GARNET LHERZOLITES FROM LOUWRENCIA, NAMIBIA: BULK COMPOSITION AND P/T RELATIONS

Boyd FR[1], Hoal KO[2], Hoal BG[3], Pearson DG[4], Nixon PH[5], and Kingston MJ[6]
[1]Carnegie Institution of Washington, USA; [2]Hazen Research, USA; [3]Society of Economic Geologists, USA; [4]University of Durham, UK; [5]Green Hammerton, UK; [6]US Geological Survey, USA

The Louwrencia kimberlite is one of a group of over 70 non-diamondiferous pipes that are clustered at Gibeon, Namibia, about 400 km west of the Kalahari line. Their ages, near 70 Ma (Davies et al, 2001), are distinctly younger than the 90 Ma-old Group 1 kimberlites on the craton. The boundaries of Louwrencia against Dwyka sediments are poorly exposed but the pipe appears to be oval, approximately 60 x 100 meters. The kimberlite and surrounding area are level except for a large prospecting pit. Wind erosion and surface wash left an original abundance of xenoliths on the surface but these are now largely removed. This paper is based on twenty-six garnet lherzolites that were of sufficient size to provide analytical samples averaging 400 grams, as required for coarse grained rocks. Some were collected by the authors. One was collected by T. Clifford and others were generously provided by I.D. MacGregor, R.H. Mitchell, J.J. Gurney and the Anglo American Research Laboratories. Whole rock analyses for these large Louwrencia xenoliths form the most extensive set of such data for any off-craton locality in southern Africa. Electron probe and isotopic analyses have also been obtained.

Although there are pronounced similarities in lithology, there are differences in abundance between the Louwrencia xenoliths and suites from the craton. Predominantly coarse, low-temperature peridotites are common and a number of sheared high-temperature peridotites have also been found. Harzburgites (cpx-free) are rare at Louwrencia and apparently only one low-Ca garnet harzburgite has been described from a Namibian kimberlite (Franz, 1966). Spinel-facies peridotites are also rare and this paucity may reflect the presence of a thicker crust with a correspondingly thinner zone in the mantle where spinel-facies peridotities are stable. There are no eclogites among the suite of over 400 mantle xenoliths collected by us at Louwrencia.

There are also strong similarities in texture and mineralogy between the Louwrencia peridotites and those from the craton. Low-temperature peridotites from Louwrencia are coarse with only three out of twenty-two having significant development of neoblasts, estimated to be 10% or less. High-temperature peridotites are all sheared with neoblast proportions ranging from 10-90%. Coarse olivine commonly ranges up to 1 cm, more in a few specimens. Pyroxenes are less coarse and some orthopyroxenes are mantled with secondary clinopyroxene in textures similar to those described for Udachnaya peridotites (Boyd et al., 1997). The habit of garnet is irregular, ranging from grains over 1 cm to 1-5 mm rounded crystals. Kelyphite is variable, from absent to as thick as 0.5 mm, and in some specimens is mantled by phlogopite. In one low-temperature peridotite the garnet is replaced by round clots of polycrystalline mica that are mantled by clinopyroxene. Spinel is commonly dispersed in 1-3 mm rounded grains but in several specimens is intimately intergrown with garnet.

COMPOSITIONAL RELATIONS

Compositional variations in peridotite xenoliths are most easily evaluated and compared by use of modes, calculated from the bulk and probe analyses, as well as with oxides. There is a range of modal olivine in low-temperature Louwrencia lherzolites of 57-79 wt.%, similar to but not as large as the range of 44-81 wt.% in Kaapvaal lherzolites (Fig. 1). The comparable variation in modal orthopyroxene is 11-40 wt.% for Louwrencia and 11-44 wt.% for the Kaapvaal. A striking feature for both suites is a limited range of mg number. Values for olivines from Louwrencia average 91.6 in comparison to 92.6 for the Kaapvaal with very little overlap. The wide ranges of modal olivine at restricted mg number are incompatible with an origin as unmodified residues. Whatever process of segregation (Boyd et al., 1997) or metasomatism (Keleman et al., 1998) has caused these relations appears to have operated in the formation of the Nambian lithosphere as well as the Kaapvaal root.

