10th International Kimberlite Conference, Bangalore - 2012

10IKC-87

HIGH-Mg CARBONATITIC HDFs, KIMBERLITES AND THE SCLM

Y. Weiss[1], W.L. Griffin[2], D.R. Bell[3] and O. Navon[1]

[1] *The Institute of Earth Sciences, the Hebrew University of Jerusalem, Israel*
[2] *GEMOC, Macquarie University, NSW, Australia*
[3] *School of Earth and Space Exploration, Arizona State University, AZ, USA*

INTRODUCTION

The story of diamonds is interwoven with that of kimberlitic volcanism (Gurney et al., 2010), but the genetic relationship between them has been debated ever since kimberlite was first identified. At first, diamonds were believed to be phenocrysts from early crystallization phases of the kimberlitic magma (Dawson, 1971; Harte, 1980). However, evidence for deep lithospheric pressures for the entrapment of inclusions (see reviews by Meyer, 1987; Stachel and Harris, 2008), the occurrence of diamonds in lamproites and mantle xenoliths, and the recognition that most diamonds are much older than their host kimberlite (Richardson et al., 1984; Gurney et al., 2010) has led to a consensus that most diamonds are xenocrysts in kimberlites. The case for a kimberlitic origin was still raised for fibrous diamonds (Javoy et al., 1984; Boyd et al. 1987). However, the compositions of the high-density fluids (HDFs) they have trapped indicate that they are xenocrysts as well. Navon et al. (1988) pointed out a broad similarity in major-element composition between the fluids trapped in fibrous diamonds and the bulk compositions of Group II kimberlites, and suggested a genetic link at depth. A general similarity between the trace-element abundance patterns of HDFs and kimberlites was noted first by Akagi and Masuda (1988) and later by Schrauder et al. (1996) Zedgenizov et al. (2007), Tomlinson et al. (2009) and Rege et al. (2010), but no attempt has been made to test this idea quantitatively.

In the present work we compare the trace-element data of high-Mg carbonatitic HDFs from Kankan, Guinea, and Udachnaya, Sibiria, with that of kimberlites and consider models for a possible genetic links between them.

HIGH-Mg CARBONATITIC HDFs

The high-Mg carbonatitic HDFs are characterized by very high MgO and CaO content. The SiO_2 and Al_2O_3 content are low and the K_2O content is variable. It is very high in Siberian HDFs and lower in Guinean ones (Klein-BenDavid et al., 2009a; Weiss et al., 2009). All are highly enriched in the most incompatible trace-elements, with levels of up to a few thousand times the primitive-mantle values (Figure 1). The Kankan high-Mg carbonatitic HDFs show depletion of K, Rb, Cs, Nb and Ta and enrichment in Ba, Th, U and LREE relative to the Siberian HDFs. These differences in the highly incompatible elements (Cs–Sr) define two characteristic patterns. Ratios such as La/Nb, Th/Nb, Nb/Rb and Sr/Rb highlight these differences and can be used to distinguish between the two suites. Elements that are more compatible than Sr show similar characteristics and define overlapping patterns (Figure 1).

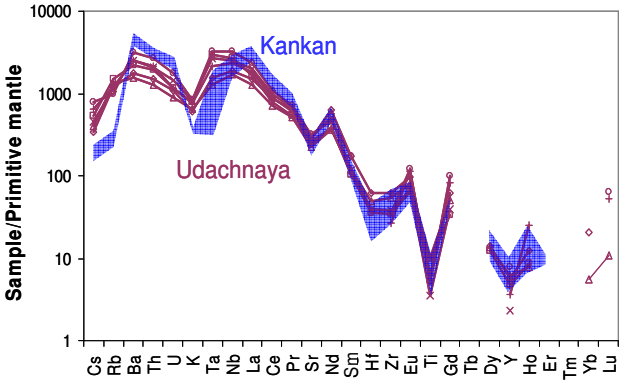

Figure 1: Trace-element patterns of high-Mg carbonatitic HDFs. The different symbols represent the trapped HDFs in six Udachnaya diamonds while the shaded area represents the range for the HDFs in three Kankan diamonds. The uncertainties on the values of Yb and Lu are large and they can be regarded as qualitative only. Primitive-mantle values are from McDonough and Sun (1995).

