of eclogitic garnets on the basis of variable FeO, MgO or CaO content, as in the garnet classification scheme of Schulze (2003), provides little advantage for the diamond explorer and we accordingly choose to define our eclogitic garnet category across a range of compositions, as outlined below. It is noted that these compositional limits also encompass the ranges observed for garnets in alkremite and certain lower crustal garnet granulite xenoliths. Our eclogitic G3 category has:

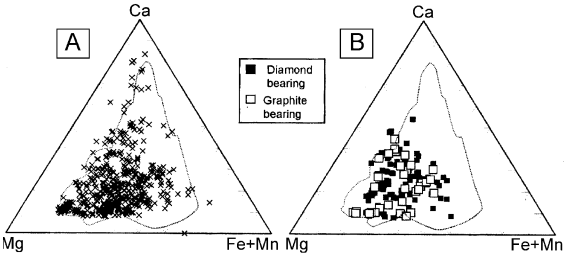

Fig. 6. (A, B) Mg–Ca–(Fe + Mn) diagrams illustrating the compositional range of garnet in (A) carbon-free eclogite xenoliths from kimberlites ($n = 687$), and (B) carbonaceous eclogite xenoliths from kimberlites ($n = 100$). Compositions of worldwide eclogitic garnets outlined in stipple (after Haggerty, 1995). Diagram is from Grütter and Quadling (1999).

Cr_2O_3 [wt.%]: 0 to < 1.0
CaO [wt.%]: ≥ 6 to < 32.0
MGNUM: ≥ 0.17 to < 0.86
TiO_2 [wt.%]: $< 2.13 - 2.1*\mathrm{MGNUM}$
TiO_2 [wt.%]: < 2.0

4.8. Na_2O in G3, G4 and G5 garnets

Eclogitic garnet inclusions in diamond are known to commonly have $Na_2O > 0.07$ wt.% (Sobolev and Lavrent'ev, 1971; McCandless and Gurney, 1989), though this threshold provides incomplete discrimination from garnet compositions in graphite-bearing eclogite xenoliths (Grütter and Quadling, 1999). Further investigation of the phase-relations of carbon, garnet and sodic pyroxene may yield a basis for accurately constraining diamond-facies eclogitic, websteritic and pyroxenitic garnet compositions, thereby permitting the suffix "D" to be added to either of these garnet categories with high confidence. In the interim the $Na_2O > 0.07$ wt.% threshold noted in Gurney (1984) and documented further in Gurney et al. (1993, their Fig. 8) could be applied for this purpose, leading to garnet categories G3D, G4D and G5D within the framework of the current classification scheme. The G3D and G4D categories would constitute a replacement for the term "Group 1 eclogite" which originally referred to a coarse-grained eclogite texture (MacGregor and Carter, 1970), but now also has compositional connotations (McCandless and Gurney, 1989).

4.9. Unclassified (G0)

Kimberlites and related mantle-derived magmas occasionally contain xenocrystic garnets derived from uncommon, unusual or "polymict" mantle lithologies. The scheme proposed here makes no specific provision to classify such grains, instead leaving them to collect in an unclassified category labelled G0 by default. Manual inspection of this group may reveal their affinity to the groups defined above.