Modal proportions of clinopyroxene and garnet in Louwrencia and Kaapvaal suites overlap in the range up to 10 wt.%. These relations are illustrated in an oxide plot in Figure 2. On an average the Louwrencia lherzolites are a little richer in CaO but there are a few with less combined CaO and Al_2O_3 than even the Kaapvaal low-Ca harzburgites. Peridotites in both suites are strongly depleted in Ca and Al relative to pyrolite (Fig. 2), but their overlapping trends are probably not entirely due to melt depletion events. The near constancy of mg numbers together with large variations in Ca and Al is inconsistent with a simple melt depletion model. Garnet and diopside may have been introduced long after initial depletion (e.g. Pearson et al., 2001). The relatively tight trends for CaO and Al_2O_3 for the Louwrencia suite, suggest combined introduction, but that model may be inconsistent with trace element disequilibrium between diopside and garnet (Simon et al., 2001).

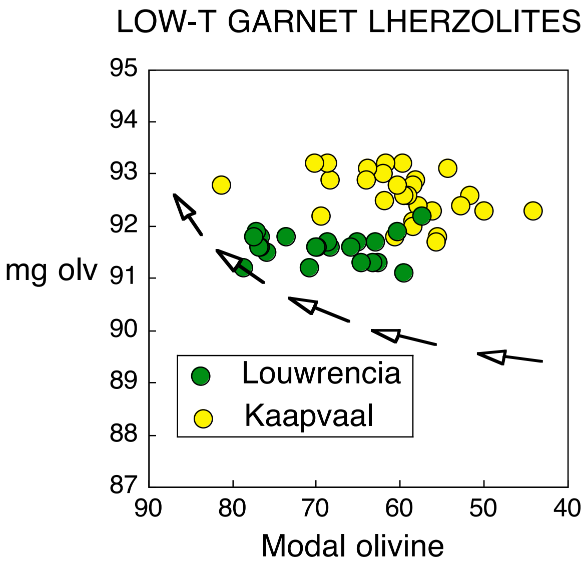

Figure 1: Modal olivine, calculated from bulk and electron probe compositions, plotted against the mg number of olivine. The arrows describe an oceanic depletion trend (Boyd, 1989).

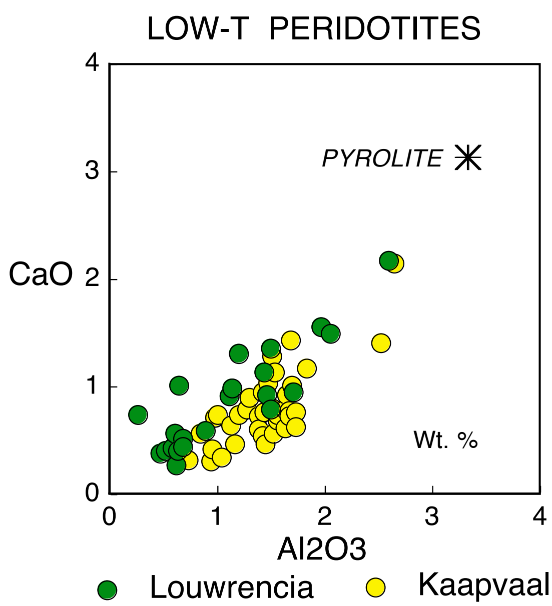

Figure 2: A comparison of CaO vs Al_2O_3 in low-temperature peridotites from Louwrencia and the Kaapvaal.

Bulk compositions for Louwrencia and the Kaapvaal have concordant overlapping trends for Al_2O_3./Cr_2O_3. If Al_2O_3 has been introduced, it would appear necessary that Cr_2O_3 also be substantially of metasomatic origin. Average bulk TiO_2 in the low-temperature Louwrencia lherzolites is 0.04 wt.%, identical to the average for our Kaapvaal data set. Evidently there has not been a metasomatic addition of TiO_2 as appears to have occurred during formation of the high-temperature peridotites

