

Origin of the sub-cratonic harzburgite

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Abstract: Peridotite xenoliths from kimberlites, representing sub-cratonic upper mantle materials, can be classified into three types in terms of Al-Cr minerals, garnet peridotite, garnet-spinel peridotite and spinel peridotite. The degree of refractoriness roughly increases in this order; garnet peridotite is lherzolitic and spinel peridotite is harzburgitic. It is possible that the three groups are isobaric, i.e. were formed under the garnet lherzolite stability field, and have different degree of melt extraction. The melt in equilibrium with the spinel harzburgite should have an extremely high Mg# and is komatiitic or picritic. The chemical similarity of refractory mineral inclusions (= peridotite suite) in diamond to those in the spinel harzburgites may imply a genetical relationship between the two.

Introduction

Kimberlitic rocks have many deep-seated xenoliths derived from sub-cratonic mantle. They are the deepest sample of all mantle materials available for us and are very useful as an insight into mantle processes beneath cratons. Unlike spinel peridotite xenoliths from the continental rift zones they may provide us information on relatively old processes recorded.

Garnet peridotites characterize the xenolith suites in kimberlitic rocks, but garnet-free spinel (or chromite) harzburgites are frequently associated with them (e.g., Boyd and Nixon, 1973). They are quite different in petrological characteristics from spinel peridotites in other settings, e.g., solid intrusive peridotites from ocean floors, fore-arc regions and ophiolites, and xenolithic peridotites from oceanic hotspots and continental rift zones (e.g., Arai, 1993). The spinel peridotites from kimberlites will be compared with those from other settings in order to place some constraints on their origin.

The content of this paper had been included in the early version of the manuscript of Arai (1993), written in 1989, and have been later eliminated from the manuscript by some editorial reasons. Conclusions similar to this paper have already been made by Boyd (1989), Walker et al. (1989) and Takahashi (1990). The conclusion of the present paper, however, had been obtained independently, mainly based on mineral chemical data and especially on the systematics discussed in Arai (1993).

Olivine-spinel mantle array

Spinel peridotites derived from the upper mantle plot in a relatively narrow region, the olivine-spinel mantle array, in terms of combination of Fo of olivine and Cr# (= Cr/(Cr +

Al) atomic ratio) of chromian spinel (Arai, 1987, 1993). The olivine-spinel mantle array terminates approximately at Fo=87 to 88, Cr#= 0.08, where the peridotite is very close to pyrolite in composition (Arai, 1987). Arai (1991, 1993) demonstrated that spinel peridotites from one tectonic setting occupy one specific region on the Fo-Cr# plane (Fig. 1). For example the peridotites from fore-arc regions have relatively high Cr# of spinel and relatively low Fo of olivine. Those from oceanic hotspots and continental rift zones are characterized by low Cr# of spinel and relatively high Fo of olivine (Fig. 1).

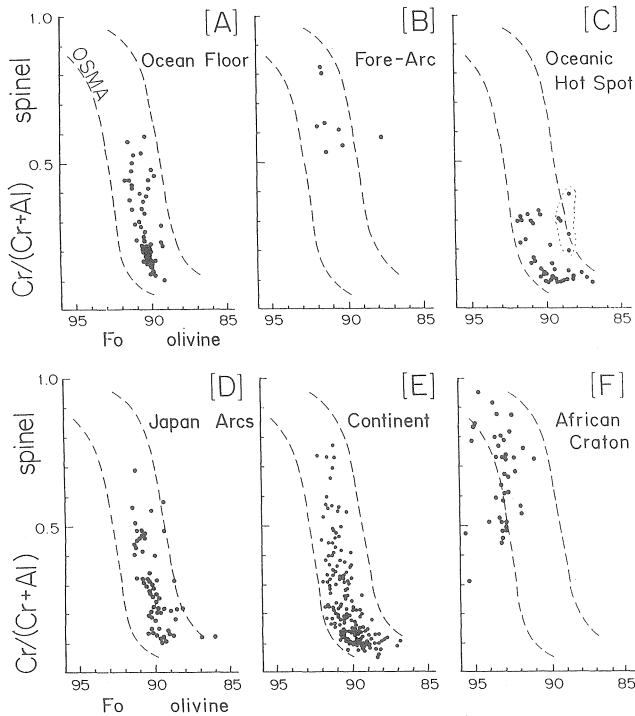


Fig. 1. Relationships between Fo of olivine and Cr# of spinel in spinel peridotites from various tectonic settings (Arai, 1993). OSMA, olivine-spinel mantle array (Arai, 1987). Some iron-rich peridotites from oceanic hotspots (C) are enclosed by a dotted line.

are briefly described and reviewed. Boundary between harzburgite and lherzolite is placed on clinopyroxene/(orthopyroxene + clinopyroxene) volume ratio = 0.1 rather than on clinopyroxene volume = 5 % (standard nomenclature) (Arai, 1984).