THE KIMBERLITE CONNECTION

The major-element compositions of the high-Mg HDFs (Klein-BenDavid et al., 2009a; Weiss et al., 2009; Zedgenizov et al., 2007, 2009) resemble experimentally-produced near-solidus melts of carbonate-bearing peridotite (Brey et al., 2008; Dasgupta and Hirschmann, 2007). The high-pressure experimental results of Dalton and Presnall (1998a,b) in the system $CaO–MgO–Al_2O_3–SiO_2–CO_2$ connect the high-Mg carbonatitic HDFs and the near-solidus melts of carbonated peridotite with both Group I

and Group II kimberlites (Figure 2). This suggests that with continuous heating, an initial high-Mg carbonatitic fluid becomes poorer in CaO and richer in SiO_2, Al_2O_3 and MgO and evolves toward a kimberlitic melt.

The trace-element patterns of Udachnaya high-Mg HDFs exhibit close similarity to those of Group I kimberlites from Africa, Canada, Siberia, Greenland, Finland, India and Brazil (Figure 3). Compared to Group II kimberlites the Udachnaya high-Mg HDFs reveal higher Nb and Ta relative to Ba, Th, U, La and Ce. This can be seen best using La/Nb *vs* Th/Nb diagram. The Udachnaya HDFs fall in the field of Group I kimberlites, whereas the Kankan high-Mg HDFs, with their lower Nb and Ta and higher correlative ratios, fall close to Group II kimberlites (Figure 3).

Overall, the major- and trace-element similarities suggest a genetic link between the high-Mg HDFs from Udachnaya and Group I kimberlites and between Kankan HDFs and Group II kimberlites.

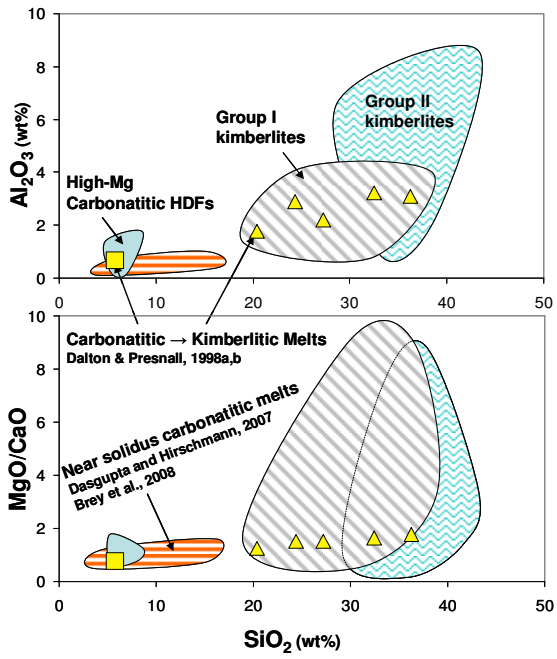

Figure 2: Major-element plots comparing HDFs and kimberlites with near-solidus melts of carbonated peridotite. The trend of kimberlites to much higher MgO/CaO reflects assimilation of olivine.

CRYSTALLIZING THE ASCENDING KIMBERLITE

Cooling of kimberlitic melt and crystallization of olivine, garnet, pyroxene, carbonate and ilmenite may lead to the formation of high-Mg carbonatitic residual fluids. Figure 4 shows the trace-element pattern of the residual fluid after 80% crystallization. For most elements, the overall pattern of the resulting fluid is very similar to that of the measured high-Mg HDF. It is harder to reconcile the low initial K_2O content of the kimberlite with the high K_2O of the Siberian HDFs, or their similar water content, with the predictions of