TRACE ELEMENTS AND Os ISOTOPES

Minerals from a selection of Louwrencia peridotites (JJG2523; PHN6133; E11) have been analysed using an ion-microprobe to determine trace element concentrations. These data are in addition to those that Jones (1984) obtained for bulk separates. Diopside and garnet from the Louwrencia xenoliths show similar trace element characteristics to those within Kaapvaal cratonic xenoliths. This is in agreement with data for mineral concentrates (Hoal et al., 1994). Diopsides are consistently LREE-enriched, with La and Ce concentrations between 10 and 100X chondritic, as observed for Kaapvaal low-T peridotites (Shimizu, 1975; Pearson & Nowell, 2002; Simon et al., in press). Garnets are generally LREE depleted. However, garnet from PHN6199, together with 2 garnets reported by Jones and several garnets from concentrate reported by Hoal et al. (1994), show "sigmoidal" REE patterns of the type commonly observed in sub-calcic garnets (Shimizu et al., 1999). The Louwrencia garnets, however, are all Ca-saturated. This type of enrichment is generally associated with very unradiogenic Nd isotope compositions and thus taken to be an ancient feature of the metasomatic history of these rocks. Burgess & Harte (in press) suggest that the sigmoidal REE patterns observed in peridotitic garnets can be explained by interaction with a melt that fractionated the Cr-poor megacryst assemblage. Studies on other Kaapvaal peridotites support this idea (Simon et al., in press). Such a model raises the possibility that the imposed REE pattern may be of a recent origin. The occurrence of these highly fractionated "sigmoidal" REE patterns in off-craton garnet peridotites that contain Ca-saturated garnets indicates that this type of metasomatic process is not restricted to low-Ca garnets and is consistent with a melt interaction model that could have introduced additional garnet into these rocks.

Calculated REE patterns of melt compositions in equilibrium with the diopsides from Louwrencia peridotites are very LREE enriched and closely resemble those of the host kimberlite "melt". This observation has previously been made for diopsides from Kaapvaal low-T peridotites (Shimizu, 1999; Simon et al., in press). Isotopic studies also indicate a general similarity between diopside and the host kimberlite (Simon et al., this volume). Thus, both trace element and isotopic systematics in the diopsides from on- and off-craton low-

T peridotites indicate that much/all of the diopside in low-T peridotites is likely to have formed from a melt associated with the host kimberlite (Simon et al., in press).

Twenty low-T garnet peridotites from Louwrencia and one high-T peridotite have been analyzed for Re-Os isotopes (Pearson et al., 1994). The whole rock Re-Os isotope analyses define a range of Os isotopic compositions, with gammaOsi values ranging from –2.9 to –11.4. The range of isotopic compositions most likely represents disturbance of the peridotites by interaction with sulfide-bearing melts following silicate melt depletion. The least radiogenic Os isotope values generally occur in peridotites that have platinum group element (PGE) patterns typical of melt residues that have not experienced significant post-depletion melt enrichment (Pearson et al., 2002). These samples give Re-depletion (TRD) ages of c. 2.2 Gyr that are in agreement with their TMA ages. It is possible that even the 2.2 Gyr ages represent re-worked Archean lithosphere. However, until detailed sulfide studies are performed, we take the samples with Re - PGE depleted and least radiogenic Os isotope signatures to provide the depletion age of the bulk of the lithospheric mantle root in this region, in the Mid-Proterozoic.

TEMPERATURE-DEPTH ESTIMATES

Both cores and rims of grains were analyzed and either can be used for thermobarometry. Orthopyroxenes in low-temperature peridotites are systematically zoned to about 10% higher Al_2O_3 in the rims. Such zoning is greatly reduced or absent in the high-temperature peridotites. The zoning affects pressure estimates for individual specimens by an amount that is commonly less than 5% and the aggregate effect on a geotherm plot is small. Franz et al (1966b) have noted similar zoning in peridotite xenoliths from other Gibeon pipes. We believe the core compositions best reflect conditions at depth, but the conclusions of this study are not significantly affected by choice of core or rim compositions for thermobarometry.

Estimates of equilibrium conditions for the low-temperature Louwrencia lherzolites form well defined geotherms in the depth range of 75-150 km. Plots using either the TBKN/PBKN thermobarometer of Brey and Kohler (1990) or the FB/MC model system approach advocated by Finnerty and Boyd (1987) agree relatively well (Figs. 3 and 4). This is also true for plots made with the O'Neill/Wood thermometer (O'Neill and Wood, 1979) or with TA97/NGmod (Taylor, 1998). Moreover these plots are remarkably close to an average craton geotherm (Kalahari geotherm) calculated by Rudnick and Nyblade (1998).