Garnet peridotite xenoliths in kimberlites can be classified into two groups, granular and sheared ones (Boyd, 1973; Nixon and Boyd, 1973). Granular peridotites are generally more refractory and have been derived from deeper parts than the sheared ones (Boyd, 1973; Nixon and Boyd, 1973). The peridotites discussed in this article all belong to the granular peridotites.

Based on the experimental results of Jaques and Green (1980), Arai (1987, 1993) considered that Fo-Cr# trajectories of peridotites upon melt extraction are dependent on pressure and water-vapor pressure. Arai (1990, 1993) interpreted that the difference in Fo-Cr# depending on the tectonic setting is due to difference of melting conditions (pressure, temperature and water vapor pressure) depending on the tectonic setting.

Petrological characteristics of the sub-cratonic peridotites

Petrological characteristics of peridotite xenoliths from kimberlites (mainly from Africa)

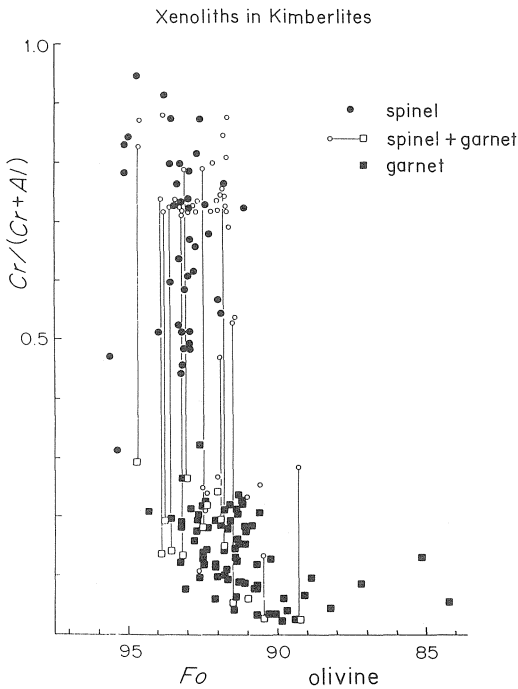


Fig. 2. Relationships between Fo of olivine and Cr# of spinel or garnet in granular peridotite xenoliths in kimberlites. Data are from Boyd et al. (1976), Carswell et al. (1979), Danchin (1979), Danchin and Boyd (1976), Delaney et al. (1979), Emeleus and Andrews (1975), Ferguson et al. (1977), Hearn and Boyd (1975), Hervig and Smith (1982), Hervig et al. (1980a), Lock and Dawson (1980), MacGregor (1979), McCallum and Eggler (1976), Nixon and Boyd (1973), Reid et al. (1975), and Shee et al. (1982).

from 91 to 95 in range, is 93.2 on average (Figs. 2, 3 and 5). Fo of olivine is slightly higher in harzburgite than in lherzolite (Fig. 4). Cr# of spinel has a wide spread, from 0.3 to 0.9 (Fig. 4). It is noteworthy that the Cr# of spinel in harzburgite is not so different from that in lherzolite (Fig. 4). It is also noteworthy that the relationship between Fo of olivine and Cr# of spinel of garnet-free spinel peridotites in kimberlites is quite different from that of spinel peridotites from other settings. The difference from the Fo-Cr# relationship of fore-arc spinel peridotites, which is characterized by low Fo relative to high Cr#, is especially noteworthy (Figs. 1, 3 and 4).

Discussion

Spinel-free garnet peridotites

Spinel-free garnet peridotites in kimberlites are mostly lherzolitic. Cr# of garnet varies from 0.02 to 0.3 but mostly from 0.02 to 0.2 (Fig. 2). Fo content of olivine, roughly correlated with Cr# of garnet, varies from 84 to 94 (91.3 on average) (Figs. 2 and 5). The main cluster of the garnet peridotites seems to terminate at Fo=88 to 89, similar to that of the spinel peridotites (Arai, 1987).

