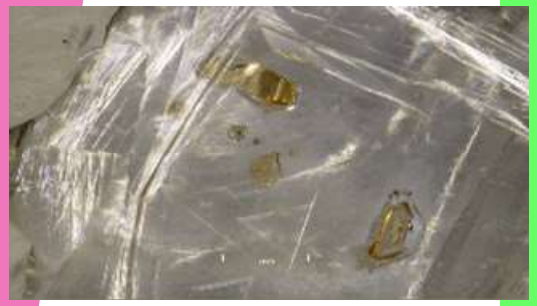
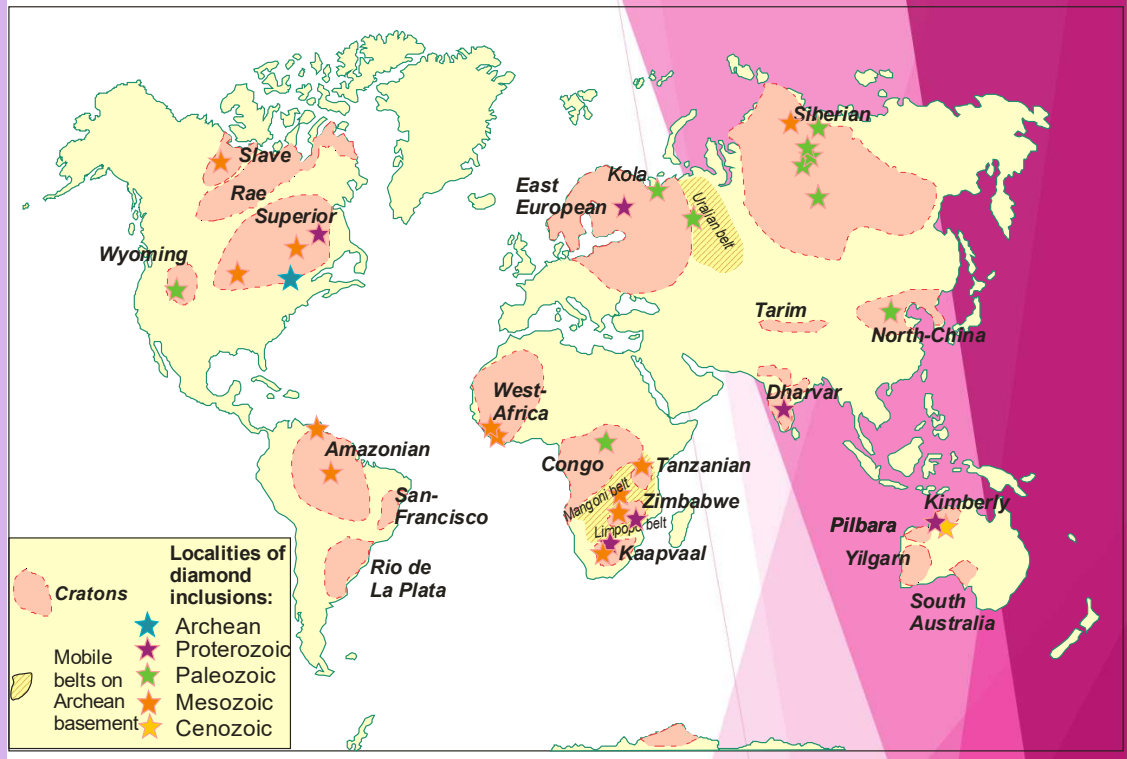


Mantle evolution beneath Siberian and Archean cratons worldwide: evidence from thermobarometry of diamond inclusions

Igor Ashchepkov (1), Alla Logvinova (1), Zdislav Spetsius (2) Hilary Downes (3)

[1]Institute of Geology and Mineralogy SD RAS, Koptyug ave 3, Novosibirsk, Russian Federation
[2]Alrosa Stock Company, Mirny, Russia
[3]Department of Earth and Planetary Sciences, Birkbeck College, University of London, UK

Thermobarometric calculations for diamond inclusions allowed systematically compare the pressure-temperature, fO_2 conditions in the mantle beneath different cratons worldwide. Beneath Siberia, Kaapvaal and other cratons, the cold geotherm branch, reconstructed using sub-Ca garnets and eclogitic diamond inclusions, relates to a major event of continental growth. Colder geotherms (32 mWm^{-2}) are related to early subduction. High temperature plume-related geotherms are common for inclusions in Proterozoic kimberlites beneath Africa. In mobile belts such as Magondi, Ural and Limpopo belts, the amount of pyroxenitic and eclogitic garnets is greater than in the central cores of cratons where dunitic pyropes prevail. Beneath the Khapchan accretionary terrane in Siberia, eclogites are highly diamondiferous. In the mantle beneath Archean cratons, peridotite pyropes differ in CaO content. Depleted peridotitic and Fe-eclogitic diamond inclusions are abundant beneath the Zimbabwe craton, whereas beneath the Congo and West Africa, diamond inclusions yield higher temperatures. Beneath North American cratons, diamond-bearing eclogites are mainly Mg-type. In the Superior craton, Archean diamond inclusions from Wawa are Fe-, Ca-rich pyropes. The diamond inclusions of the Slave and Superior cratons give complex high temperature plume-related geotherms. Beneath the Amazonian craton, peridotite garnets indicate complex layering at the base of the lithosphere and a pyroxene-rich layer in the middle. Fe-Mg eclogites form a high-temperature trend in which FeO increases with decreasing pressure. Diamond inclusions from the Kimberley craton of Australia show the greatest variations in temperature and composition. The Eastern Europe craton and the Urals have greater amounts of eclogitic diamond inclusions and advective geotherms. Estimated pressure conditions lower than diamond stability field is due to exceeding pressures around magmatic system transferred by hydraulic forces from depth.



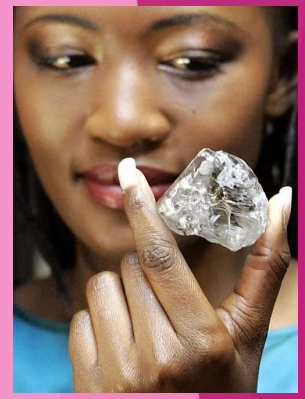
Craton settings of kimberlites with diamond inclusions worldwide

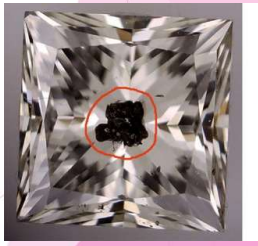
The studied mantle domains with diamond inclusions are represented on the worldwide schemes of Artemieva & Mooney (2001), Bleek,(2003) (Fig.1). This dataset is naturally incomplete but it includes >4500 published analyses collected from published and open sources (Table 1). We will show these data in some cratons, for example in the integrated diagrams, may be quite different for different areas and pipes, depending on the location in separate terranes and mobile belts and on the time of kimberlite magmatism.

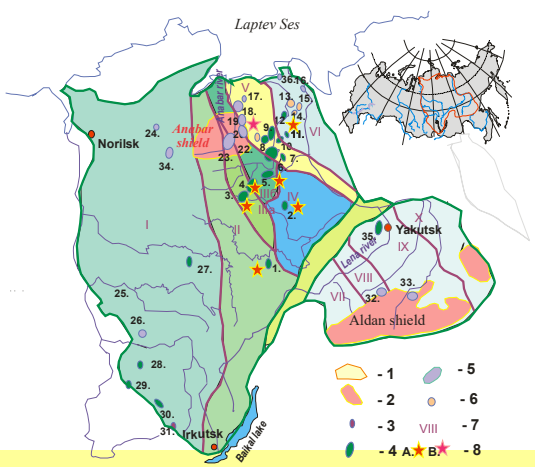
A major problem of interpretation of the location of diamonds in the SCLM is thermobarometry.

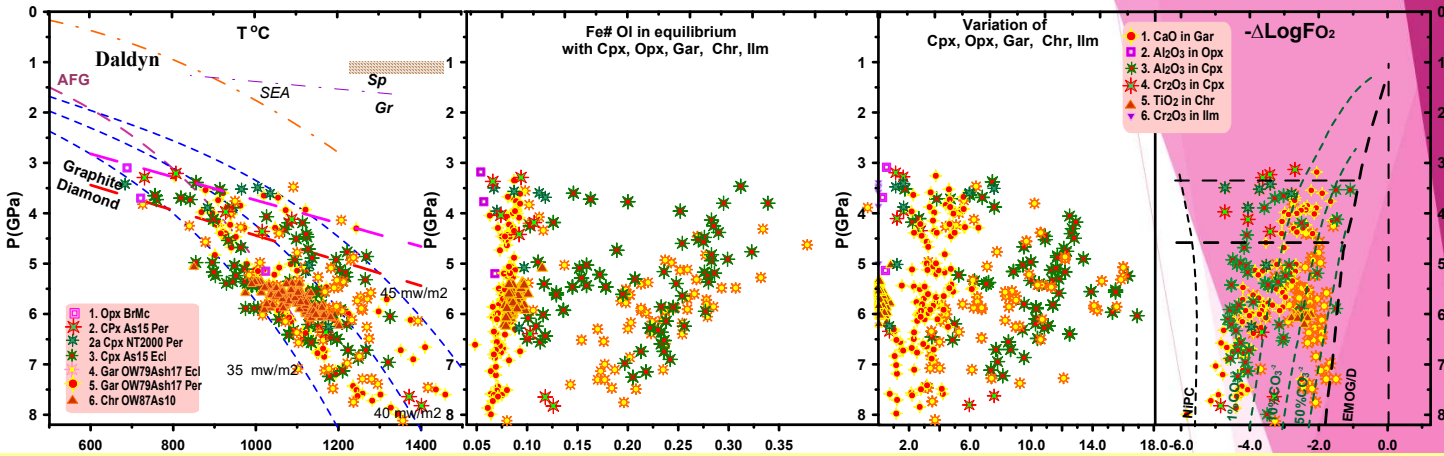
We used the system of the published thermobarometers for the major peridotitic minerals: clinopyroxenes (Cpx), orthopyroxenes (Opx), garnets (Gar), chromites (Chr), ilmenites (Ilm) (Ashchepkov et al., 2010; 2017a). For the Cpx in peridotitic system Jd-Di barometer (Ashchepkov, 2002; Ashchepkov et al., 2011; 2017) is used. The corrected Jd- Cpx barometry is used also for the omphacites in eclogitic system (Ashchepkov et al, 2010; 2017a). The modified Cr- garnet barometer (Ashchepkov, 2006; Ashchepkov et al., 2017a) is used for pyrope garnets. The eclogite garnet barometer gives appropriate results for the Ca-, Na-bearing garnets with FeO varying from 12 to 30 wt.% (Ashchepkov et al., 2017a) with the precision ~0.3-0.4 GPa. The alternative garnet eclogite barometer (Beyer, Frost 2017) based on majorit content is working only for the high pressure >6 GPa assemblages. The precision of the Cpx method for peridotites, calibrated using > 950 associations is very close to that of P.Nimis, W.Taylor (200) method ~0.2 GPa. The clinopyroxene eclogite method (>650 associations used) have precision ~0.3 GPa. And give similar estimates as Gar-CPa barometer (Beyer et al., 2015).For the Cr-spinels and chromites, we calibrated their dependence of Cr# on pressure separately in garnet and spinel mantle facies (Ashchepkov et al., 2010). The barometer is in combination with the spinel-olivine thermometer of Taylor et al. (1998) where the Fe#Ol is calculated from Fe#Ilm and T^{o}C by the empirical equations Although ilmenite inclusions are rare in diamonds, we successfully used the dependence geikelite mineral ($MgTiO_3$) (Ashchepkov et al., 2014) from pressure for barometry in combination with the ilmenite-olivine thermometer of Taylor et al. (1998) where the Fe#Ol is calculated from Fe#Ilm and T^{o}C by the empirical equations. The orthopyroxene barometer of McGregor (1974) in combination with the thermometer of Brey & Kohler (1990) using in iteration scheme it PT program give very similar results with those obtained by the Gar-Opx barometry (Nickel & Green, 1985; Brey & Kohler,1990). All these thermobarometers are combined in the PT program Ter55 written in FORTRAN-70 (Ashchepkov, 2011) and is modified each year.