The high-temperature peridotites plot at systematically higher temperatures in clusters of varying depth and shape depending on which thermobarometer is used (Figs. 3 and 4). Similar inflections have been noted in previous studies of Louwrencia xenoliths by MacGregor (1975) and Mitchell (1984). The slope of this thermal anomaly is relatively gentle in the TFB/PMC plot and if correct it might be explained as a steady state

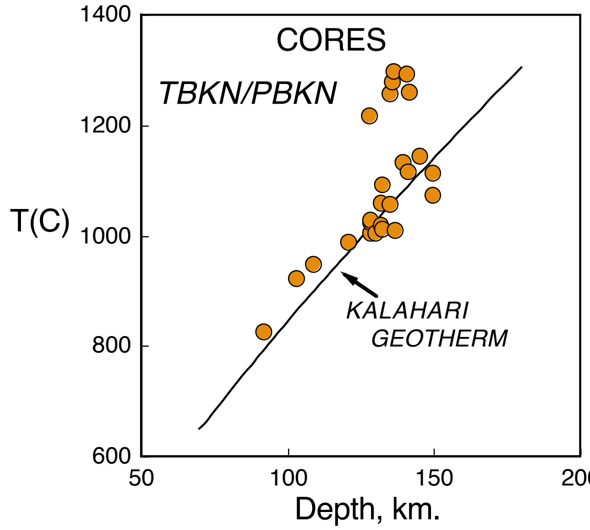

Figure 3: A temperature/depth plot for mineral core compositions in Louwrencia garnet lherzolites using the TBKN/PBKN thermobarometer of Brey and Kohler (1990).

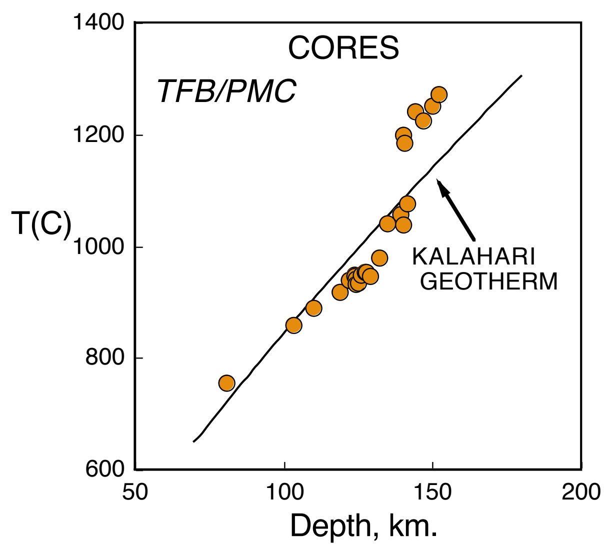

Figure 4: A temperature/depth plot for mineral core compositions in Louwrencia garnet lherzolites using the FB/MC thermobarometer of Finnerty and Boyd (1987).

phenomenon produced by interaction of continental and oceanic lithospheres in a manner suggested by Lenardic and Moresi (2000). Nevertheless, the anomaly is much more abrupt in a TBKN/PBKN plot and if that estimate were correct, the anomaly would more likely have an igneous origin as suggested in previous studies by Mitchell (1984) and Franz et al (1996).

There is a reason apart from the anomaly itself for believing that the igneous interpretation is more likely to be correct. Aspects of the origin of high-temperature peridotites are not well understood as yet, but it can be reasonably argued that they have been metasomatised and erupted from near the base of the conductive lithosphere (e.g. Griffin et al., in press). Their depths of origin are taken to be measures of the thickness of the lithosphere. At Louwrencia at the time of kimberlite eruption this thickness is estimated to have been 140-150 km. On the Kaapvaal craton prior to 90 my the thickness was in the range 175-200 km. Both lithospheres, however, had thermal gradients close to the average Kalahari geotherm (Figs. 3 and 4). Under steady-state conditions a thinner conductive lithosphere would be expected to have a steeper T/P slope. The fact that the Namibian and cratonic gradients are nearly the same implies that the Louwrencia lithosphere at the time of kimberlite eruption was approximately the same thickness as that of the craton. Bell et al. (in press) have reached a similar conclusion. These observations are interpreted to mean that the Namibian lithosphere was thermally eroded and thinned a short time prior to kimberlite eruption. The time interval must have been sufficiently brief in order that the shallower portion of the geotherm be unaffected. A possible cause of a sudden increase in temperature at the base of the craton root might be lithospheric thinning/de-lamination accompanied by rapid replacement by hot, upwelling asthenospheric mantle. (Griffin et al., 1998, Brown et al., 1998). Present day surface heat flow in the Gibeon area is 60-65 mWm^2 in contrast to 40-45 mWm^2 on the craton (Jones, 2001). The difference might be caused by greater heat production in a thicker crust in Namibia but might in part be due to the mantle heat responsible for the high-temperature thermal anomaly being conducted to the surface following kimberlite eruption.