Spinel-garnet peridotite

Spinel-garnet peridotites are mostly lherzolitic. Cr# of garnet and Fo of olivine are roughly similar to those in spinel-free garnet peridotites, mostly from 0.1 to 0.3 and from 91 to 94, respectively (Fig. 2). The averaged values are, however, slightly higher than those in spinel-free garnet peridotites (Figs. 3 and 5). Cr# of spinel is higher than that of coexisting garnet, varying from 0.1 to 0.8 (Fig. 2).

Garnet-free spinel peridotite

Garnet-free spinel peridotites are mostly harzburgitic. Fo content of olivine,

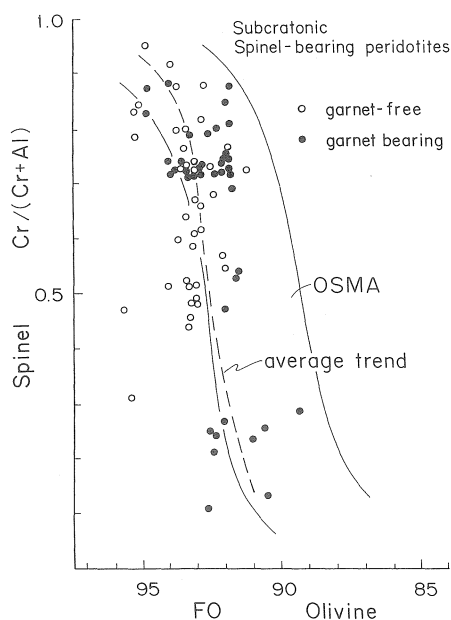


Fig. 3. Relationships between Fo of olivine and Cr# of spinel in spinel-bearing peridotites in kimberlites. Note that their averaged Fo-Cr# trend is very close to the high-Fo boundary of the olivine-spinel mantle array (OSMA). Data source is the same as in Fig. 2.

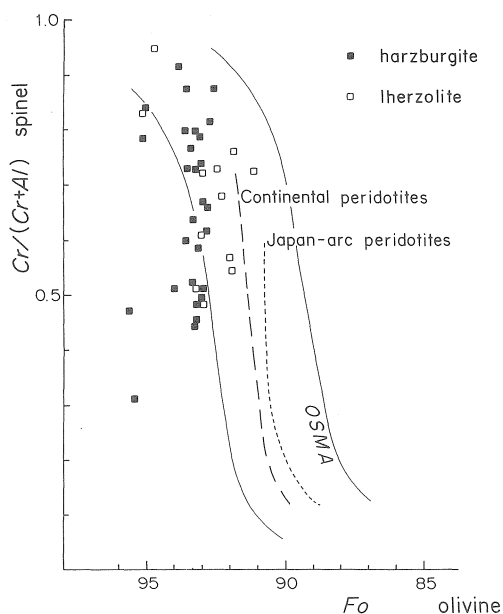


Fig. 4. Relationships between Fo of olivine and Cr# of spinel in garnet-free spinel peridotites in kimberlites. Note that lherzolite is lower in Fo than harzburgite although the spread of Cr# of spinel is not different. Data source is the same as in Fig. 2. Averaged Fo-Cr# trends for continental spinel peridotites from rift zones and for spinel peridotite xenoliths from the Japan arcs are shown. OSMA, olivine-spinel mantle array (Arai, 1987).

It is most probable that the degree of refractoriness increases from spinel-free garnet peridotites to garnet-free spinel peridotites through spinel-garnet peridotites, because the clinopyroxene/(orthopyroxene + clinopyroxene) ratio decreases and the Fo content of olivine increases in this order (Figs. 4 and 5). The garnet-free spinel peridotites, therefore, could be refractory residue formed at the garnet lherzolite stability field. In the model peridotite system $\text{MgO-Al}_2\text{O}_3\text{-Cr}_2\text{O}_3\text{-SiO}_2$, the Al-Cr phase associated with olivine and pyroxene is expected to vary from garnet to spinel through garnet + spinel with an increase of Cr/Al ratio, that is, refractoriness of the system (Fig. 5). In the context of the olivine-spinel mantle array the averaged Fo-Cr# trend of the spinel peridotites in kimberlites can be deduced to be the highest pressure one available for us (Fig. 5). It can be speculated that spinel-free garnet lherzolite, spinel-garnet lherzolite (of harzburgite) and garnet-free spinel harzburgite make the zoned structure similar to the Horoman peridotite (Takahashi, 1992) in the deep part of the upper mantle.