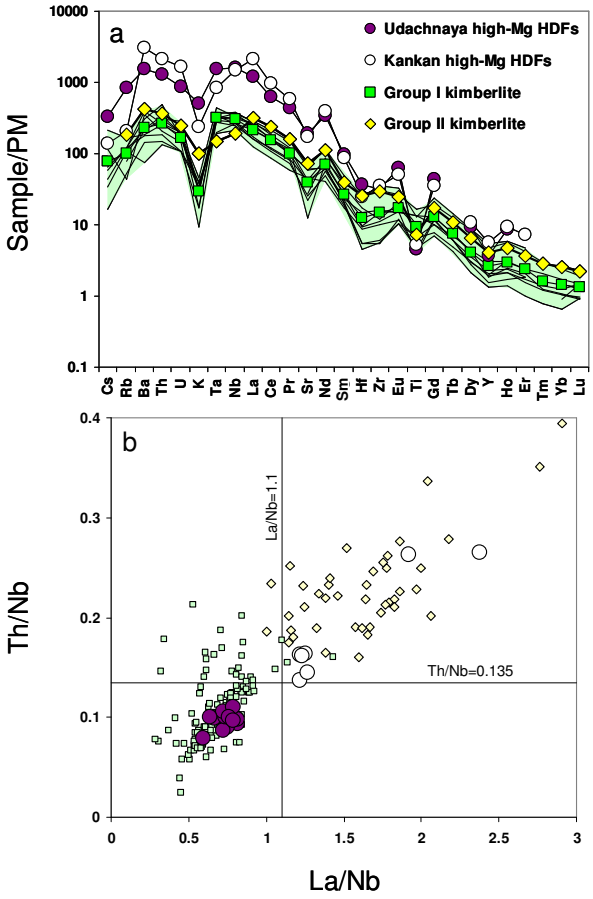

Figure 3: Trace-element characteristics of high-Mg carbonatitic HDFs and kimberlites. (a) The average trace-element pattern of high-Mg carbonatitic HDFs in diamonds from Udachnaya and Kankan, worldwide average Group I kimberlite pattern (green squares) as determined by averaging the compositions of Group I kimberlites from Africa, Canada, Siberia, Greenland, Finland, India and Brazil (thin black lines within the light green area) and the average pattern of South African Group II kimberlites. (b) La/Nb *vs* Th/Nb values in Group I and Group II kimberlite compared with high-Mg carbonatitic HDFs in Kankan and Udachnaya diamonds. See Weiss et al. (2011) for data sources.

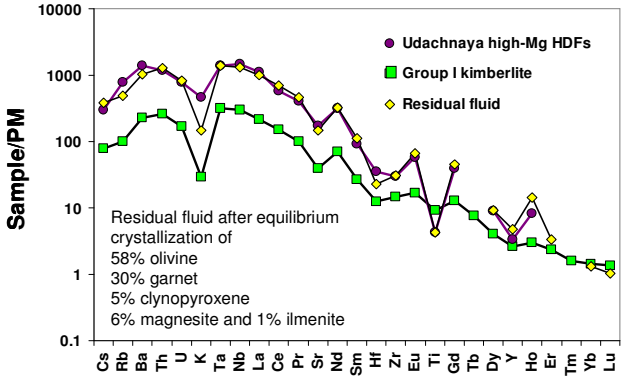

Figure 4: Crystallization of kimberlite to form high-Mg HDF. Ti concentration is based on the mass balance calculation of the cumulate. The values for the average Group I kimberlite are as in Figure 3.

a fractional crystallization model. However, these discrepancies cannot fully dismiss such a scenario, as the K_2O content of the kimberlite may have been higher at depth (Kamenetsky et al., 2004) and the water discrepancy may have its origin in the near-surface modification of the kimberlite (Sheppard and Dawson, 1975; Bell et al., 2004).