REFERENCES

Bell, D.R., Schmidt, M.D., Janney, P.E., in press. Mesozoic thermal evolution of the southern African mantle lithosphere. In: Jones, A. (Ed.) Lithos Special Volume.

Boyd, F.R., 1991. Compositional distinction between oceanic and cratonic lithosphere. Earth Planet. Sci. Letters 96, 15-26.

Boyd, F.R., Pokhilenko, N.P., Pearson, D.G., Mertzman, S.A., Sobolev, N.V., Finger, L.W., 1997. Composition of the Siberian cratonic mantle: evidence from Udachnaya peridotite xenoliths. Contrib. Mineral. Petrol. 128, 228-246.

Brey, G.P. and Kohler, T, 1990. Geothermobarometry in four phase lherzolites II. New thermobarometers and practical assessment of existing thermobarometers. Jour. Petrol. 31, 1353-1378.

Brown, R.W., Gallagher, K., Griffin, W.L., Ryan , C.G., deWit, M.C.J., Belton, D.X., Harman, R., 1998. Kimberlites, accelerated erosion and evolution of the lithospheric mantle beneath the Kaapvaal craton during the Mid-Cretaceous. In: Extended Abstracts, 7th International Kimberlite Conference, Cape Town, 105-107.

Burgess, S.R., Harte, B., in press. Tracing lithosphere evolution through the analysis of heterogeneous G9/G10 garnets in peridotite xenoliths, II: Trace element chemistry. Jour. Petrol.

Davies, G.R., Spriggs, A.J., Nixon, P.H., 2001. A non cognate origin for the Gibeon kimberlite megacryst suite, Namibia: implications for the origin of Namibian kimberlites:. Jour. Petrol. 142, 159-172.

Finnerty, A.A. and Boyd, F.R., 1987. Thermobarometry for garnet peridotites: basis for the determination of thermal and compositional structure of the upper mantle. In: Nixon, P.H. (Ed.), Mantle Xenoliths, John Wiley & Sons, pp. 381-402.

Franz, L., Brey, G.P., Okrusch, M., 1966a. Steady state geotherm, thermal disturbances, and tectonic development of the lower lithosphere underneath the Gibeon kimberlite provence, Namibia. Contrib. Mineral. Petrol. 126, 181-198.

Franz, L., Brey, G.P., Okrusch, M., 1966b. Reequilibration of ultramafic xenoliths from Namibia by metasomatic processes at the mantle boundary. Jour. Geol. 104, 599-615.

Griffin, W.L., O'Reilly, S.Y., Natapov, L.M., Ryan, C.G., in press. The evolution of lithospheric mantle beneath the Kalahari craton and its margins. In: Jones, A. (Ed.), Lithos Special Volume.

Griffin, W.L., Andi Zhang, O'Reilly, S.Y., Ryan, C.G., 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean craton. In: Flower, M.F.J., Chung Sun Lin, Lo Ching Hua, Lee Tung Yi (Eds.). Mantle dynamics and plate interactions in East Asia. Amer. Geophys. Union, Washington, D.C., Geodynamics Series 27, 107-126.

Hoal, K.E.O., Hoal, B.G., Erlank, A.J., Shimuzu, N. 1994. Metasomatism of the mantle lithosphere recorded by rare earth elements in garnets. Earth Planet. Sci. Letters, 126 303-314.

Jones, M.Q.W., 2001. Heat flow in southern Africa and thermal structure of the Kaapvaal lithosphere. In: Extended Abstracts, The Slave-Kaapvaal Workshop, Merrickville, Ontario.

Jones, R.A., 1984. Geochemical and isotopic studies of some kimberlites and included ultrabasic xenoliths from southern Africa. PhD Thesis, University of Leeds, UK.

Kelemen, P.B., Hart, S.R., Bernstein, S., 1998. Silica enrichment in the continental upper mantle via melt/rock reaction. Earth Planet. Sci. Letters 164, 387-406.

Lenardic, A., Moresi, L., 2000. A new class of equilibrium geotherms in the deep thermal lithosphere of continents. Earth Planet. Sci. Letters 176, 331-338.