The spinel peridotites (mostly "chromite harzburgites") beneath the cratons are possibly very old, Precambrian in age, because there has not occurred distinct igneous

activities since the Archaean. One of candidates for the melts genetically related to the formation of the refractory peridotites is komatiite. This conclusion is consistent with experimental results that the komatiite magma genesis requires some high pressures (e.g., Takahashi and Scarfe, 1985). Fo content of the most magnesian liquidus olivine in

peridotitic komatiites attains to 95 (e.g., Hill et al., 1990), which is equivalent of that in the most refractory spinel peridotite (Figs. 2 and 5).

The highly magnesian peridotitic komatiite melts are characterized by the undersaturation with chromian spinel components (e.g., Hill et al., 1990), which probably means the absence of spinel in the residual phase. Cr content in komatiitic melts is the highest (approximately 3,000 ppm) between 20 to 30 wt % of MgO (Beswick, 1982). It is possible either that chromian spinel in the harzburgite is a subsolidus phase exsolved from olivine and/or orthopyroxene (Arai, 1978) or that spinel-bearing harzburgites are restites after extraction not of the peridotitic komatiites but of some picritic melts.

Mineral inclusions of the peridotite suite in diamonds are sometimes very refractory. Fo of olivine is 92 to 93 on average but sometimes higher than 94 (Meyer and Boyd, 1972; Meyer and Svisero, 1975; Prinz et al., 1975; Gurney et al., 1979; Hatton and Gurney, 1979; Tsai et al., 1979; Hervig et al., 1980b). Cr# of chromian spinel is very high, around 0.9 (Meyer and Boyd, 1969, 1970, 1972; Meyer, 1975; Prinz et al., 1975). Some genetical relationship can be considered between diamond and the Archaean komatiitic or picritic magmas.

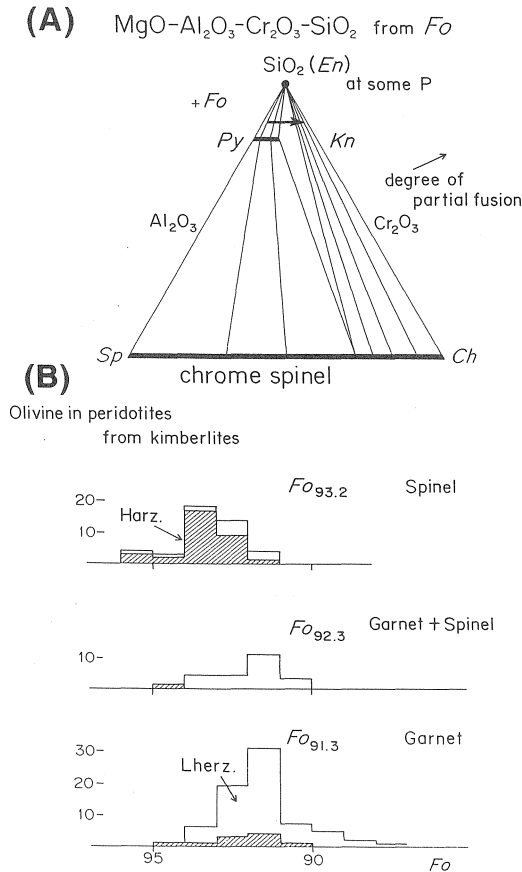


Fig. 5. (A) A simple peridotite system, $\text{MgO}-\text{Al}_2\text{O}_3-\text{Cr}_2\text{O}_3-\text{SiO}_2$ projected from forsterite (Mg_2SiO_4). Py & Kn, pyrope and knorringite, respectively. Sp & Ch, spinel (MgAl_2O_4) and magnesiochromite (MgCr_2O_4), respectively. With an increase of the degree of partial fusion (melt extraction or Cr/Al ratio of system) the Cr-Al phase varies from pyropic garnet to Cr-rich spinel through garnet + spinel. (B) Histograms of Fo of olivine in peridotite xenoliths in kimberlites. Fo, averaged value. Harzburgite and lherzolite are shown by ruled and blank parts, respectively. Note that the averaged Fo content of olivine increases in accordance with the change of the Cr-Al phase, from garnet to spinel through garnet + spinel.

