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Eclogite varieties and their distribution in cratonic mantle lithosphere worldwide.

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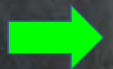
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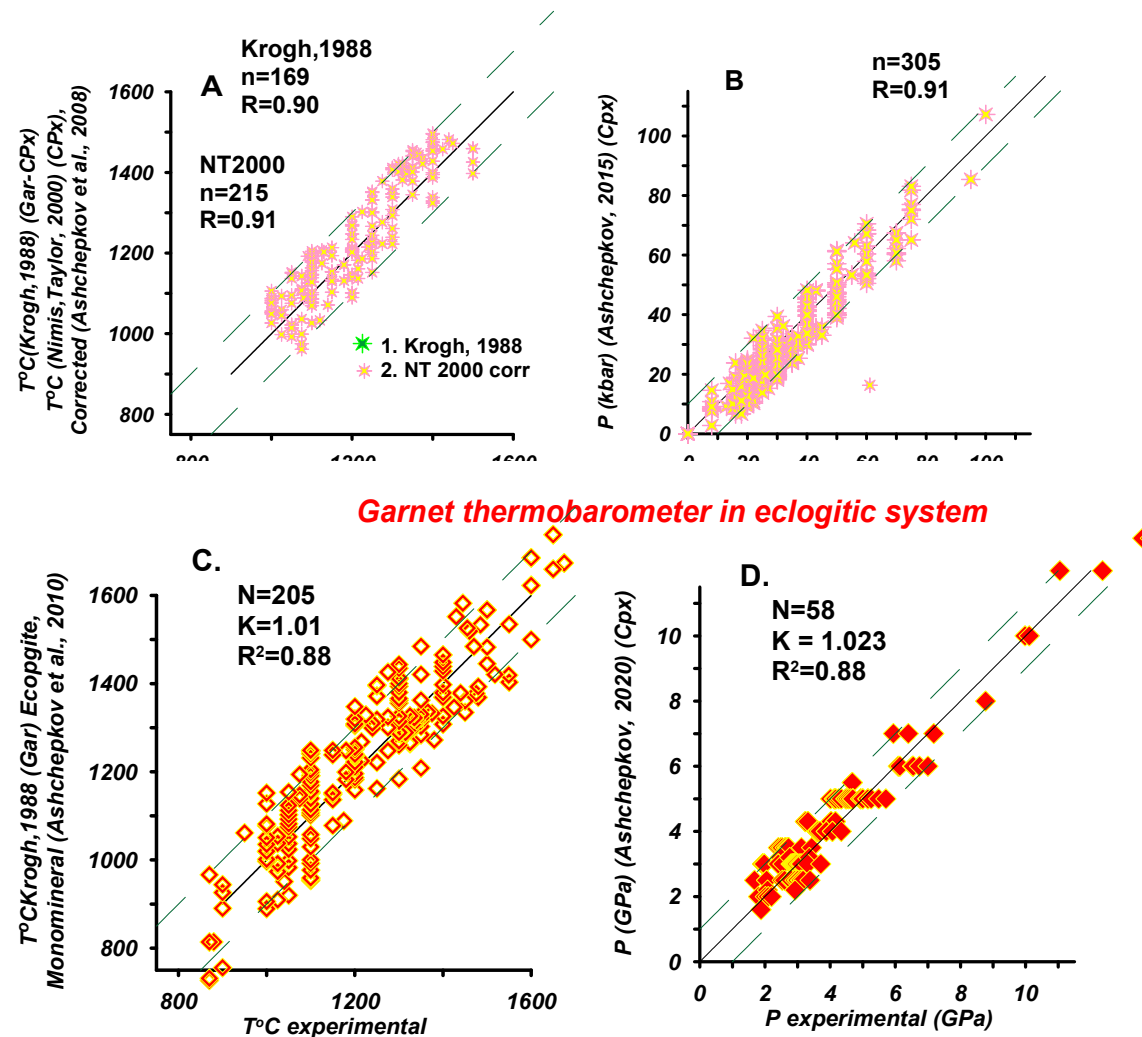
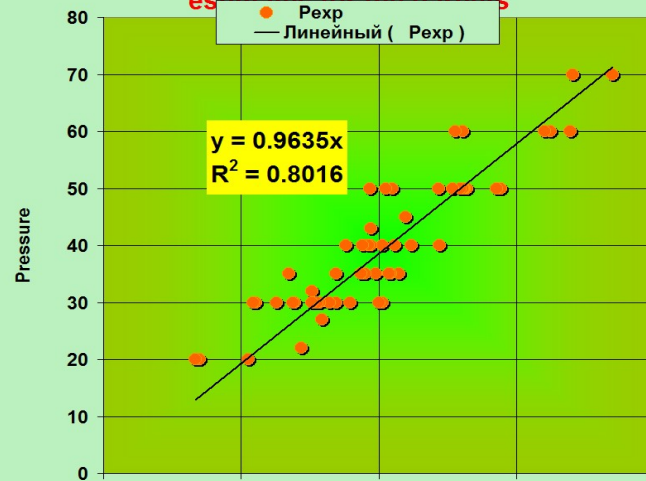