PARTIAL MELTING OF SIMILAR SOURCES

Another way to test the linkage between kimberlites and high-Mg HDFs is by modeling them as product of melting of a common source. We calculated the trace element concentrations of peridotite (66% olivine, 26% orthopyroxene, 3% clinopyroxene and 5% garnet) in equilibrium with the Udachnaya high-Mg HDFs, average Udachnaya kimberlite, an average South African Group I kimberlite and a worldwide average of Group I kimberlites (Figure 5a). All the calculated sources have similar patterns. The closest match of these calculated sources is obtained using partial melting of F=3% for the Udachnaya kimberlite, 2% for the South African and worldwide average Group I kimberlite and 0.2% for the high-Mg HDFs. The similarity in trace-element patterns between the calculated sources of Group I kimberlites and the Udachnaya high-Mg HDFs, combined with experimental studies that fit their major-element compositions (Dalton and Presnall, 1998a,b; Brey et al., 2008), strongly suggest that the two enriched melts can be formed by different degrees of melting of the same (or very similar) mantle source. The $^{87}Sr/^{86}Sr$ ratios of the trapped high-Mg HDFs in four of the Udachnaya diamonds (Klein-BenDavid et al., 2009b) vary between 0.7043 and 0.7053, well within the range of Group I kimberlites (0.7030–0.7055; Smith, 1983; Becker and le Roex, 2006 and references therein). This correspondence in $^{87}Sr/^{86}Sr$ ratios provides further support for the suggested connection between Udachnaya high-Mg HDFs and Group I kimberlites.

High-Mg HDFs trapped in diamonds from Kankan, Guinea have lower levels of alkalis and higher contents of LREE, Ba, Th and U than the Udachnaya high-Mg HDFs (Figure 1 and 3). This may reflect smaller degrees of melting compared to the Siberian HDFs and retention of phlogopite in their source rocks. Similarly, the composition of Group II kimberlites argues for phlogopite in their source (Mitchell, 1995), and they represent lower degrees of melting than Group I kimberlites (Becker and le Roex, 2006). When calculating the source compositions, a good fit is obtained if the Kankan HDFs represent F=0.1% and are in equilibrium with a source that carries 0.3% phlogopite, while Group II kimberlites are produced by 1% melting in equilibrium with a source with 0.1% phlogopite (Figure 5b). The lower amount of phlogopite in equilibrium with Group II kimberlite is consistent with their relatively higher degree of melting, their higher Al_2O_3 and SiO_2 compared to the Kankan high-Mg HDFs (Figure 2), and their higher K_2O contents compared to Group I kimberlites (Mitchell, 1995; Becker and le Roex, 2006). Here as well, farther support is provided by the high $^{87}Sr/^{86}Sr$ ratio (0.7079) in a single Kankan diamond, ON-KAN-386 (Klein-BenDavid unpublished data), well outside the range of Group I kimberlites but within the range of Group II kimberlites ($^{87}Sr/^{86}Sr$=0.7072–0.7083; Smith et al., 1983; Becker and le Roex, 2006 and references therein).

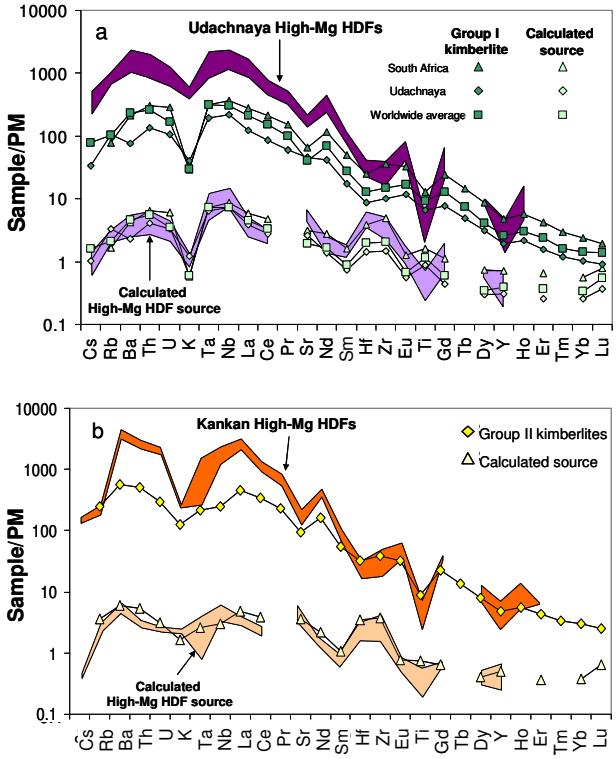

Figure 5: Calculated source trace-element composition for high-Mg HDFs and kimberlites. (a) Udachnaya high-Mg HDFs and Group I kimberlites and their calculated source patterns. (b) Kankan high-Mg HDFs and average South African Group II kimberlites and their calculated sources. Mineral/carbonatitic-melt partition coefficients for olivine, orthopyroxene, clinopyroxene and garnet are from Dasgupta et al. (2009) and for phlogopite from Sweeney et al. (1995) and Schmidt et al. (1999).