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References

- Arai, S. (1978). Chromian spinel lamellae in olivine from the Iwanai-dake peridotite mass, Hokkaido, Japan. *Earth Planet. Sci. Lett.*, v. 39, p. 267-273.
- (1984). Igneous mineral equilibria in some alpine-type peridotites in Japan. In Sunagawa, I. (ed.) *Materials Science of the Earth's Interior*. Terra Sci. Pub., Tokyo, p. 445-460.
- (1987). An estimation of the least depleted spinel peridotite on the basis of olivine-spinel mantle array. *N. Jb. Mineral. Mh.*, v. 1987, p. 347-354.
- (1991). Origin of upper mantle spinel peridotites. *Kagaku*, v. 60, p. 103-112 (in Japanese).
- (1993). Characterization of spinel peridotites by olivine-spinel compositional relationships: review and interpretation. *Chem. Geol.* (in press).
- Beswick, A.E. (1982). Some geochemical aspects of alteration and genetic relations in komatiitic suites. In Arndt, N.T. and Nisbet, E.G. (eds.) *Komatiites*, George Allen & Unwin, London, p. 283-308.
- Boyd, F.R. (1973). A pyroxene geotherm. *Geochim. Cosmochim. Acta*, v. 37, p. 2533-2546.
- (1989). Compositional distinction between oceanic and cratonic lithosphere. *Earth Planet. Sci. Lett.*, v. 96, p. 15-26.
- , Fujii, T. and Danchin, R.V. (1976). A noninflected geotherm for the Udachnaya kimberlite pipe, USSR. *Carnegie Inst. Year Book*, n. 75, p. 523-531.
- Carswell, D.A., Clarke, D.B. and Mitchell, R.H. (1979). The petrology and geochemistry of ultramafic nodules from Pipe 200, northern Lesotho. In Boyd, F.R. and Meyer, H.O.A. (eds.) *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics*, Amer. Geophys. Union, Washington, D.C., p. 127-144.
- Danchin, R.V. (1979). Mineral and bulk chemistry of garnet lherzolite and garnet harzburgite xenoliths from the Premier mine, South Africa. In Boyd, F.R. and Meyer, H.O.A. (eds.) *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics*, Amer. Geophys. Union, Washington, D.C., p. 104-126.
- and Boyd, F.R. (1976). Ultramafic nodules from the Premier kimberlite pipe,

- South Africa. *Carnegie Inst. Year Book*, n. 75, p. 531-538.
- Delaney, J.S., Smith, J.V. and Nixon, P.H. (1979). Model for upper mantle below Malaita, Solomon Islands, deduced from chemistry of lherzolite and megacryst minerals. *Contrib. Mineral. Petrol.*, v. 70, p. 209-218.
- Emeleus, C.H. and Andrews, J.R. (1975). Mineralogy and petrology of kimberlite dyke and sheet intrusions and included peridotite xenoliths from South-West Greenland. *Phys. Chem. Earth*, v. 9, p. 179-197.
- Ferguson, J., Ellis, D.J. and England, R.N. (1977). Unique spinel-garnet lherzolite inclusion in kimberlite from Australia. *Geology*, v. 5, p. 278-280.
- Gurney, J.J., Harris, J.W. and Rickard, R.S. (1979). Silicate and oxide inclusions in diamonds from the Finsch kimberlite pipe. In Boyd, F.R. and Meyer, H.O.A. (eds.) *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics*, Amer. Geophys. Union, Washington, D.C., p. 1-15.
- Hatton, C.J. and Gurney, J.J. (1979). A diamond - graphite eclogite from the Roberts Victor mine. In Boyd, F.R. and Meyer, H.O.A. (eds.) *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics*, Amer. Geophys. Union, Washington, D.C., p. 29-36.
- Hearn, B.C. and Boyd, F.R. (1975). Garnet peridotite xenoliths in a Montana, U.S.A., kimberlite. *Phys. Chem. Earth*, v. 9, p. 247-255.
- Hervig, R.L. and Smith, J.V. (1982). Temperature-dependent distribution of Cr between olivine and pyroxenes in lherzolite xenoliths. *Contrib. Mineral. Petrol.*, v. 81, p. 184-189.
- , ——— and Steele, I.M. (1980a). Fertile and barren Al-Cr-spinel harzburgites from the upper mantle: ion and electron probe analyses of trace elements in olivine and orthopyroxene: relation to lherzolites. *Earth Planet. Sci. Lett.*, v. 50, p. 41-58.
- , ———, ———, Gurney, J.J., Meyer, H.O.A. and Harris, J.W. (1980b). Diamonds: minor elements in silicate inclusions: pressure-temperature implications. *Jour. Geophys. Res.*, v. 85, p. 6919-6929.
- Hill, R.E.T., Barnes, S.J., Gole, M.J. and Dowling, S.E. (1990). *Physical Volcanology of Komatiites - A Field Guide to the Komatiites between Kalgoorlie and Wiluna, Eastern Goldfields Province, Western Australia*. Geol. Soc. Australia, West. Aust. Div. Excursion Guidebook 1, 74 p.
- Lock, N.P. and Dawson, J.B. (1980). Garnet-olivine reaction in the upper mantle: evidence from peridotite xenoliths in the Letseng-la-Terae kimberlites, Lesotho. *Trans. Roy. Soc. Edinburgh: Earth Sci.*, v. 71, p. 47-53.
- MacGregor, I.D. (1979). Mafic and ultramafic xenoliths from the Kao kimberlite pipe. In Boyd, F.R. and Meyer, H.O.A. (eds.) *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics*, Amer. Geophys. Union, Washington, D.C., p. 156-172.
- McCallum, M.E. and Eggler, D.H. (1976). Diamonds in an upper mantle peridotite