Al methods were checked by cross-calibration using tens of thousands natural mineral assemblages and are mutually consistent (Ashchepkov et al., 2017a) and this was shown in diagrams and supplementary files using experimental data sets (>2000 together). They are consistent with the barometers checked by C Beyer and colleagues (2018).







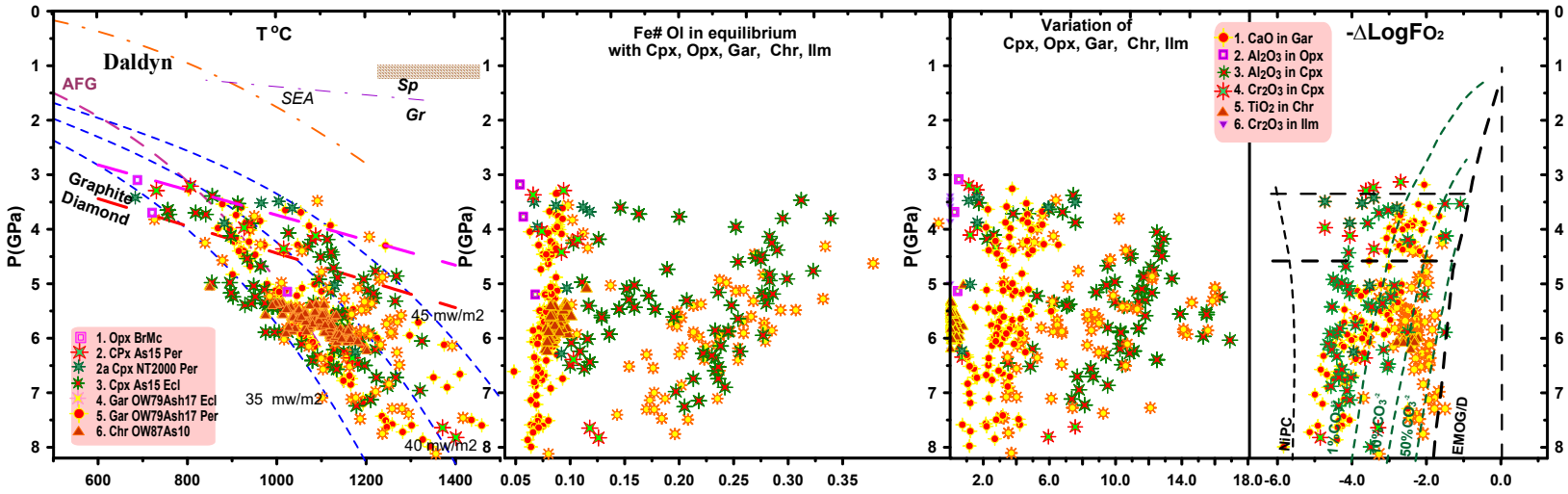


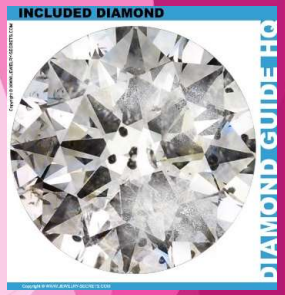
Daldyn field

Pyrope garnets of the Daldyn are mainly from diamonds from Udachnaya pipe and several grains from Dalnyaya and Zarnitsa pipes (Table 1). The PT array for garnet inclusions is clearly divided into two groups near 5 GPa. They formed the joint array of increasing Fe# with decreasing pressures (IFDP), but they differ in CaO. Variations in CaO are quite wide and the most depleted garnets belong to the depth interval >6.5 GPa. There is an increase and splitting of the P- CaO trends with decreasing pressure. Eclogite clinopyroxenes and garnets show two IFDP trends of increase of iron content from Fe#Ol ~ 10-15 to 16-37 wt% with a decrease in pressure from 7.5 to 3.5 GPa. The latter nearly coincides with the garnet IFDP trend. The decrease in Fe in pyroxenes is found at 7-7.5 GPa. The most CaO-rich garnets and Al_2O_3 clinopyroxenes are found at 5-6 GPa. Clinopyroxene differences are less dependent on the estimated depth. (Fig. 3A). The chromite IFDP trend is nearly coinciding with the Cr-pyrope trend in 6.2-5 GPa interval being slightly higher in Fe#.

The trend for the eclogitic garnets splits into two trends in the PT plot (Fig.3A). The low temperature (LT) branch coincides with the LT branch of pyrope garnets. The others form rather scattered plot between the 45 and 35 mWm^{-2} geotherms. The chromites plot on the dense cluster together with the high population of the eclogitic garnets just at the inflection of the convective branch usually traced by the deformed or sheared peridotites (Boyd et al., 1997). Many eclogitic and pyroxenitic varieties plot in the high temperature (HT) field and coincide with the diamond-graphite boundary (Kennedy and Kennedy, 1976; Day et al., 2012).

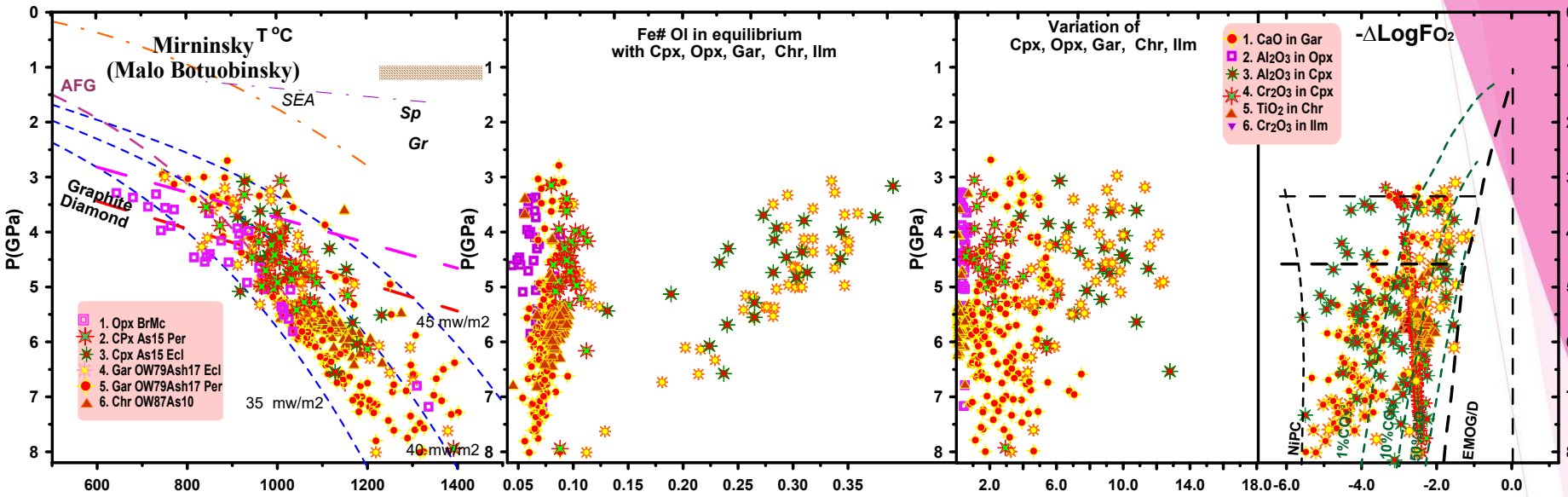
In the P-fO_2 diagram, the eclogitic CPx and Cr-rich garnets form the less oxidized branches ~-5 relative to ΔQMF (Quartz-Magnetite-Fayalite buffer) and this is common trend for Slave craton (McCammon et al., 2004; Fedortchouk et al., 2003) and other cratons Worldwide. At lower pressure they form the inclined trend. The diamond stability boundary for peridotitic (Stagno, Frost, 2010) and eclogitic associations practically coincide (Stagno et al., 2013). . The peridotitic clinopyroxenes, eclogitic garnets and chromites are essentially more oxidized to -1ΔQMF





Alakit field Among the Alakit diamond inclusions (Table 1), sub-calcic dunitic pyropes dominate over eclogitic garnets. The Cr-rich garnets reveal nearly the same trend of IFDP in P- Fe# plot as those from Daldyn but more Cr-rich varieties strongly prevail. Varieties of Cr garnets with 4 and 6 wt% CaO are found at greater lower depth than more depleted varieties. They reveal two separate branches at pressures < 6 GPa. The chromite trend is nearly the same in large diamondiferous pipes and the amount of chromites in DIA everywhere prevail over the garnets. Eclogite pyroxenes and garnets (Table 1) form a similar upward IFDP trend as in Daldyn field but with a steeper increase of iron and the Fe-rich part is mainly composed of garnets. The low-Cr Mg-rich pyroxenes are confined mainly to the average pressure range as well as for enstatites which belong to the 5.0-3.5 GPa interval and mainly form the pyroxenite layer. The proportion of chromites is much higher compared to Daldyn diamonds (Fig. 3B).