DIAMOND-FORMING HIGH-Mg HDFs AND KIMBERLITES AS METASOMATIC AGENTS

It is now widely accepted that the sub-continental lithospheric mantle (SCLM) was strongly depleted through extensive extraction of mafic melts and that it was later refertilised by interaction with trace element-rich mantle-derived melts and fluids (Erlank et al., 1987). In spite of the diverse patterns of individual xenoliths, the average trace-element compositions of Archaean xenoliths from the Siberian, Canadian, North Atlantic and the Kaapvaal cratons are highly comparable (Schmidberger and Francis, 2001; Gre'goire et al., 2003; Ionov et al., 2010; Simon et al., 2007; Wittig et al., 2008). The similarity is surprising, as the lithosphere in the various localities are separated both

physically and by the age of formation. All these averages are different from the calculated average of basalt-hosted peridotite xenoliths from the post-Archaean SCLM (McDonough, 1990).

The trace-element patterns of Udachnaya high-Mg carbonatitic HDFs and Group I kimberlites are similar in shape to the pattern of the average post-Archaean xenolith rather than to the average of the Archaean ones (Figure 6a). This is remarkable since the HDF-bearing diamonds and many kimberlites are found on Archaean cratons. Figure 6b shows that the similarity in shape can be explained by a simple mixing model with addition of 2.5% of average Group I kimberlitic magma or 0.5% of the Udachnaya high-Mg carbonatitic HDF to a depleted SCLM (modeled as MORB source or a more depleted one). The question remains as to why the average post-Archaean, rather than the Archaean, xenoliths have trace element patterns that are similar to those of kimberlitic magmas or high-Mg carbonatitic HDFs.

The average compositions of different regions of the SCLM may actually be referred to as the average enrichment, due to different metasomatic events that the SCLM experienced between the time of its depletion and its sampling as xenoliths. Thus, the trace-element similarity of the average post-Archaean xenoliths may be the result of metasomatism mostly by kimberlites, high-Mg HDFs and other melts with similar patterns. Some of the Archaean xenoliths have enriched trace-element patterns that are comparable to the average of the post-Archaean ones, suggesting that they as well were metasomatically influenced by such melts. On the other hand, many Archaean xenoliths and their cratonic-average compositions are characterized by different patterns, suggesting that fluids other than kimberlites or high-Mg HDFs were metasomaticaly enriching the Archaean SCLM. Indeed, other diamond-forming HDFs with different compositions and patterns have been found (10IKC abstract No. 174). Mixing of these HDFs with a depleted SCLM source explains some of the different trace-element characteristics, as sampled by Archaean metasomatized xenoliths. The similarity of the average pattern of xenoliths from various Archaean cratons suggests that long integration of interactions with different metasomatic agents leave broadly similar, large-scale, enriched litospheric reservoirs.

CONCLUSIONS

The similar trace-element patterns of kimberlites and HDFs strongly support a common source for both. The patterns and element ratios also suggest that the Udachnaya HDFs are closer to Group I kimberlite, while the Kankan HDFs are associated with Group II. These associations are reflected in their respective Sr-isotope compositions. The close relation between HDFs that were trapped at depth and kimberlites sampled at the surface, places constraints on the chemical composition of kimberlitic magmas at depth and indicates that their incompatible-element compositions did not change much *en route*.

The similarity of the trace-element patterns of both HDFs and kimberlites to that of the post-Archaean SCLM may reflect the interaction of such melts with the lithospheric keel, its melting to produce HDF and/or kimberlites or melting of deeper sources that led to formation of HDFs and kimberlite and to widespread metasomatism of the SCLM.