Fig. 1. Correlations: A) between temperatures of experimental runs and values estimated with -Cpx thermometer (Nimis, Taylor, 2000) corrected and $T^{\circ}\text{C}$ values for experimental runs in eclogite system; C) monomineral garnet (Krogh, 1988) thermometer in eclogitic system

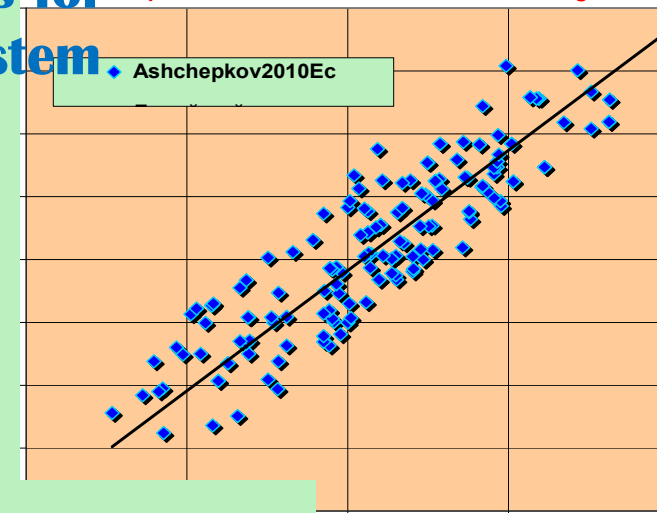
Correlations between pressures B) experimental values and those determined by universal clinopyroxene barometer in eclogitic systems (data set from Ashchepkov et al., 2017 with additions); D) monomineral garnet barometer for eclogite (Ashchepkov et al., 2017 modified) (see equations in supplementary file 1 –SF1). Data for experimental runs in eclogite system taken from sources listed in Sf3 (Keshav et al., 2005; Thomsen et al., 2008; Spandler et al., 2008; Rapp et al., 2003; Pertermann & Hirschmann, 2003; Litvin et al., 2005; Kogiso et al., 2004; Hirschmann & Stolper, 1996; Ghosh et al., 2009; Yaxley & Green, 1994; Wang et al., 2011; Kogiso & Hirschmann, 2007; Kessel et al., 2005; Nakamura & Hirajima, 2005; Yaxley & Brey, 2004; Kiseeva et al., 2012; 2013; Bulatov et al., 2014; Perchuk et al., 2018; Woodland et al., 2019) (See list of reference in supplementary file 3)