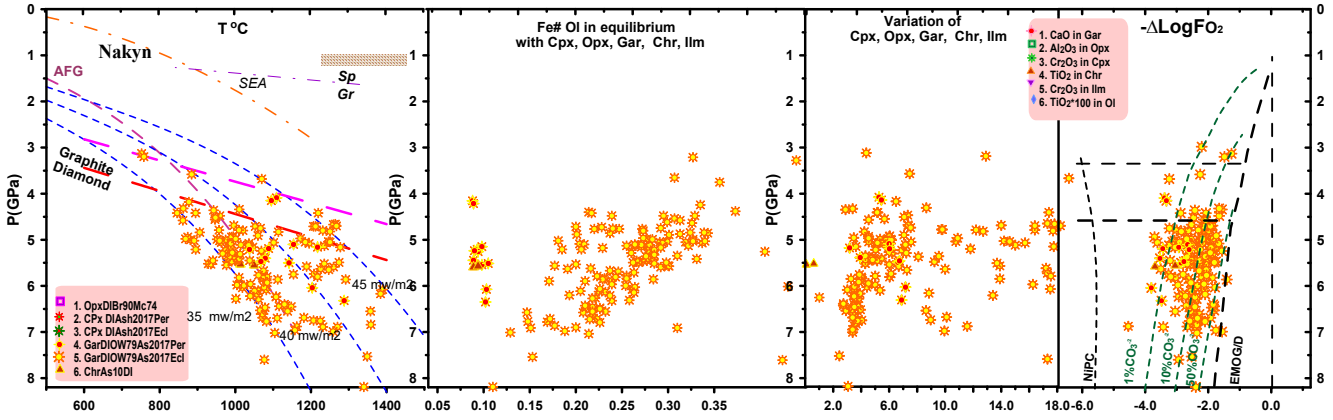
The situation in the PT plot is similar to the Daldyn field but the distinct position of the chromites and high pressure eclogites in the convective branch is clearer. This possibly relates to the influence of the last Devonian plume and protokimberlites on the mantle lithosphere and creation of the new position of the diamond-bearing association. The pyroxenitic association is more HT than the previous clot and this means that they trace the advective branch arising from the lithosphere-asthenosphere boundary (LAB).

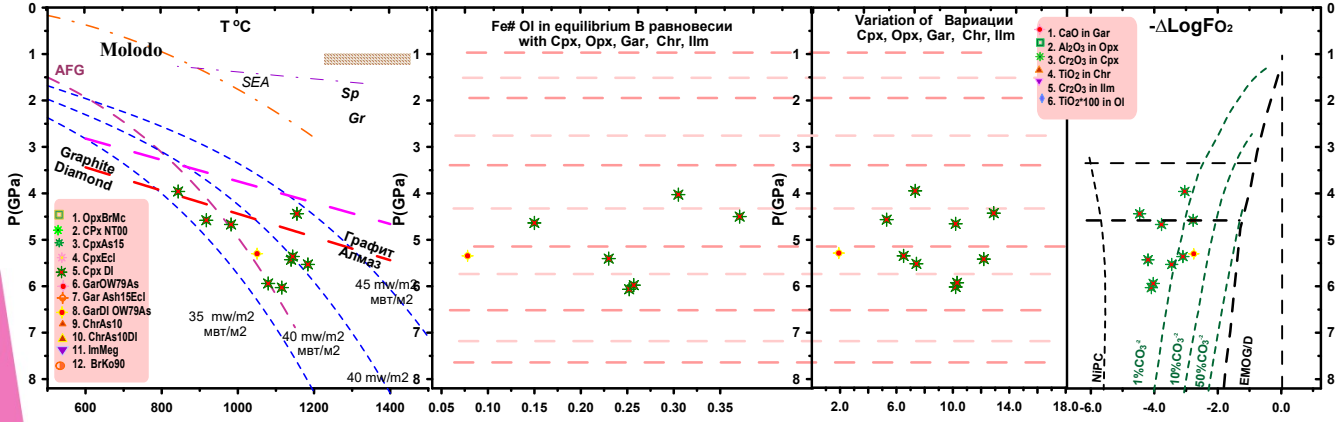


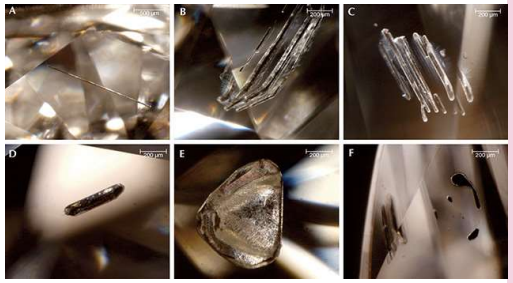
Malo – Botuobinsky field **In the PT plot for the Mirninsky region (Malo-Botuobinsky), the DIA pyropes have an opposite trend, i.e., the largest variations in CaO are in the lower part of the section and the most magnesian dunite varieties form an interval from 6.5 to 5 GPa, and then above them the harzburgitic garnets again appear in the middle of the SCLM. There is a high proportion of peridotite Cr-bearing varieties of ortho-and clinopyroxenes in the middle part of the mantle column, which suggests that the pyroxenites originated from the peridotite partial melts. This more enriched horizon possibly is complementary to the depleted lower SCLM. Omphacites together with garnets form an IFDP in PT P-Fe# plot (Fig. 4A).**

The geothermal conditions traced by diamond inclusions also refer to two branches. Even Cr-garnets partly trace the convective branch is not so evident in the middle part. The Cr gar

nets are found also at more HT conditions at the deeper part of the SCLM. But most of them are plotting within the 35-40 mWm^{-2} geothermal interval. The Cr-pyroxenites and Cr-diopsides form the colder branches – to 35 mWm^{-2} geotherm or even lower. In the P-fO_2 diagram the less oxidized conditions correspond to the eclogitic clinopyroxenes in the middle SCLM. At high pressures the lowest in f_{O2} conditions corresponds to the Cr-rich garnets.

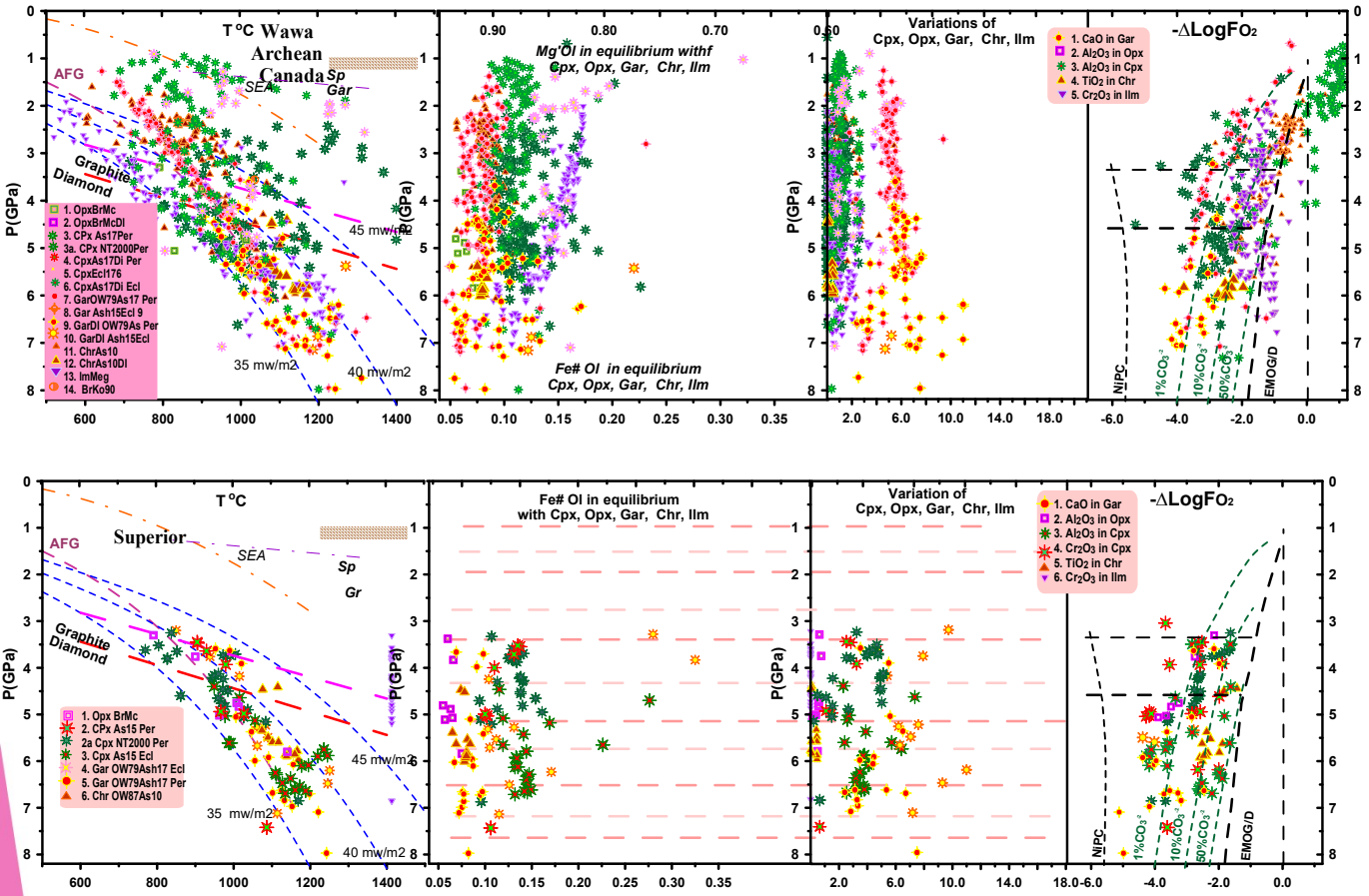






Nakyn field In Nakyn field all pipes are very rich in eclogitic material and Al-rich Cpx prevail in the mantle peridotites and eclogites (Table 1). Cr-pyropes are relatively rare and belong to the lherzolite harzburgite type and the latter is even more rarely found. Among inclusions, almandines dominate, which also form a broad uptrend of P-Fe#. They formed the dispersed IFDP trend. The Fe-poor garnets yield deeper conditions. Two horizons with the Ca-rich associations going to grospidites are found at 6 GPa and in 6-7 GPa intervals. The Fe-enriched varieties are rare and refer to the MSCLM (Fig. 4.B).The geotherm formed by the eclogitic garnet varies from the 33-37 mWm^{-2} (most of garnets) to 45 mWm^{-2}. The separate clots trace the diamond-graphite boundary in various heating degrees. Practically all Cr-garnets show HT temperature conditions, some of them trace the convective branch and the others yield even more heated conditions.

4 Molodo field The diamond placer along the Molodo river also contains mainly inclusions in diamond of eclogite source (SF1, Fig. 1) similar to those from the previous two localities. The plots in P-Fe# and P-Al2O3 are very scattered also. They form the dispersed geotherm from 37 to 45 mWm-2. One Cr- pyrope of dunitic type refer to 5 GPA and 37 mWm-2 geotherm. All of them suggest very cold conditions. All inclusions are reduced to -3-5 relative QMF buffer.