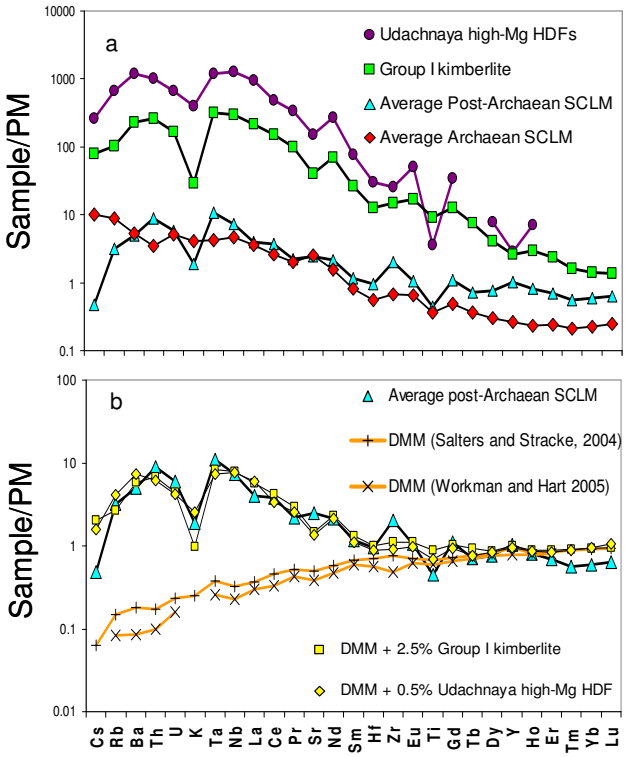

Figure 6: (a) Trace-element patterns of the Udachnaya high-Mg HDFs, worldwide average Group I kimberlites (from Figure 3) and the average composition of the Archaean and post Archaean SCLM. (b) The enriched post-Archaean SCLM is closely fitted by mixing either kimberlitic melt or high-Mg HDF with depleted mantle source, represented by the average depleted MORB mantle (DMM) composition (other, more depleted composition would yield similar results).

References

Akagi, T., Masuda, A., 1988. Isotopic and elemental evidence for a relationship between kimberlite and Zaire cubic diamonds. Nature 336, 665–667.

Becker, M., le Roex, A.P., 2006. Geochemistry of South African on- and off-craton, group I and group II kimberlites: petrogenesis and source region evolution. J. Petrol. 47, 673–703.

Bell, D.R., Rossman, G.R., Moore, R.O., 2004. Abundance and partitioning of OH in a high pressure magmatic system: megacrysts from the Monastery kimberlite, South Africa. J. Petrol. 45, 1539–1564.

Birkett, T.C., McCandless, T.E., Hood, C.T., 2004. Petrology of the Renard igneous bodies: host rocks for diamond in the northern Otish Mountains Region, Quebec. Lithos 76, 475–490.

Boyd, S.R., Mattey, D.P., Pillinger, C.T., Milledge, H.T., Mendelson, M., and Seal, M., 1987. Multiple growth events during diamond genesis: an integrated study of carbon and nitrogen isotopes and nitrogen aggregation state in coated stones. Earth and Planetary Science Letters 86, 341-353.

Brey, G.P., Bulatov, V.K., Girnis, A.V., Lahaye, Y., 2008. Experimental melting of carbonated peridotite at 6–10 GPa. Journal of Petrology 49, 797–821.

Dalton, J.A., Presnall, C., 1998b. The continuum of primary carbonatitic–kimberlitic melt compositions in equilibrium with lherzolite: data from the system CaO–MgO–Al2O3–SiO2–CO2 at 6 GPa. Journal of Petrology 39, 1953–1964.

Dalton, J.A., Presnall, D.C., 1998a. Carbonatitic melts along the solidus of model lherzolite in the system CaO–MgO–Al2O3–SiO2– CO2 from 3 to 7 GPa. Contrib. Mineral. Petrol. 131, 123–136.

Dasgupta, R., Hirschmann, M.M., 2007. A modified iterative sandwich method for determination of near-solidus partial melt compositions. II. Application to determination of near-solidus melt compositions of carbonated peridotite. Contributions to Mineralogy and Petrology 154, 647–661.