5. Summary and implementation

The current classification scheme is formulated to be as simple as possible, whilst also trying to address the multivariate nature of the classification problem and the diversity of chemical, physical and lithological environments in which mantle garnets and diamonds occur. The compositional fields for garnet categories outlined in this work are illustrated in terms of Cr_2O_3 and CaO contents in Fig. 7. Compositional overlaps have been resolved in order to keep the scheme robust, implying that certain simplifying choices have been made which reflect the needs of diamond explorationists, rather than those of mantle researchers (for which see Schulze, 2003). Thus harzburgitic (G10), lherzolitic (G9) and wehrlitic (G12) garnet compositions are separated in the scheme by recognizing natural bounds in Ca-intercept values (e.g. Figs. 4 and 7), the latter being a continuous geometric function anchored to the well-known G10/G9 divide of Gurney (1984, see Fig. 3). Megacrystic (G1) and high-TiO_2 peridotitic (G11) garnets occur on the Ti-rich and Mg-rich side of all other garnet compositions (Fig. 5), and their classification presents the only computational directive of the scheme: G1 and G11 categories have to be assigned prior to any other. At low Cr_2O_3 content a compromise is made by excluding pyroxenitic (G5) garnets from overlapping with lherzolitic (G9) garnets at Mg-numbers >0.7 and by defining a very low-Cr "pyroxenitic" (G4) group that also includes all low-CaO eclogitic garnet compositions. A further group of common eclogitic garnets (G3) extends across a range of Mg–Fe compositions to much higher CaO content (Fig. 7). An unclassified category (G0) completes the scheme.

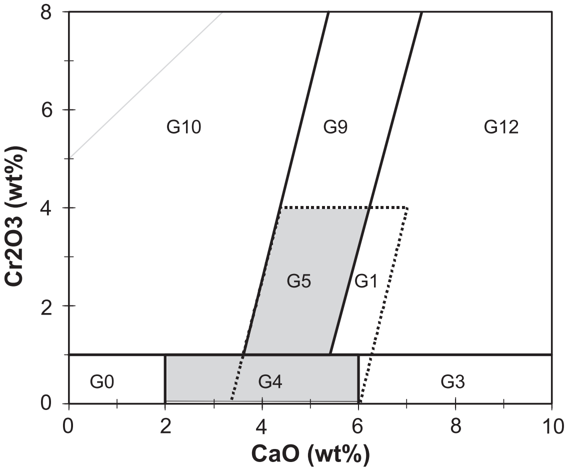

Fig. 7. G-number nomenclature of the classification scheme as viewed in a conventional Cr_2O_3 vs. CaO diagram. Megacryst group G1 (stippled parallelogram) does not actually overlap groups G3, G4, G5, G9 or G12 since it occurs at higher TiO_2 content (see Fig. 5B). Pyroxenitic categories G5 and G4 are indicated by fill pattern. Group G5 garnets are separated from G9 garnets by a Mg-number <0.7 threshold. Note unclassified category G0 at low CaO and Cr_2O_3 content.

It is recommended that implementation of the scheme sequentially tests an unknown grain for compositional compliance in the order G1–G11–G10–G9–G12–G5–G4–G3–G0, slightly different from the order in which they are defined above. A strong geochemical and petrologic association with diamond is indicated by adding a "D" suffix, currently only applicable to G10, G5, G4 and G3 garnet compositions.

The scheme has been applied to the garnet compositions used in the multivariate studies of Dawson and Stephens (1975), Danchin and Wyatt (1979) and to the databases compiled for this investigation, with results summarised in Tables 1–4. Known petrogenetic and lithological associations are given in the left-hand column of each table and garnet classifications according to the current scheme are aligned in similar petrogenetic associations along the upper row. Moderate to high degrees of correlation are evident as

Table 1
Dawson and Stephens (1975) database

N = 398		G10	G9	G11	G1	G5	G4	G3	G12	G0
	n =	*83*	*77*	*20*	*45*	*2*	*37*	*86*	*26*	*22*
DINCL	*53*	64	–	4	–	–	9	17	–	6
HZB	*2*	–	100	–	–	–	–	–	–	–
LHZ	*34*	–	71	15	6	–	3	3	3	–
PRX	*13*	–	39	–	15	–	39	8	–	–
ECL	*99*	–	1	–	–	–	20	73	–	6
WEH	*2*	–	–	–	–	–	–	–	100	–
KCONC	*180*	26	19	7	22	1	3	2	13	7
UNK	*15*	13	67	–	7	7	–	–	–	7