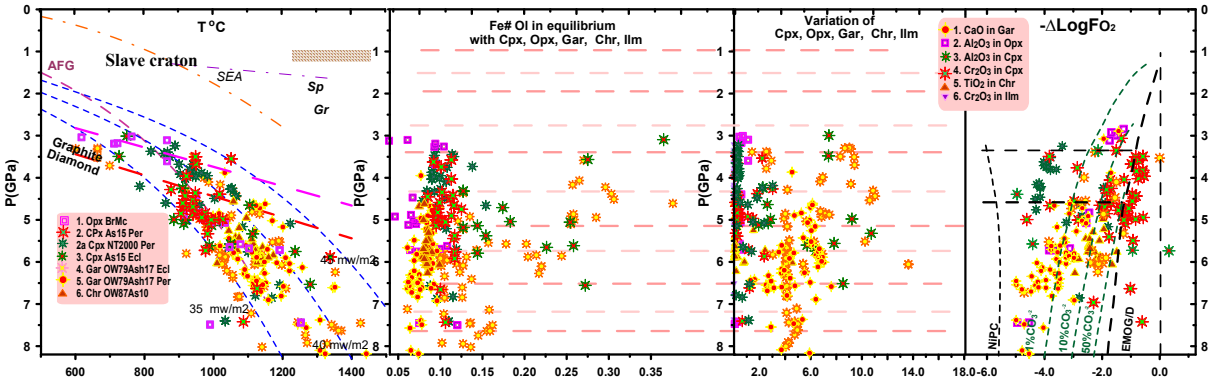
Superior craton, Phanerozoic kimberlites There are significant differences between the Archean diamond inclusions and those found in diamonds from Devonian and Mesozoic and other later kimberlites. Those from Wawa are, on average, even more enriched in Fe and Ca than those in younger kimberlites. Diamond inclusions of peridotitic and eclogitic types in the Jurassic (180–174 Ma) Attawapiskat kimberlites (Aulbach et al., 2018) and Renards kimberlites (Stachel at al., 2006; 2018; Smith et al., 2014; Hunt et al., 2012) yield a semi-advective geotherm. The peridotitic inclusions (orthopyroxene and garnet) in the upper part at 3-5 GPa are more fertile types and give the 40-45 mWm^{-2} geotherm than in the LAB where near 7 GPa they are low temperature (35 -37 mWm^{-2}). They coincide in PT conditions with the Mg-rich eclogites falling on the low-temperature branch while the chromites together with the more Fe-rich pyroxenes marking the inflection to the convective branch (Fig. 5B). The Fe-rich eclogitic garnet and clinopyroxenes refer to the middle part of mantle and HT conditions.

Superior craton, Wawa province, Archean lamprophyres

The Superior craton in Canada contains the most ancient lamprophyre pipes with abundant diamonds and inclusions in the Wawa province. The pipes yield an age of 2.7 Ga (Wyman et al., 2002), which give the possibility to model the structure of Archean mantle at a time of the worldwide peak of crustal growth accompanied by intense percolation of hydrous melts through craton keels (Stachel et al., 2006; De Stefano et al., 2006). We reconstructed the whole mantle section using placer kimberlite indicator minerals (Morris et al., 1998) as well as diamond inclusions.

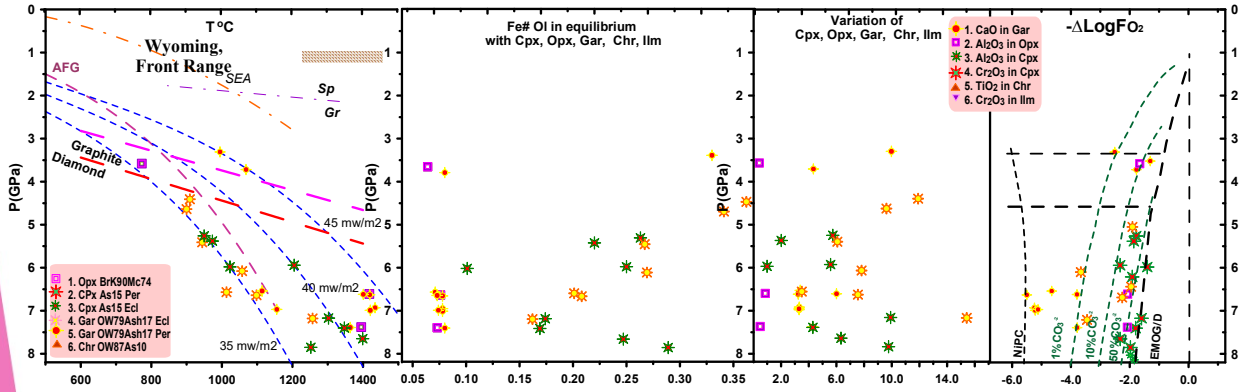
The garnet geotherm is resembles that from the Archangelsk mantle (Afanasiev et al., 2013) and is close to semi-advective type with low temperature conditions near the LAB and a higher temperature part near the Moho (Ashchepkov et al., 2019). The pyrope garnets just follow this geotherm and only the Ca-, Fe-rich pyroxenitic group deviates to the high-T conditions. There is some increase in temperature near the LAB. In the P-CaO diagram there is a split to high-Ca and low-Ca branches. There are at least 4 low-Ca, low-Fe fluctuations in P-CaO -Fe# diagrams for garnets followed by the Opx (Fig. 5A).

The clinopyroxenes are low-Al and low-Cr group typical of the depleted cratonic mantle keel. A few follow the ilmenite trend. The Fe-rich pyroxenitic garnets are found in shallow < 2 GPa in the upper SCLM. Ilmenites form the long fractionation trend with continuous increase of Cr_2O_3 to lower pressures (Ashchepkov et al, 2014b). There are now serious differences between the Archean diamond inclusions and those found in Devonian and Mesozoic and other later kimberlites. Though those from Wawa are, on average, even more enriched in Fe and Ca than those in younger kimberlites. The clinopyroxenes are low-Al and low-Cr group typical of the depleted cratonic mantle keel. A few follow the ilmenite trend. The Fe-rich pyroxenitic garnets are found in shallow < 2 GPa in the upper SCLM. Ilmenites form the long fractionation trend with continuous increase of Cr_2O_3 to lower pressures (Ashchepkov et al, 2014b).



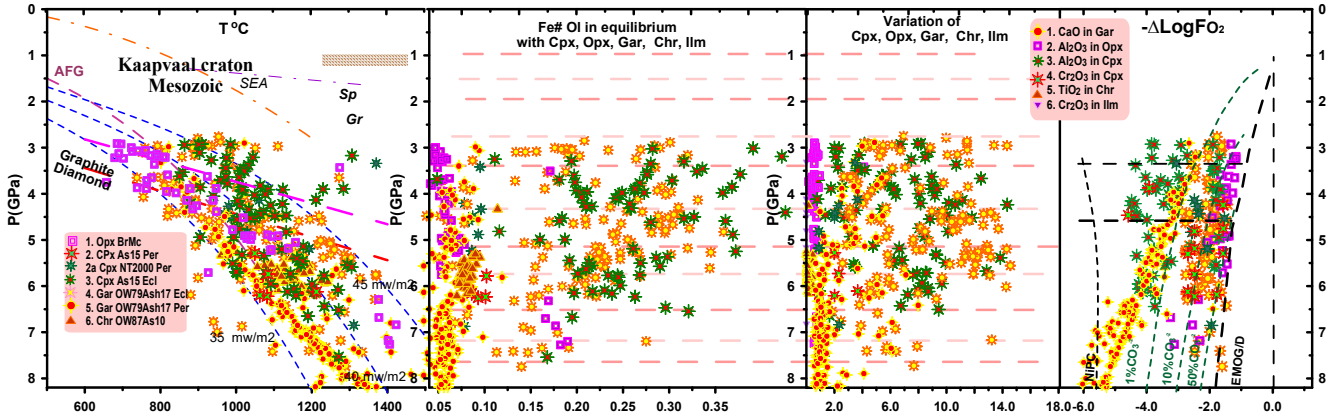
Wyoming craton

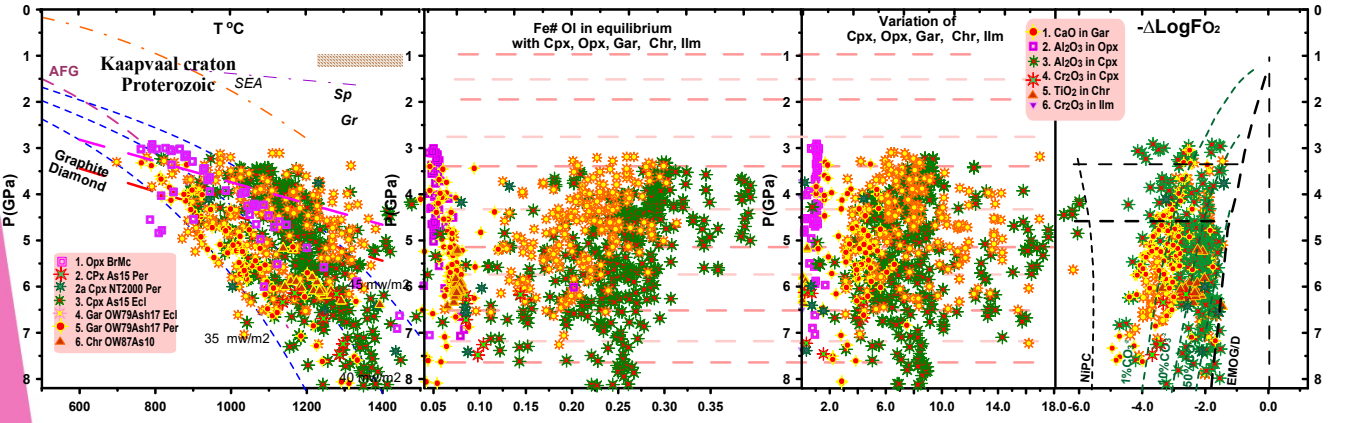
Late Devonian kimberlites in Wyoming craton (Ashchepkov et al., 2013b) have different type of diamond inclusions In the Sloan pipe (Otter & Gurney, 1986) the peridotitic inclusions prevail while the Kelsey Lake (Schulze et al., 2008) pipe contains more eclogitic garnets and CPx. Altogether the PT estimates compile the low-T geotherm at 35 mWm^{-2} from 3 to 6 GPa but in the lower part the from 6 to 8 GPa the mantle keel was extremely heated up to 1450°C and the peridotite Cr- pyropes gives the highest temperatures (Fig.6B). They are rather Mg rich, on average having Fe#Ol 0.07-008. The eclogitic inclusions as common create the IFDP trend with variations of Fe# from 0.15 to 0.37 and pressures from 8 to 3.5 GPa.