Dasgupta, R., Hirschmann, M.M., McDonough, W.F., Spiegelman, M., Withers, A.C., 2009. Trace element partitioning between garnet lherzolite and carbonatite at 6.6 and 8.6 GPa with applications to the geochemistry of the mantle and of mantle-derived melts. Chem. Geol. 262, 57–77.

Dawson, J.B., 1971. Advances in kimberlite geology. Earth-Sci. Rev. 7, 187-214.

Erlank, A.J., Waters, F.G., Hawkesworth, C.J., Haggerty, S.E., Allsopp, H.L., Rickard, R.S., Menzies, M.A., 1987. Evidence for mantle metasomatism in peridotite nodules from the Kimberly pipes, South Africa. In: Menzies, M.A., Hawkesworth, C.J. (Eds.), Mantle Metasomatism. Academic Press, pp. 221–311.

Gre'goire, M., Bell, D.R., Le Roex, A.P., 2003. Garnet lherzolites from the Kaapvaal Craton (South Africa): trace element evidence for a metasomatic history. J. Petrol. 44, 629–657.

Gurney, J.J., Helmstaedt, H.H., Richardson, S.H., Shirey, S.B., 2010. Diamonds through Time. Economic Geology 105, 689–712.

Harte, B., Gurney, J.J., Harris, J.W., 1980. The formation of peridotitic suite inclusions in diamonds. Contributions to Mineralogy and Petrology 72, 181-190.

Ionov, D.A., Doucet, S.L., Ashchepkov, I.V., 2010. Composition of the lithospheric mantle in the Siberian Craton: new constraints from fresh peridotites in the Udachnaya- East Kimberlite. J. Petrol. 51, 2177–2210.

Javoy, M., Pineau, F., Demaiffe, D., 1984. Nitrogen and carbon isotopic composition in diamonds from Mbuji Mayi (Zaire). Earth and Planetary Science Letters 68, 399-412.

Kamenetsky, M.B., Sobolev, A.V., Kamenetsky, V.S., Maas, R., Danyushevsky, L.V., Thomas, R., Sobolev, N.V., Pokhilenko, N.P., 2004. Kimberlite melts rich in alkali chlorides and carbonates: a potent metasomatic agent in the mantle. Geology 32, 845–848.

Klein-BenDavid, O., Logvinova, A.M., Schrauder, M., Spetius, Z.V., Weiss, Y., Hauri, E.H., Kaminsky, F.V., Sobolev, N.V., Navon, O., 2009a. High-Mg carbonatitic microinclusions in some Yakutian diamonds – a new type of diamond-forming fluid. Lithos 112, 648-659.

Klein-BenDavid, O., Pearson, D.G., Nowell, G.M., Ottley, C., 2009b. Sr isotope and trace element systematics in diamond forming fluids—the relative roles of asthenosphere and lithosphere. Abstract, MicroAnalysis Processes Time, Edinburgh.

McDonough, W.F., 1990. Constraints on the composition of the continental lithospheric mantle. Earth Planet. Sci. Lett. 101, 1–18.

McDonough, W.F., Sun, S.S., 1995. The composition of the Earth. Chemical Geology 120, 253-223.

Meyer, H.O.A., 1987. Inclusions in diamond. In: Nixon, P.H. (Ed.), Mantle Xenoliths, John Wiley & Sons, Chichester, U.K, 501–522.

Mitchell, R.H., 1995. Kimberlites, Orangeites, and Related Rocks. Plenum Press, New York. P. 410.

Navon, O., Hutcheon, I.D., Rossman, G.R.,Wasserburg, G.J., 1988. Mantle derived fluids in diamond micro inclusions. Nature 335, 784–789.

Rege, S., Griffin, W.L., Pearson, N.J., Araujo, D., Zedgenizov, D., O'Reilly, S.Y., 2010. Trace-element patterns of fibrous and monocrystalline diamonds: Insights into mantle fluids. Lithos, 118, 313-337.

Richardson, S.H., Gurney, J.J., Erlank, A.J., Harris, J.W., 1984. Origin of diamonds in old enriched mantle. Nature 310, 198–202.