Classification of garnet compositions by the current scheme. Percentages listed are rounded and calculated as a proportion of the known garnet category given in the left-hand column. Category abbreviations are ALK = Alkremite; DINCL = Inclusion in diamond; DIXEN = Diamondiferous xenolith; ECL = Eclogite; GRAN = Lower crustal granulite; HZB = Harzburgite; KCONC = Concentrate from kimberlite; LHZ = Lherzolite; LHZ_DEF = Deformed lherzolite; MEG = Megacryst; MICXEN = Microxenolith; OTH = Other; PER = Unspecified peridotite; PRX = Pyroxenite; UNK = Unknown; WEB = Websterite; WEH = Wehrlite. The garnet compositions of Dawson and Stephens (1975) and cross-tabulated raw counts for Tables 1–4 are available as digital supplementary data in the online version.

high-valued vectors running from top left to bottom right in each of Tables 1–4, implying that upper mantle garnet compositions are usefully separated and categorized by the current classification scheme. Table 3 shows good correlations to exist for harzburgitic, lherzolitic, unspecified peridotitic, megacrystic and wehrlitic garnets, and similar correlations are also evident in Tables 1, 2 and 4. The re-defined and newly introduced low-Cr "pyroxenitic/websteritic" G4 category shows acceptably low overlap with the low-Cr G3 "eclogitic" category, but separation of G5 Cr-bearing pyroxenitic and websteritic garnets from G9 lherzolitic garnets remains a challenge. Garnets in lower crustal granulite and in alkremite xenoliths classify predominantly as eclogitic, as expected. The current scheme has a low overall incidence of unclassified (G0) garnets, a noteworthy feature given the significantly expanded database compiled for this investigation (Tables 3 and 4).

Table 2
Danchin and Wyatt (1979) database

N = 1777		G10	G9	G11	G1	G5	G4	G3	G12	G0
	n =	*257*	*455*	*137*	*237*	*8*	*289*	*281*	*86*	*27*
DINCL	*191*	57	4	3	2	–	9	24	–	2
DIXEN	*30*	80	7	13	–	–	–	–	–	–
HZB	*57*	39	30	32	–	–	–	–	–	–
LHZ	*168*	2	81	13	1	1	1	–	1	–
LHZ_DEF	*101*	2	33	35	31	–	–	–	–	–
PER	*27*	15	67	4	11	–	–	–	4	–
MEG	*39*	–	3	–	67	–	18	–	10	3
PRX	*80*	18	30	14	13	–	21	4	1	–
WEB	*33*	–	46	–	3	3	46	–	–	3
ECL	*332*	–	3	0	3	–	33	59	0	1
ALK	*18*	–	–	–	–	–	22	72	–	6
WEH	*3*	–	–	33	–	–	–	–	67	–
KCONC	*698*	11	27	5	22	1	17	3	11	2

Layout and abbreviations as in Table 1.

Table 3
Xenolith database compiled for this investigation

N = 4532		G10	G9	G11	G1	G5	G4	G3	G12	G0
	n =	*350*	*1495*	*380*	*601*	*20*	*698*	*872*	*83*	*33*
HZB	*284*	97	–	3	–	–	–	–	–	0
LHZ	*1378*	2	79	13	3	–	2	–	2	0
LHZ_DEF	*316*	–	33	42	25	–	–	–	1	–
PER	*240*	14	61	16	3	–	5	–	2	0
MEG	*515*	–	0	3	88	0	6	1	0	1
PRX	*252*	0	24	–	2	7	55	8	2	1
WEB	*139*	–	31	1	2	1	62	–	2	1
ECL	*1113*	–	1	–	1	–	32	64	1	1
ALK	*37*	–	8	–	–	–	8	60	3	22
WEH	*37*	–	8	14	–	–	–	–	78	–
GRAN	*153*	–	–	–	–	–	26	72	–	2
MICXEN	*68*	32	57	2	4	–	–	–	4	–

Layout and abbreviations as in Table 1.