Slave craton

 # Peridotite inclusions are particularly abundant in diamonds from the Slave craton and mainly come from the Lac de Gras cluster (Table 1). Calculations made for inclusion from the, Panda pipe Diavik, Jericho and Lac de Gras field together, with a predominance of peridotite diamond inclusions and addition Snap Lake, show rather wide geothermal conditions from the LAB to the graphite-diamond boundary. Many relatively enriched types of pyropes fall on the high-temperature geotherm. In the middle SCLM, they are related to the advective branch. There is impression that there are several arrays of the convective geotherm which compile together the scattered plot in the middle part. The cold branch is mainly composed of the eclogitic garnets at the deeper part and Cr-pyroxenites in the middle and the upper most part of cold branch is marked by the eclogitic Cpx. Cpx from diamond-bearing Mg-type eclogites are located at the 4.5 6 GPa interval and garnets of this type are found to 8 GPa. The AFDP trend compiled together by the Gar and Cpx points is rather steep and starts from 6 GPa, with Fe#Cpx ~0.2 and rises to 3 GPa where Fe#Cpx = 0.3-0.35 (Fig. 6A).





Africa Kaapvaal craton

Data on the inclusions in diamonds the kimberlites from Africa are the most abundant and the Kaapvaal craton with their numerous kimberlite pipes is the most studied (Table 1). The kimberlites are of various ages starting from the Proterozoic like Roberts Victor and Premier, to the Mesozoic Letlhakane, Finsch, Jagersfontain, Koffiefontain, Bultfontain, Letseng, Bellsbank, DeBeers Pool, Orapa, Monastery (SF1, Fig. 3-16) and other pipes of similar compositions of the diamond inclusions formed during the Mesozoic episodes of activity, which trace the tails of the major plume events.

Mesozoic kimberlites from Kaapvaal craton

We made the combined diagram including the diamond inclusions from the listed Mesozoic pipes to make the diagram for the Mesozoic stage (Fig.7A). The garnet trend there is represented by the dunitic pyropes only, which create the low-T geotherm slightly heated to the lithosphere base. The Opx estimates form several fields there. The HT branch made by the Fe- enriched (Fe#~0.2) inclusions together with several points of the pyropes garnets at 6 -7 GPa related to the plume heating. The several points together with the very low-T eclogitic garnets marking 30-33 mWm^{-2} geotherm. There are three steps of the gentle heated geotherms strengthening along the line of the diamond- graphite boundaries. The eclogitic garnets compiles also several branches – One practically repeats the cold geotherm made up by the pyrope garnets the others repeats the OPX stepped geotherms but in a wider range. The omphacites from the eclogites practically repeats the positions of the eclogitic garnets. The chromites similar to Siberian inclusions mainly compiles the heated branch at 6 GPa. Cpx from the Cr-pyroxenites follow this estimate.

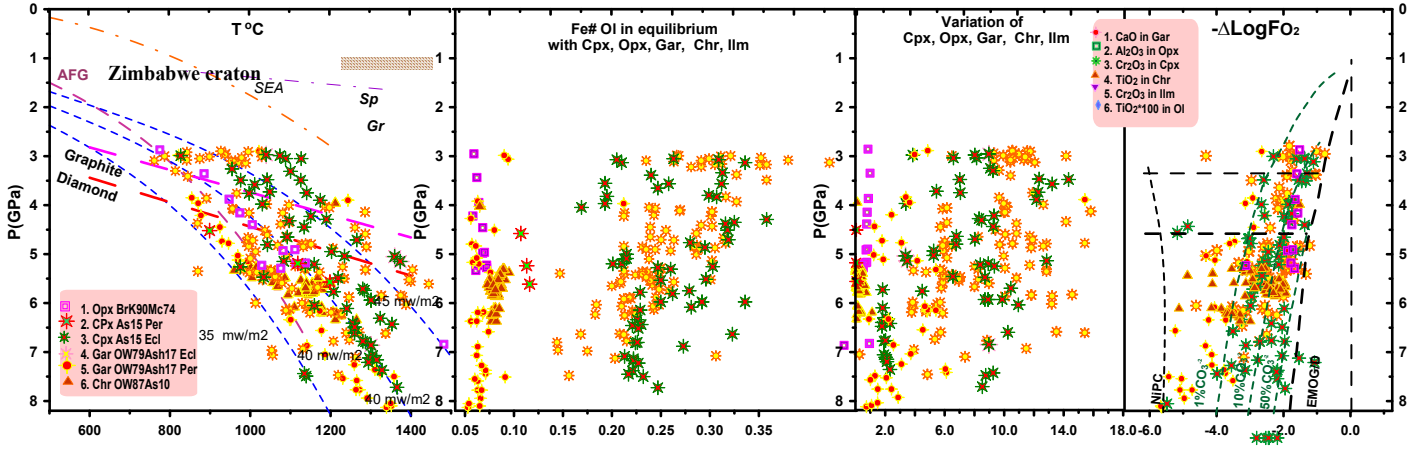
The eclogitic garnets and Cpx formed in the P-Fe# diagrams make up several branches of the IFDP trends on the diagram with the different inclinations joining at the 4.5 and 6 GPa levels possibly they are reflecting the melting and fractionation or interaction of the partial eclogite melts at several levels in the SCLM.

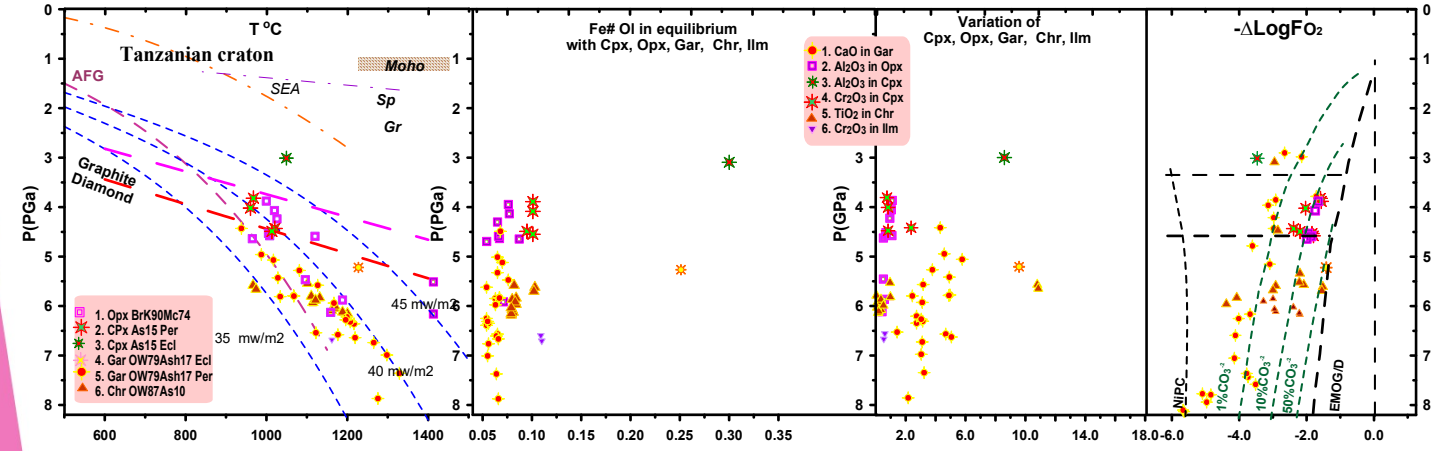
The low-Fe# peridotitic area of this diagram shows several clots referring to the mantle layering. There is the Fe-rich clot for the chromites possibly caused by the protokimberlite melts heating. In the P-fO_2 diagrams there are two major trends. Those very low in f_{O2} are related to the ascending high-Mg trend which made the majority of the ancient pyrope sub-Ca garnets. The second event traces the diamond stability field starting from ~ -2 ΔQMF.

The special compositions of the DIA in the Voorspoed pipe (Viljoen et al., 2018) (supplementary file1) which are close to the megacrystic suite (SF1Fig.1). The trend starts with low-Cr megacrystic Garnets Cpx and Opx. The joint cotectic crystallization pass of Cpx and Gar is tracing to the 45 mWm^{-2} geotherm from 6.5 to 2.8 GP. The Opx-Cpx clot deviates to the lower T conditions possibly refer to the intermediate magmatic source with the joint crystallization of two pyroxenes. The eclogitic garnets and clinopyroxenes are more Fe-rich and yield colder conditions in general.

- *Proterozoic kimberlites Kaapvaal craton* We used the analyses of the diamond inclusions from two most studied pre-Mesozoic pipes – Premier and Roberts Victor pipe . The first pipe is famous for extremely large diamonds and the second one for the abundance of the various eclogites dominated also among the diamond inclusions. The PT diagram for this stage is represents the hottest material from all studied groups (Fig. 7B). The peridotitic garnets are represented by the relatively fertile harzburgite-lherzolite and even pyroxenitic varieties. The latter refer to ~ 40 mWm^{-2} close and below 7 GPa and at the common for the Cr-spinels level near 6 GPa and 1200-1350°C. Garnets of the harzburgitic type gives the colder parts of PT array showing the layered structure of the mantle keel by the 7-8 low T° fluctuations from 3 to 6.5 GPa. The Opx from this stage reveals the HT conditions tracing 45 mWm^{-2} geotherm from 7 to 3 GPa going to 40 mWm^{-2} geotherm at the top/ the relic very low T geotherm ~ 32 mWm^{-2} which also is traced by the eclogitic garnets and Cpx. The garnets from eclogites are pyrope almandine type and give the low- mean temperature conditions at the lithospheric part of mantle giving the estimates practically coinciding with those for the pyrope garnets. They also create the exclusively HT part of the PT plots to 50 mWm^{-2} from 3 to 6 GPa together with the HT eclogitic Cpx. The latter form the advective branch from 1450°C and 8 GPa to 3 GPa to 1250°C. The other omphacites trace the PT estimates of the pyrope garnets within the lithospheric part of mantle column. In the P-Fe# plot the peridotitic minerals form the nearly coinciding trend with the gradual rise of the Fe# from 0.05 at 3GPa to 0.11 at 7GPa with the deviations to Mg part for the OPx. The eclogitic CPx are in general more Fe-rich than eclogitic garnets. They are forming the High Fe group (Fe# to 0.4) from 3 to 5 GPa. The deepest Cpx plot to 0.25 – 8—8.5 GPa. The Al-Ca rich eclogitic minerals are found in al pressure interval but they create the clot ~ 5 GPa. The P-fO_2 plot is characterized by the nearly continuous variations of the FO_2 in all pressure interval. The deepest part is characterized by the more oxidized condition near and lower than EMOG buffer. The more reduced conditions give the pyrope garnets with the staring of the array from -5 ΔQMF, which corresponds to the 15 CO_3^{-2} according to Stagno et al. (2013).