Salters, V.J.M., Stracke, A., 2004. Composition of the depleted mantle. Geochem. Geophys. Geosyst. 5. doi:10.1029/2003GC000597.

Schmidberger, S.S., Francis, D., 2001. Constraints on the trace element composition of the Archean mantle root beneath Somerset Island, Arctic Canada. J. Petrol. 42, 1095–1117.

Schmidt, K.H., Bottazzi, P., Vannucci, R., Mengel, K., 1999. Trace element partitioning between phlogopite, clinopyroxene and leucite lamproite melt. Earth Planet. Sci. Lett. 168, 287-299.

Schrauder, M., Koeberl, C., Navon, O., 1996. Trace element analyses of fluid-bearing diamonds from Jwaneng, Botswana. Geochimica et Cosmochimica Acta 60, 4711–4724.

Sheppard, S.M.F., Dawson, J.B., 1975. Hydrogen, carbon and oxygen isotope studies of megacryst and matrix minerals from Lesothan and South African kimberlites. Phys. Chem. Earth 9, 747–764.

Simon, N., Carlson, R.W., Pearson, D.G., Davies, G.R., 2007. The origin and evolution of the Kaapvaal cratonic lithospheric mantle. J. Petrol. 48, 589–625.

Smith, C.B., 1983. Pb, Sr and Nd isotopic evidence for sources of southern African Cretaceous kimberlites. Nature 304, 51–54.

Stachel, T., Harris, J.W., 2008. The origin of cratonic diamonds - Constraints from mineral inclusions. Ore Geology Review 34, 5-32.

Sweeney, R.J., Prozeskyb, V., and Przybylowiczb, W., 1995. Selected trace and minor element partitioning between peridotite minerals and carbonatite melts at 18–46 kb pressure. Geochim. Cosmochim. Acta 59, 3671-3683.

Taylor, W.R., Tompkins, L.A., Haggerty, S.E., 1994. Comparative geochemistry of West African kimberlites: evidence for a micaceous kimberlite end member of sublithospheric origin. Geochim. Cosmochim. Acta 58, 4017–4037.

Tomlinson, E.L., Müller, W., EIMF, 2009. A snapshot of mantle metasomatism: Trace element analysis of coexisting fluid (LA-ICP-MS) and silicate (SIMS) inclusions in fibrous diamonds. Earth and Planetary Science Letters, Volume 279, 362-372.

Weiss, Y., Griffin, W.L., Bell, D.R., Navon, O., 2011. High-Mg carbonatitic melts in diamonds, kimberlites and the sub-continental lithosphere. Earth and Planetary Science Letters, 309, 337-347.

Weiss, Y., Kessel, R., Griffin, W.L., Kiflawi, I., Klein-BenDavid, O., Bell, D.R., Harris, J.W., Navon, O., 2009. A new model for the evolution of diamond-forming fluids: evidence from microinclusion-bearing diamonds from Kankan, Guinea. Lithos 112, 660–674.

Wittig, N., Pearson, D.G., Webb, M., Ottley, C.J., Irvine, G.J., Kopylova, M., Jensen, S.M., Nowell, G.M., 2008. Origin of cratonic lithospheric mantle roots: a geochemical study of peridotites from the North Atlantic craton, West Greenland. Earth Planet. Sci. Lett. 274, 24–33.

Workman R. K. and Hart S. R. (2005) Major and trace element composition of the depleted MORB mantle (DMM). Earth Planet. Sci. Lett. 231, 53–72.

Zedgenizov, D.A., Ragozin, A.L., Shatsky, V.S., Araujo, D., Griffin, W.L., Kagi, H., 2009. Mg and Fe-rich carbonate–silicate high-density fluids in cuboid diamonds from the Internationalnaya kimberlite pipe (Yakutia). Lithos 112, 638-647.

Zedgenizov, D.A., Rege, S., Griffin, W.L., Kagi, H., Shatsky, V.S., 2007. Composition of trapped fluids in cuboid fibrous diamonds from the Udachnaya kimberlite: LAMICPMS analysis. Chemical Geology 240, 151–162.