Updated statistics for garnets included in diamond are given in Table 4. The data set is dominated by peridotitic inclusions and the ratio G10/(G9 + G10) is 82%, still essentially the same as that calculated by Gurney (1984), even though the currently applied definition for peridotite has a lower Cr_2O_3 threshold

Table 4
Inclusions in diamonds compiled for this investigation

N = 637		G10	G9	G11	G1	G5	G4	G3	G12	G0
	n =	*271*	*60*	*16*	*12*	*1*	*63*	*205*	*1*	*8*
D suffix	*n* = *494*	*n* = *255*	–	–	–	*n* = *1*	*n* = *50*	*n* = *188*	–	–
PER	*348*	78	16	5	1	–	–	–	–	1
WEB	*13*	–	31	–	15	8	15	–	8	23
ECL	*273*	–	–	–	3	–	22	75	–	–
OTH	*3*	–	–	–	–	–	33	–	–	67

Layout and abbreviations as in Table 1.

(1.0 instead of 2.0 wt.% Cr_2O_3). The familiar eclogitic (G3) association with diamond is clearly evident and it is noted that the newly defined G4 category contains more diamond-inclusions than the G9 category, even though the latter garnets are much more abundant in the upper mantle (Table 3). Following the methodology and thresholds presented in the updated scheme, a total of 494 of the 637 garnets in our diamond-inclusion data set are assigned the diamond-facies "D" suffix (i.e. 78%). In particular, the "D" suffix is found to be applicable in 255 of 271 G10 (94%), 1 of 1 G5, 50 of 63 G4 (79%) and 188 of 205 G3 (92%) compositions (Table 4). These statistics should inspire confidence in the use of the G10D, G5D, G4D and G3D categories by diamond explorers.

6. Conclusion

The classification scheme outlined above utilises a few relatively simple criteria to categorise the compositions of garnet grains that may be associated with diamond-bearing intrusives. The scheme is reliant only on the major and minor element compositional data that industry-standard electron microprobe analyses can provide and has superior accuracy compared to historical or contemporary classification schemes because it specifically incorporates both geochemical and petrological constraints that appear to determine the occurrence of peridotitic, eclogitic and "websteritic" diamonds in the lithospheric upper mantle. Improvements in Ca-in-garnet and Na-in-garnet thermobarometry are required to further improve the accuracy of the current scheme.

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Appendix A. Data sources

Benoit and Mercier (1986)
Bloomer and Nixon (1973)
Boyd et al. (2004)
Boyd and Danchin (1980)
Boyd and Nixon (1978)
Boyd and Nixon (1979)
Boyd et al. (1993)
Boyd et al. (1997)
Burgess and Harte (1999)
Carswell et al. (1979)
Cox et al. (1973)
Danchin and Boyd (1976)
Daniels et al. (1995)
Dawson et al. (1978)
Dawson et al. (1980)
Delaney et al. (1979)
Delaney et al. (1980)
Eggler et al. (1987)
Ehrenberg (1978)
Ehrenberg (1982)
Exley et al. (1982)
Field and Haggerty (1994)
Field et al. (1989)
Franz et al. (1996)
Franz et al. (1997)
Griffin et al. (1989)
Griffin et al. (1993)
Hall (1991)
Hervig et al. (1986)
Ionov et al. (1993)
Kopylova et al. (2000)
Logvinova and Sobolev (1995)
Luth et al. (1990)
MacGregor (1979)
McCallum and Eggler (1976)
McGee and Hearne (1989)
Menzies (2001)

Mitchell (1984)
Mofokeng (1998)
Nixon (1987)
Nixon and Boyd (1973)
Nowicki (1990)
Pearson et al. (1990)
Pearson et al. (1994)
Pearson et al. (1999)
Pokhilenko et al. (1977)
Pokhilenko et al. (1991)
Pokhilenko et al. (1993)
Reid et al. (1975)
Robey (1981)
Rudnick et al. (1994)
Schulze (1995)
Schulze (1996)
Schulze et al. (1997)
Schulze et al. (2000)
Shee (1994)
Shee et al. (1989)
Simon et al. (in press)
Skinner (1989)
Smith (1999)
Smith and Boyd (1992)
Smith and Wilson (1985)
Smith et al. (1991)
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