- We used the analyses of the diamond inclusions from two most studied pre-Mesozoic pipes – Premier (Tsai et al., 1979; Denies et al., 1984; Viljoen et al., 1992; Dludla et al., 2006; Korolev et al., 2018) and Roberts Victor pipe (Deines et al., 1987; Jacob & Jagoutz, 1994; Viljoen et al., 1991; Korolev et al., 2018). The first pipe is famous for extremely large diamonds and the second one for the abundance of the various eclogites dominated also among the diamond inclusions. The PT diagram for this stage is represents the hottest material from all studied groups (Fig. 7B). The peridotitic garnets are represented by the relatively fertile harzburgite-lherzolite and even pyroxenitic varieties. The later refer to ~ 40 mWm^{-2} close and below 7 GPa and at the common for the Cr- spinels level near 6 GPa and 1200-1350°C. Garnets of the harzburgitic type gives the colder parts of PT array showing the layered structure of the mantle keel by the 7-8 low Ca deviations in P-CaO plot from 3 to 6.5 GPa. The Opx from this stage reveals the HT conditions tracing 45 mWm^{-2} geotherm from 7 to 3 GPa going to 40 mWm^{-2} geotherm at the top/ the relic very low T geotherm ~ 32 mWm^{-2} which also is traced by the eclogitic garnets and Cpx. The garnets from eclogites referring to pyrope almandine type give the low- mean temperature conditions at the lithospheric part of mantle giving the estimates practically coinciding with those for the pyrope garnets. They also create the exclusively HT part of the PT plots to 50 mWm^{-2} from 3 to 6 GPa together with the HT eclogitic Cpx. The latera are forming the advective branch from 1450°C, 8 GPa to 3 GPa to 1250°C. The other part of ompacites are tracing the PT estimates of the pyrope garnets within the lithospheric part of mantle column. In the P-Fe# plot the peridotitic minerals are forming the nearly coinciding trend with the gradual rise of the Fe# from 0.05 at 3GPa to 0.11 at 7GPa with the deviations to Mg part for the OPx. The eclogitic CPx are in general more Fe-rich than eclogitic garnets. They are forming the High Fe group (Fe# to 0.4) from 3 to 5 GPa. The deepest Cpx plot to 0.25 – 8—8.5 GPa. The Al-Ca rich eclogitic minerals are found in al pressure interval but they create the clot ~ 5 GPa. The P-fO_2 plot is characterized by the nearly continuous variations of the FO_2 in all pressure interval. The deepest part is characterized by the more oxidized condition near and lower than EMOG buffer. The more reduced conditions give the pyrope garnets with the staring of the array from -5 ΔQMF, which corresponds to the 15% CO_3 according to Stagno et al. (2013).





Zimbabwe craton

There are two main clusters of diamondiferous kimberlites Karowe (Motsamai et al., 2018) and Murowa (Smith et al., 20 Klein-Ben David et al., 2009) pipes. The first contains mostly eclogitic inclusions while in the second peridotitic diamond inclusions prevail.

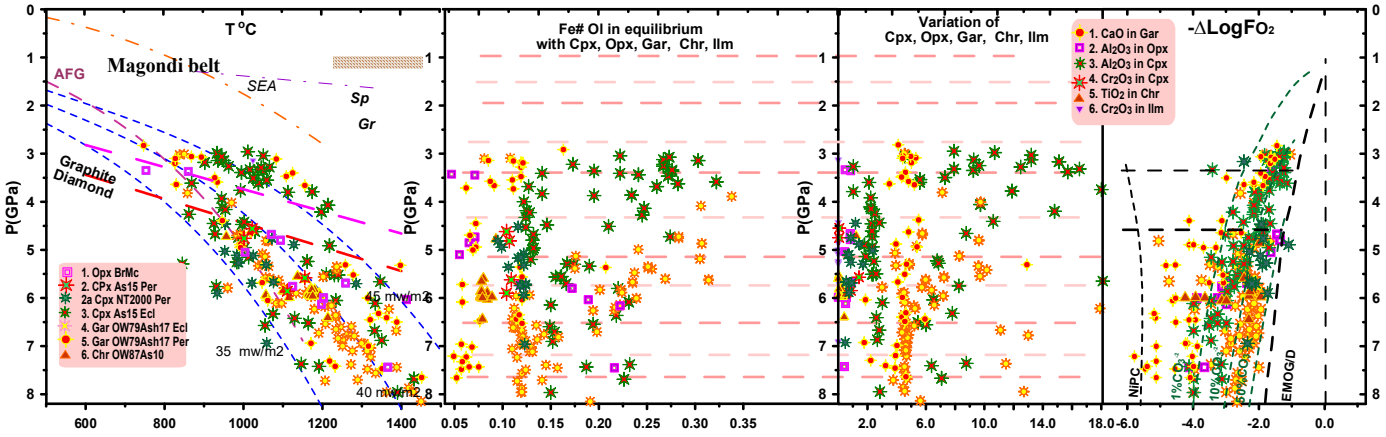
The ultra-depleted peridotitic DIA (Smith et al., 2009; Richardson et al., 2009; Kopylova et al., 1997) give the low-T branch 37 mWm^{-2} from 3 GPa to the LAB and then to 8 GPa is traced mainly by the pyropes of sub-Ca type, higher temperature branch 40 mWm^{-2} is marked by Opx from 5.5 to 3 GPa. The Sp commonly plot at the inflection from 35 mWm^{-2}at 5 GPa to 40 mWm^{-2} at 6.5 GPa. Eclogitic Cpx are mainly located along the 40 mWm^{-2} geotherm and in the upper part they go to the 45-50 mWm^{-2} geotherm. The garnets are in general lower temperature and form a LT cluster near 5 GPa and shallower level are located near the omphacitic PT estimates (Fig. 8A).

In general peridotitic mineral have low Fe# 0.05-0.07 but Cr-spinels and some Cpx are more Fe-rich to Fe#=0.12. Eclogitic minerals are mostly Fe-rich with the Fe# of 0.15-0.2 near the lithosphere base and show a rapid increase up from 6.5 to 3 GPa reaching Fe#~0.36.

Pyropes are extremely depleted in CaO near the LAB and sporadically tend to lherzolite in shallower level.

Tanzanian craton

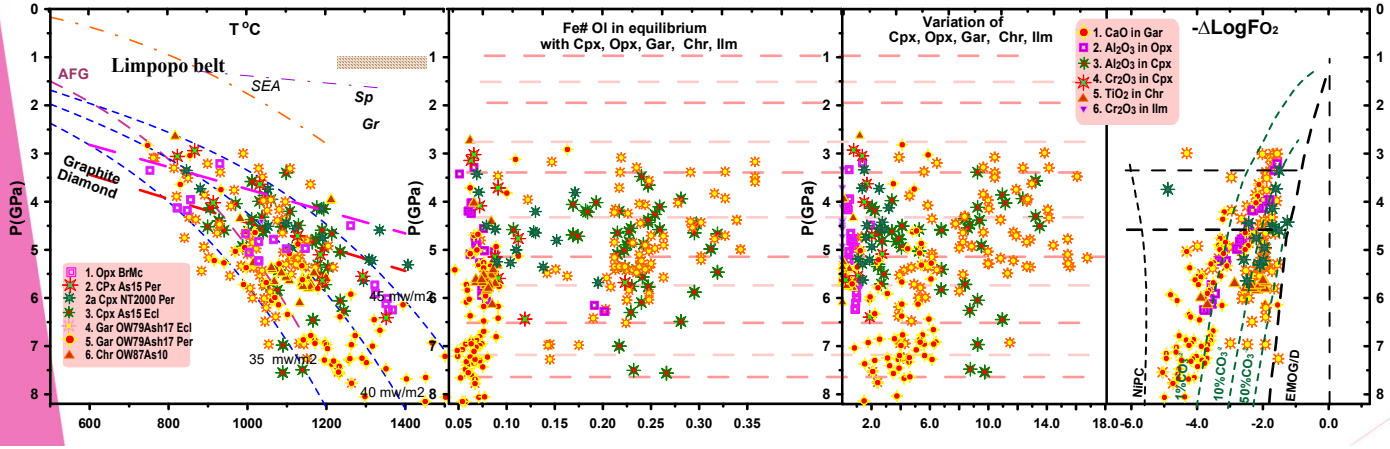
Diamond inclusions of the Tanzanian craton (Stachel et al., 2004) are mainly of peridotitic type. The PT points of the pyrope garnets are located along the 35-40 mWm^{-2} geotherm from the lithosphere base to 4 GPa. The Opx, Sp and Cpx plot in the upper part (5-3 GPa) and are a bit more high temperature 38-42 mWm^{-2} . The Cpx and Sp are slightly more Fe-rich than depleted garnets (Fig. 8B). A few eclogitic diamond inclusions are more high temperature and have Fe# ~0.25-0.30.



Magondi belt

The diagram for the Limpopo belt is compiled by the diamond inclusions from the Orapa, Venetia and Jwaneng pipes (Table 1). Pyropes form 4 clusters which represent quite different thermal conditions of 35 and 43-50 mWm^{-2}. Opx scatter between 38-42 mWm^{-2} with a few deviations to HT conditions. Cpx of low Fe type are forming relatively low temperature cluster from 4.5 to 6 GPa.

Eclogitic garnets mainly form the broad dense field from 36-43 mWm^{-2} starting from 8 to 3 GPa. Eclogitic Cpx are even more scattered and higher temperature (to 1200°C) in shallow level (Fig. 9A). But they also formed extremely low temperature geotherm 33-35 mWm^{-2} from 5 to 7.5 GPa.