MacGregor, I.D., 1975. Petrologic and thermal structure of the upper mantle beneath South Africa in the Cretaceous. Ahrens, L.H., Dawson, J.B., Duncan, A.P., Erlank, A.J. (Eds.) In: Physics and Chemistry of the Earth 9, Pergamon Press, 455-466.

Mitchell, R.H.,1984. Garnet lherzolites from the Hanaus-1 and Louwrencia kimberlites of Namibia. Contrib. Mineral. Petrol. 86, 178-188.

O'Neill, H. St.C., and Wood, B.J., 1979. An experimental study of Fe-Mg partitioning between garnet and olivine and its calibration as a geothermometer. Contrib. Mineral. Petrol. 70, 59-70.

Pearson, D.G., Newell, G.M., 2002. The continental lithospheric mantle: characteristics and significance as a mantle reservoir. Phil. Trans. R. Soc. London A360, 1-28.

Pearson, D.G., Irvine, G.J., Carlson, R.W., Kopylova, M.G., Ionov, D.A., 2002. The development of lithospheric mantle keels beneath the earliest continents: time constraints using PGE and Re-Os isotope systematics. In: Fowler, M., Ebinger, D.J., Hawkesworth, C.J. (Eds.) The Early Earth, Geological Society of London Special Publication.

Pearson, D.G., Boyd, F.R., Simon, N.S.C., 2001. Modal mineralogy and geochemistry of Kaapvaal peridotites: the origin of garnet and diopside and implications for craton stability. Extended Abstracts, the Slave-Kaapvaal Workshop, Merrickville, Ontario, Canada.

Pearson, D.G., Boyd, F.R., Hoal, K.E.O., Hoal, B.G., Nixon, P.H., Rogers, N.W., 1994. A Re-Os isotopic and petrological study of Namibian peridotites: contrasting petrogenesis and composition of on- and off-craton lithospheric mantle. Mineralogical Magazine 58A, 703-704.

Rudnick, R.L., Nyblade, A.A., 1999. The thickness and heat production of Archean lithosphere: constraints from xenolith thermobarometry and surface heat flow. In: Fei, Y., Bertka, C.M., Mysen, B O. (Eds.) Mantle Petrology: Field Observations and High-Pressure Experimentation. The Geochemical Society Special Publications No. 6, 3-12.

Shimizu, N., 1999. Young geochemical features in cratonic peridotites from southern Africa and Siberia. In: Fei, Y., Bertka, C.M., Mysen, B.O., (Eds.) Mantle Petrology: Field Observations and High-Pressure Experimentation. The Geochemical Society Special Publication No. 6, 47-55.

Shimizu, N., 1975. Rare earth elements in garnets and clinopyroxenes from garnet lherzolite nodules in kimberlites. Earth Planet. Sci. Letters 25, 26-32.

Shimizu, N., Pokhilenko, N.P., Boyd, F.R., Pearson, D.G., 1999. Trace element characteristics of garnet dunites/harzburgites, host rocks for Siberian peridotitic diamonds. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H.,(Eds.), Proc. 7th International Kimberlite Conference, Cape Town. Red Roof Designs, Cape Town, 773-832.

Simon, N.S.C., Carlson, R.W., Davies, G.R., Nowell, G.M., Pearson, D.G., in press. Os-Sr-Nd-Hf Isotope Evidence for the Ancient Depletion and Subsequent Multi-Stage Enrichment History of the Kaapvaal Craton, This Volume.

Simon, N.S.C., Carlson, R.W., Davies, G.R., Nowell, G.M., Pearson, D.G., in press. The origin of garnet and clinopyroxene in "depleted" Kaapvaal peridotites. In: Jones, A. (Ed.) Lithos Special Volume.

Simon, N.S.C., Pearson, D.G., Carlson, R.W., Davies, G.R., 2001. Origin of garnet and clinopyroxene in Kaapvaal low-T peridotite xenoliths: implications from secondary ionisation mass spectrometry (SIMS) data. Extended Abstracts, The Slave-Kaapvaal Workshop, Merrickville, Ontario, Canada.

Taylor, W.R., 1998. An experimental test of geothermometer and geobarometer formulations for upper mantle peridotites with application to the thermobarometry of fertile lherzolite and garnet websterite. N.Jb. Miner. Abh. 172, 381-408.

Contact: FR Boyd, 5251 Broad Branch Rd., NW, Washington DC, 20015-1305, USA, E-mail: boyd@gl.ciw.edu