Correlations of PT estimates for eclogitic system

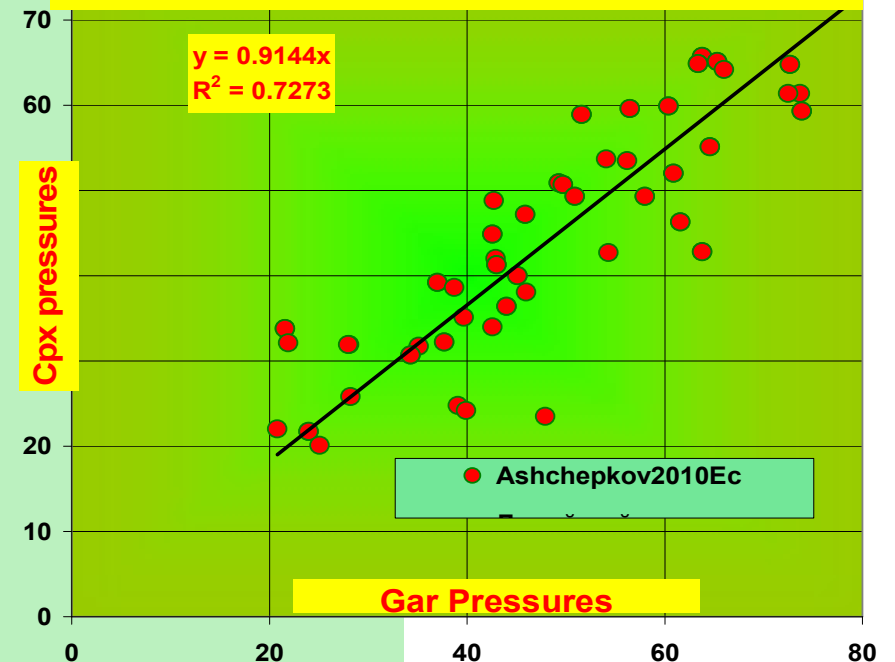
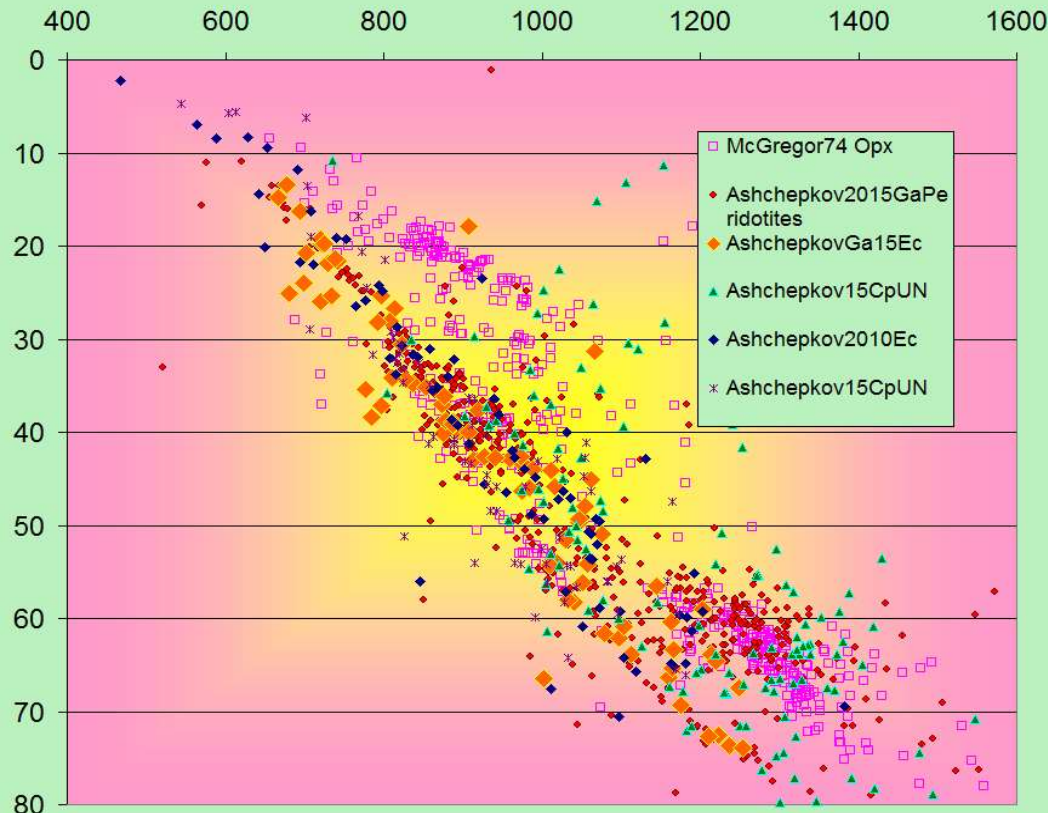
Correlations of the experimental Values and Pressure estimates for the garnets



Correlations of the Cpx And Gar Pressures for the mantle eclogites Worldwide



Correlations between Cpx and Gar Pressure estimates For Udachnaya



Clinopyroxene and garnet thermobarometry for mantle eclogites

To determine the PT conditions of eclogite origin or re-equilibration is very important for petrology. For the relatively low pressures to 2.5 GPa, this can be solved by the “Thermocalc software” (Holland and Powell, 1998) and some polymineral barometers (Ducheune & Albaredo, 1999; Nowlan et al, 2000; Krogh Ravna & Terry, 2004).

Recalibration of garnet-clinopyroxene barometer (Beyer et al., 2015) gave satisfactory results but revealed rather high dispersion in PT estimates for the Dharwar craton eclogite xenoliths (Dongre et al., 2015) and depends on the quality of the analyses of the SiO₂ in clinopyroxenes.

The recalibrated Jd-Di thermobarometer (Ashchepkov et al., 2010; 2017a) works in peridotitic, pyroxenitic and different eclogitic systems and the garnet eclogite barometry gives estimates close to those determined from omphacites (Ashchepkov et al., 2017a). Here we present the enhanced version of universal Cpx barometer and garnet eclogite barometers accounting for Fe³⁺ which increases the agreement of the methods.