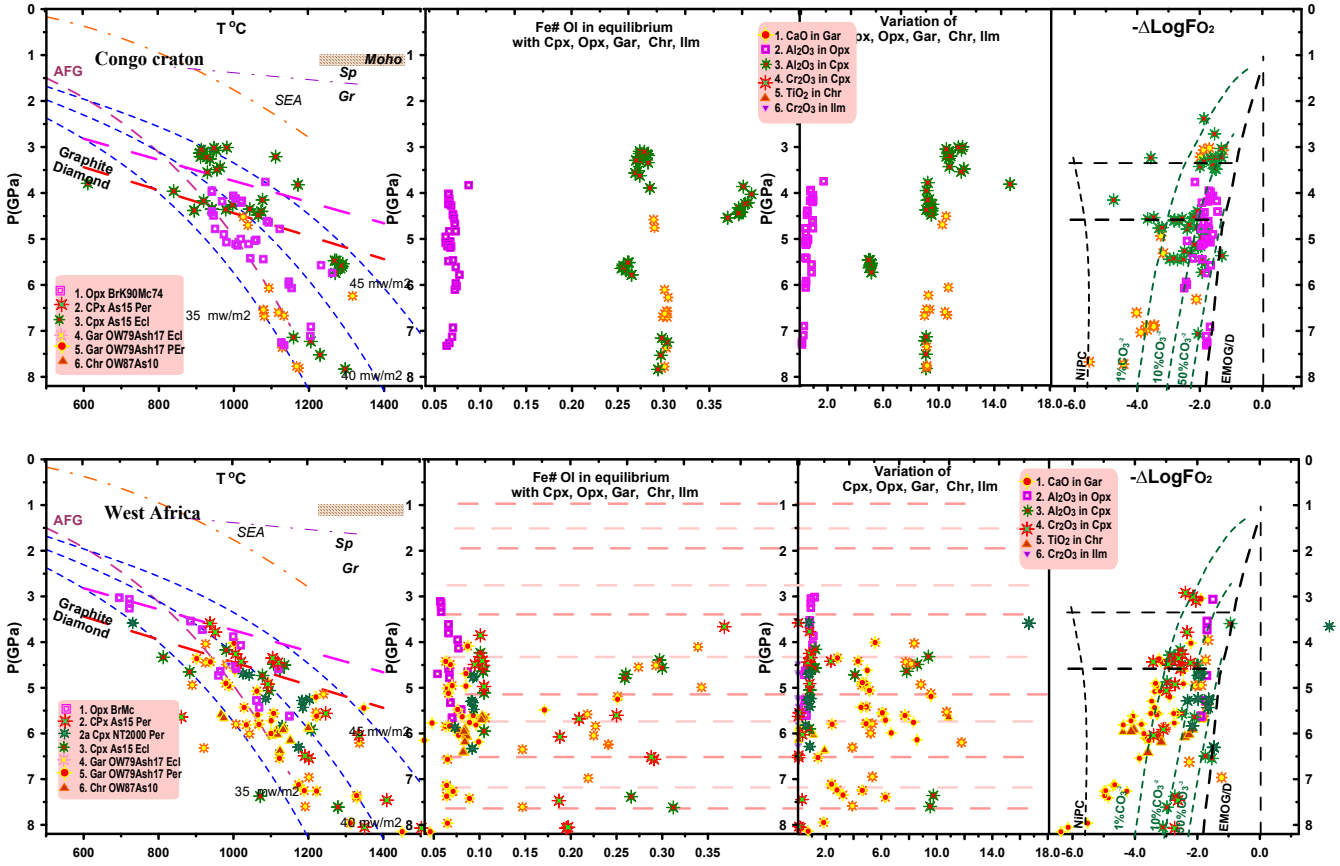


The Fe# of the peridotite garnets are different; some pyropes have Fe# 0.15 increasing in the upper level and even higher for Cpx and Opx, The eclogitic garnets show definite trend of increasing Fe with decreasing pressure. For the Cpx this tendency also exists but they show more scatter.

Limpopo belt The diagram for the Limpopo belt is compiled by the diamond inclusions from the Cambrian Venetia and Jwaneng pipes (Table 1). The diamond inclusions PT estimates also reveal the heated conditions in general and very wide variations of the geothermal conditions. The pyrope garnets give the cold inclined geotherm. Splitting to convective branch at 7 GPa which is common for the other localities. They also reveal the clots for the lherzolitic- pyroxenitic garnets plotting on the 50 mWm^{-2} geotherm at 6.5 GP and at 40 mWm^{-2} with two clusters 6.-5.5 and 7-8 GPa. The Opx conditions and compositions are quite variable. The most Fe-rich Opx are found in PT plot near the 45 mWm^{-2} geotherm.at the pressures starting from 6.5 GPa. Some of the trace the graphite- diamond boundary but there are also clots at 35 mWm^{-2} geotherm at4 GPa. The eclogitic Cpx and garnets reveal the scattering between the 50 -35 mWm^{-2}. The relic cold geotherm to 33 mWm^{-2} and even lower also exist (Fig. 7B).

The variations for the eclogitic Gar-Cpx at the P-Fe# in general are similar to the other fields with the genera ascending AFDP trend and highest Fe# at 3 GPa but there are all Fe variations among the peridotitic and eclogitic compositions(Fig. 9B).

Oxidation state of the garnets show very low values for the pyropes (-5.5ΔLogQMF) from deeper part and much less for the eclogitic garnets (to -2ΔLogQMF)



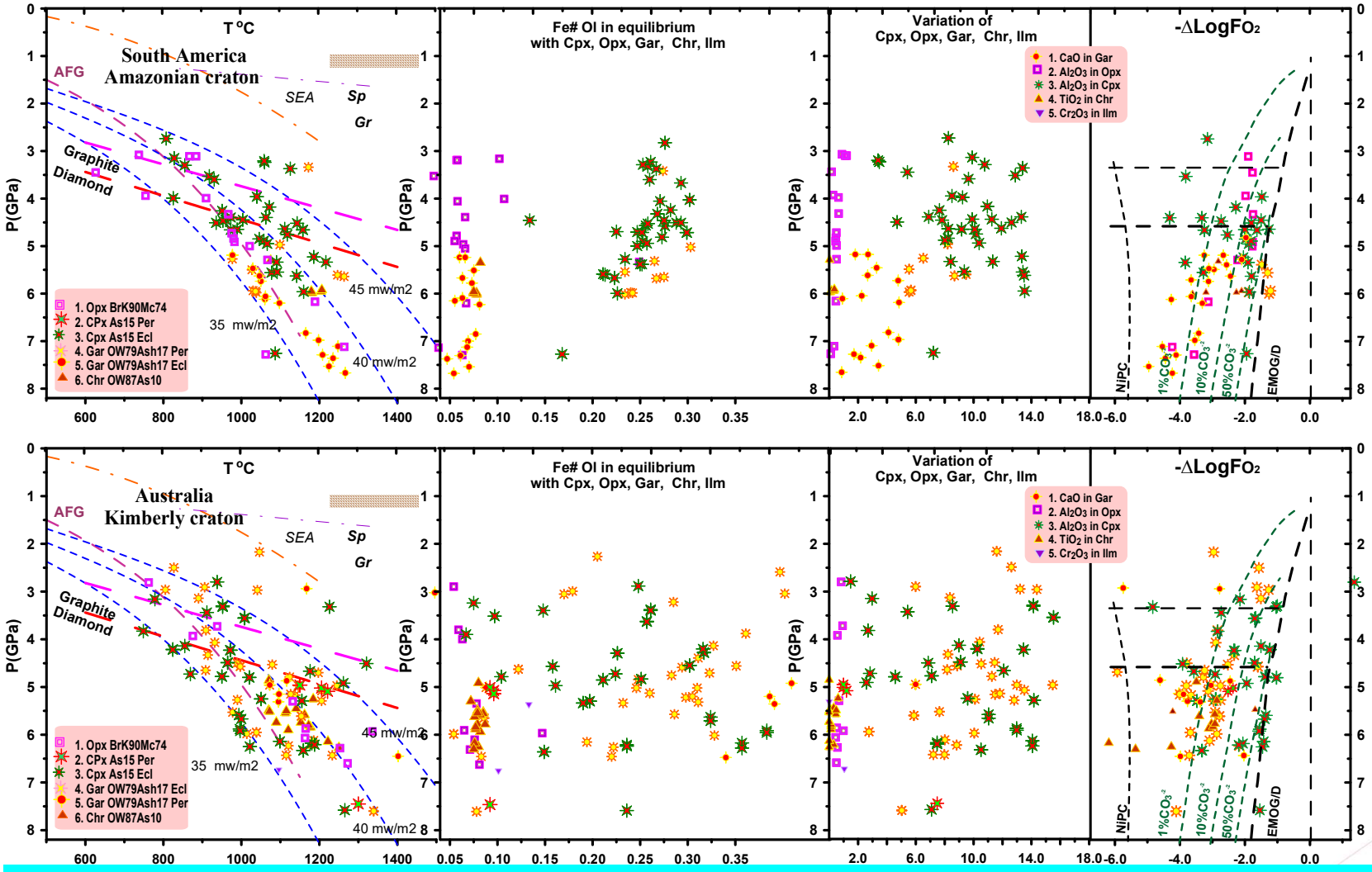
Congo craton

For the Congo craton, diamond-bearing eclogites were suggested in Catoca pipe (Nikitina et al., 2014). However, the largest data set for the diamond inclusions was published for the alluvial deposits of the Kasai River, NE Angola (Kosman et al., 2016).

The PT estimates for the Opx and other minerals in general repeat the diagram for the Limpopo belt showing the GPa 1370ºC. The HT branch from conditions are found in the lithosphere base. It was traced also by the pyroxenitic and eclogitic CPx and garnets. Opx show division to 4 discrete pressure intervals. The eclogitic Cpx are divided in to several discrete groups. The Fe-rich cpx reveal the irregularly heated conditions at 4-4.5 GPa. The eclogitic Cpx with garnets the Fe#~0.3 together forms the sub-vertical trend. The Cpx and Ga (Fe#~0.20-0.25) form another cluster in the upper LAB 6-5 GPa (Fig. 10A).

West Africa craton

In west Africa some pipes like Koidu (Aulbach et al., 2019) while in Akwatia (Smit et al., 2016) peridotitic diamond inclusions occur more often. The peridotite pyropes are divided by CaO into three groups (figure 12B). The Opx inclusions and pyropes pyroxenes belong to the advective geotherm which is close to cold 36 mWm^{-2} branch, and at 3 GPa to the heated to 48 mWm^{-2} (Fig. 10B) with high scatter near the diamond stability boundaries. Eclogitic Gar and Cpx also repeat this distribution. The Fe# of Opx varies from 0.06 at the LAB to 0.1 at 3.5 GPa. The eclogitic minerals show two clusters with close values Fe# from ~ 0.3 and the next ~0.4. The oxygen conditions vary from - 4 to -1.7, being higher near the diamond stability boundary (Stagno et al., 2013; 2015).