- nodule from kimberlite in southern Wyoming. *Science*, v. 192, p. 253-256.
- Meyer, H.O.A. (1975). Chromium and the genesis of diamond. *Geochem. Cosmochim. Acta*, v. 39, p. 929-936.
- and Boyd, F.R. (1969). Mineral inclusions in diamond. *Carnegie Inst. Year Book*, n. 67, p. 130-135.
- and ————— (1970). Inclusions in diamonds. *Carnegie Inst. Year Book*, n. 68, p. 315-322.
- and ————— (1972). Composition and origin of crystalline inclusions in natural diamonds. *Geochim. Cosmochim. Acta*, v. 36, p. 1255-1273.
- and Svisero, D.P. (1975). mineral inclusions in Brazilian diamonds. *Phys. Chem. Earth*, v. 9, p. 785-795.
- Nixon, P.H. and Boyd, F.R. (1973). Petrogenesis of the granular and sheared ultrabasic nodule suite in kimberlites. In Nixon, P.H. (ed.) *Lesotho Kimberlites*, Lesotho National Develop. Corp., Maseru, p. 48-56.
- Prinz, M., Manson, D.V., Hlava, O.F. and Keil, K. (1975). Inclusions in diamonds: garnet lherzolite and eclogite assemblages. *Phys. Chem. Earth*, v. 9, p. 797-815.
- Reid, A.M., Donaldson, C.H., Brown, R.W., Ridley, W.I. and Dawson, J.B. (1975). Mineral chemistry of peridotite xenoliths from the Lashine volcano, Tanzania. *Phys. Chem. Earth*, v. 9, p. 525-543.
- Shee, S.R., Gurney, J.J. and Robinson, D.N. (1982). Two diamond-bearing peridotite xenoliths from the Finsch kimberlite, South Africa. *Contrib. Mineral. Petrol.*, v. 81, p. 79-87.
- Takahashi, E. (1990). Speculations on the Archean mantle: missing link between komatiite and depleted garnet peridotite. *Jour. Geophys. Res.*, v. 95, p. 15,941-15,954.
- and Scarfe, C.M. (1985). melting of peridotite to 14 GPa and the genesis of komatiite. *Nature*, v. 315, p. 566-568.
- Takahashi, N. (1992). Evidence for melt segregation towards fractures in the Horoman mantle peridotite complex. *Nature*, v. 359, p. 52-55.
- Tsai, H.M., Meyer, H.O.A., Moreau, J. and Milledge, H.J. (1979). Mineral inclusions in diamond: Premier, Jagersfontein and Finsch kimberlites, South Africa, and Williamson mine, Tanzania. In Boyd, F.R. and Meyer, H.O.A. (eds.) *Kimberlites, Diatremes, and Diamonds: Their Geology, Petrology, and Geochemistry*. Amer. Geophys. Union, Washington, D.S., p. 16-26.
- Walker, R.J., Carlson, R.W., Shirley, S.B. and Boyd, F.R. (1989). Os, Sr, Nd, and Pb isotope systematics of southern African peridotite xenoliths: Implications for the chemical evolution of subcontinental mantle. *Geochim. Cosmochim. Acta*, v. 53, p. 1583-1595.