More detailed diagrams were obtained using the data for eclogitic xenoliths and eclogitic diamond inclusions, adding new data for Udachnaya (Ragozin et al., 2014; Agashev et al., 2018; Kolesnichenko et al., 2018) and associations and published data for xenoliths from Mir, Komsomolskaya and Sytykansкая kimberlite pipes from Siberia (Snyder et al., 1997; Sobolev et al., 1999; 2003; Spetsius et al., 2009; Taylor et al., 1979; Jacob et al., 2004; Liu et al., 2009; Beard et al., 2006; Misra et al., 2004; Pernet-Fisher et al., 2014; Shatsky et al., 2008; 2015). For the other pipes from Siberia, PTX diagrams can be found at DOI: 10.13140/RG.2.2.34796.56961

The calculated PT conditions with the monomineral barometers using data for eclogites from the Wyoming craton (USA) (Ater et al., 1984; Ashchepkov et al., 2013c), Slave craton (Creighton, 2009; 2010; Davies et al., 2007; Aulbach et al., 2007; Cartigny et al., 2009; Heaman et al., 2006; De Stefano et al., 2009; Smart et al., 2009), the eastern part of the Dharwar craton in India (Patel et al., 2009; Ashchepkov et al., 2013a, Dongre et al., 2015), Angola (Ashchepkov et al., 2012; Nikitina et al., 2014) and several localities from South Africa (Jacob et al., 1994; 2009; Burgess et al., 1989; Carlson et al., 2000; Haggerty, 2001; Hopp et al., 2008; Appleyard, et al., 2004; Korolev et al., 2018 etc) allow us: (1) to estimate the position of different types of eclogites from different groups varying in K₂O, CaO, Na₂O, Al₂O₃ and FeO contents, (2) to recognize the layering of the sub-cratonic lithospheric mantle (SCLM) beneath different cratons and (3) to investigate the primary origin of eclogites. We also analyzed new data from concentrates and used published analyses from Roberts Victor in addition to the published materials (Smyth, 1977; Schulze et al., 2000; Jacob et al., 2005; Gréau et al., 2011; Huang et al., 2014a,b etc) and added new published data from Orapa, Premier (Dludla et al., 2006; Korolev et al., 2018) and other pipes.

Temperature estimates for eclogites determined using the thermometer by Krogh (1988) give the best agreement with the experimental results for the bi-mineral associations. For the single grain garnet thermobarometers, we added corrections calculating the missed values of Fe in garnets (Ashchepkov et al., 2010; 2017). High deviations were corrected for the Fe-rich varieties because of the high Fe³⁺ content, the calculated values may be applied mainly for eclogites with $Fe\#Ol = Fe/(Fe+Mg) < 0.35$, which cover the values for mantle eclogite compositions). The Fe#Ol for garnets (Fe# for olivines in equilibrium with garnets) is determined by the empirical equations (see supplementary file 3). For single omphacites, the thermometer after Nimis & Taylor (2000) in modified version (Ashchepkov et al., 2010) gives appropriate results. We made additional correction in this paper using more statistics from experiments in high pressures. All new modification are in the supplementary files.

1. Subdivisions of mantle eclogites

Many investigators consider most mantle eclogites to be of subduction origin (Jagoutz et al., 1994; Jerde et al., 1993; Pearson et al., 1999; Pearson et al., 2005; Pearson & Wittig, 2014; Snyder et al., 1997). Moreover they concluded that most eclogites are close to MORB compositions. In fact, subducted slabs are layered and consist of peridotites, lower cumulative pyroxenites, gabbro and upper ophitic gabbro which are variable in bulk rock compositions especially in Al_2O_3 , CaO and Na_2O in Mg'. Authors reconstructed common bimimetic eclogites often show nearly flat REE patterns and the spiderdiagrams which are interpreted as primary tholeiitic (Shchukina et al., 2017; 2018; Radu et al., 2019; Aulbach et al., 2018). But experimental results show that eclogites should be melted and essentially transformed during subduction and upwelling (Richardson et al., 2014; Rosenthal et al., 2014; 2018; Herzberg, 2019). Eclogites commonly showing the range of the Fe# ($= \text{Fe}/(\text{Mg}+\text{Fe})$) $\sim 0.1-0.35$ for clinopyroxenes were used for the classifications show clustering in diagrams and should be of different origin. Cpx with Fe# 0.08-0.15 should crystallize from partial mantle melts. The Cpx in their Fe# are close to that of bulk rock of eclogites, the variations due to temperature distributions between Cpx and Gar (Ellis & Green, 1979; Krogh, 1988; Davis et al., 2013) are not high, \