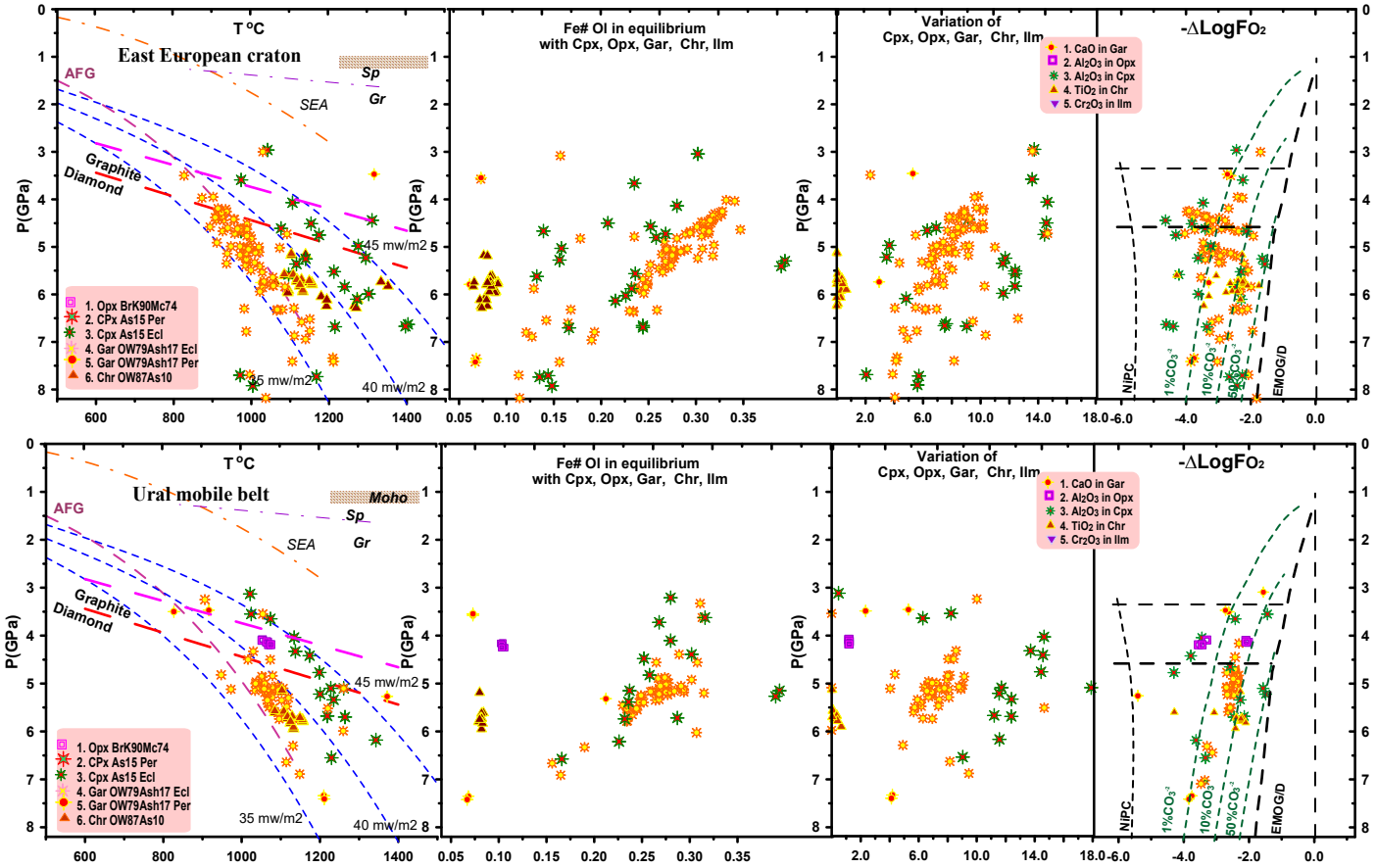
South America

Amazonian craton

Data for the Amazon craton of South America are limited (Table 1). The peridotite part is orthopyroxene and garnet, medium-low temperature (35-40 mWm^{-2}). They have variations of Fe#~0.05-0.10 showing higher value for Opx from upper level. Garnets are reveal variations from dunitic to pyroxenitic values. Eclogitic form a fairly high-temperature trend and, as usual, a joint trend of increasing iron content (0.16-0.32) with decreasing pressure from 7.2 to 2.8 GPa. The Cpx are mainly of the high –Al type (Fig. 11A).

. Australia Kimberly craton

Eclogite inclusions of the Kimberley craton, Australia (Table 1) vary widely in temperature regime and composition (Fig. 12B). The Cr-Mg peridotitic inclusions are moderately Fe-enriched but extremely Al-depleted and give a relatively HT geotherm tracing the advective branch from 7 to 4.5 GPa crossing the 40 mWm^{-2} 2 geotherm. The eclogites are in general lower in temperatures and scatter from 35 to 40 mWm^{-2} geotherm though the exclusively HT varieties also occur. They also scatter in the P-Fe# plot (Fig. 11B).



East European craton

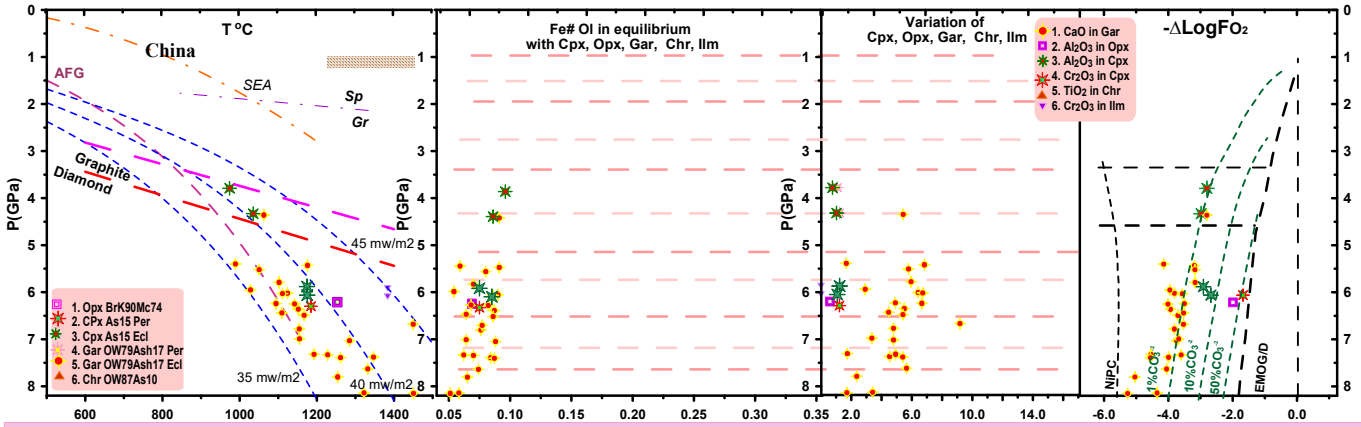
For the Eastern European craton kimberlites are found in the Baltic Shield (Peltonen et al., 2002) and the Arkhangelsk province (Sobolev et al., 1997). Eclogitic garnet inclusions are located along the 36 mWm^{-2} geotherm while the omphacites plot between 40 and 45 mWm^{-2} peridotitic chromites are located near 6 GPa at 3.8 mWm^{-2}. The eclogitic Gar and Cpx DIA together form the IFDP trend. It is less steep for garnets and more scattered and more HT for the Cpx (Fig. 13A).

The eclogitic Gar and Cpx DIA together are forming the AFDP trend. It is less steep for garnets and more scattered and more HT for the Cpx (Fig. 12A).

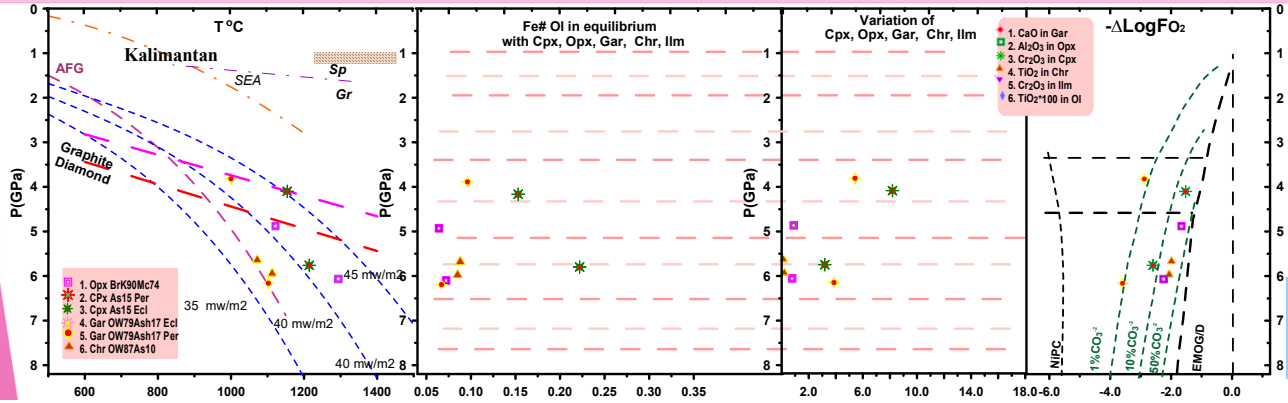
Urals

In Polar Urals (Laiginhas, 2008; 2009; Sobolev et al.,2019), a few peridotite DIA were found. Eclogite omphacites are higher-temperature than garnets. The compositions of the prevailing eclogitic and Cpx gives together the relatively HT conditions but garnets are determined the lower T scattered geotherm below 40 mWm^{-2}. The Cpx give the advective geotherm from the lithosphere base to 3 GPa.

The Cr-Mg trend is relatively scarce and represented by the lherzolite-harzburgite garnets chromites (5-6 GPa) and Opx at 4 GPa (Fig. 12B).



Sino –Korean (North China) craton. In North China craton the only known DIA are from Shengli1, N 50 pipes are mainly Cr- pyrope garnets (Wang et al., 2000). They vary from dunitic and harzburgitic to lherzolitic varieties. In the PT plot they give ~37 mWm^{-2} geotherm with the more heated to 40 mWm^{-2} below 7 GPa, though this geotherm is sporadically traced to 4 GPa (Fig. 13). Only one sample is heated to 45 mWm^{-2}. The clinopyroxenes plot in the deepest part of the mantle column and Opx at 6 GPa. The Fe# of the olivine in equilibrium with the garnets is varying from 0.05 to 0. 1, the latter values are typical of the Cpx also while the Opx show Fe#~0.08. The CaO content of the garnets is rising with the decreasing pressure. Thus the DIA from the Sino-Korea craton represent very deep heated and relatively fertile or fertilized mantle source of diamond. *Kalimantan*. In Borneo kimberlites or lamproites were not found alluvial diamond inclusions (Smith et al ., 2009) give rather high temperature conditions for both peridotitic and eclogitic suits. Only pyrope garnet and chromites drop the 38 mW/m^2 geotherm at 6 GPa . The Opx , eclogite and pyroxenite PT estimates are plotting between 40 and 45 mW/m^2 geotherm.



Conclusions

Diamonds are excellent containers of ancient cratonic mantle preserving PT conditions during diamond growth and giving the clues to the SCLM origin and evolution.

1. The PT conditions of DIA for the ancient kimberlites and later kimberlites differ becoming in general lower temperature and more complex in composition in time.
2. There are some regularities in depth distributions of DIA in mantle columns. Pyroxenitic inclusions are tending to concentrate in middle part of mantle section as well as Fe-rich eclogites. Chromite and often Ca-Al rich pyropes in are often located just above the lithosphere – asthenosphere boundary.
3. Commonly the peridotitic inclusions are lower temperature than pyroxenitic and eclogitic ones due to a greater degree of reaction to plume influences of later inclusions.
4. Pressures above the diamond stability field could result from the expanding of the diamond stability field at fluid and volatile influence. Another possibility is in increasing of pressures transferring from depth due to hydraulic effect.
5. The kimberlites in off-craton settings and mobile belts show also higher temperature conditions and prevailing pyroxenitic and eclogitic assemblages.
6. There are essential difference in compositions of garnets from mantle sub-terrains such as Alakit and Daldyn (and other examples) containing continental arc and abyssal oceanic material, respectively.

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