The melts equilibrated with Archean olivines 0.05-0.08 (Griffin et al., 2001) have Fe# $\sim 0.18-0.27$ using melt-solid partition coefficient ~ 0.33 for Fe (Albarede, 1992) and corresponds to the komatiites- picrites and Mg basalts, andesites and other primitive mantle magmas. There is suggestion that eclogites with high Al omphacites and Fe# 0.15-0.25 could be cumulates or restites of arc Archean magmas (Horodyskyi et al., 2007). The higher values could correspond to subducted basalts of different types or Mg-rich crustal rocks. Only basalt composition (Fe# $\sim 0.25-0.35$) could produce eclogites during subduction.

We divided eclogites into four large groups instead of three groups based on MgO- Na_2O variations in clinopyroxene (Dawson, 1980; Neal et al., 1992). As was done in previous studies (Spetsius et al., 2008; Viljoen et al., 2010; Aulbach et al., 2018), we add the high Ca-Al group often containing kyanites. Several more subgroups can be identified according to their positions on the PTX diagrams and trace element signatures

1. The high-Mg eclogites (Fe# 0.07-0.19) (Group A) consist of several Groups: 1a) a Cr-bearing group formed after crystallization of partial melts produced by volatile fluxes or heating (Heaman et al., 2006; Smart et al., 2009); 1b) a group formed by hybridization of subduction-related melts and fluids with mantle peridotites (Aulbach et al., 2011); 1c) group derived from the differentiated of protokimberlite melts (Haggerty et al., 1979; Kamenetsky et al., 2009); 1d) a low-Cr group which could be restites (Wyman & Kerrich, 2009) or deep cumulates from tonalite-trondhjemitic magmas or Mg-rich arc magmas (Horodyskyi et al., 2007; Barth et al., 2002).

2. The largest group (Group B) with Fe# $\sim 0.20-0.30$, moderate Al_2O_3 and Na_2O values, suggested to be subduction-related eclogites; they commonly have Eu anomalies. The most abundant rocks forming Group 2a are interpreted as subducted basalts and their modifications as well as eclogitized metagabbro (with relics of ophitic structures), close to MORB (Jagoutz et al., 1974; Beard et al., 1996; Pearson, 1999; Snyder et al., 1997) or essentially reacted with oceanic water (Neal et al., 1990). Enriched "gabbroic" type of group 2b eclogites are thought to be products of fluid melting of ancient oceanic crust and interaction with peridotites during subduction (Aulbach et al., 2007). Group 2c eclogites may be interpreted as shallow mantle cumulates derived from plume or ancient arc and basaltic magmas in cratonic margins (Wyman & Kerrich, 2009); the eclogites located near Moho may be eclogitized lower crustal cumulates (Shu et al., 2014). Group 2d eclogites are metabasaltic formed by re-melting or hybridization with protokimberlite and other plume melts (Shatsky et al., 2008).

3. The high-Fe-Na Group 3 (Group C) eclogites (Fe# > 0.27) may be subducted Fe- basalts (Group 3a); Ca-enriched varieties may be meta-tonalites or trondhjemitic (Group 3b) (Barth et al., 2002) and those which are very rich in Al could be metasediments (greywackes and metapelites) (Group 3c) (Mazzone & Haggerty, 1989).

4. High-Ca-Al Group eclogites were divided into: Group 4a rocks high in Ca and low-Fe varieties, commonly Al-rich and kyanite-bearing (sometimes with coesite) (grosspyrites) which may be originally carbonate metasomatites (Smyth, 1977) or metapelites (Liou et al., 2014). Group 4b eclogites are high-Ca and moderate-Fe and may be ancient Mg-granites (Barth et al., 2002; Jacob et al., 2004).

We put compositions of clinopyroxenes from the high pressure experimental work which we used for calibration of clinopyroxene and garnet universal thermobarometers (Ashchepkov et al., 2017) (Fig.2A) and the compositions of studied clinopyroxenes and worldwide eclogites on variation diagrams (Fig.2A, B). In addition the compositions of clinopyroxenes obtained in experimental works used for the calibration are shown in the Sf1 and in tables in Sf 2. Group B dominates the middle part of the diagrams (Fig. 2). Ca-rich varieties are represented by eclogites from India which are low-Fe and Al-rich.

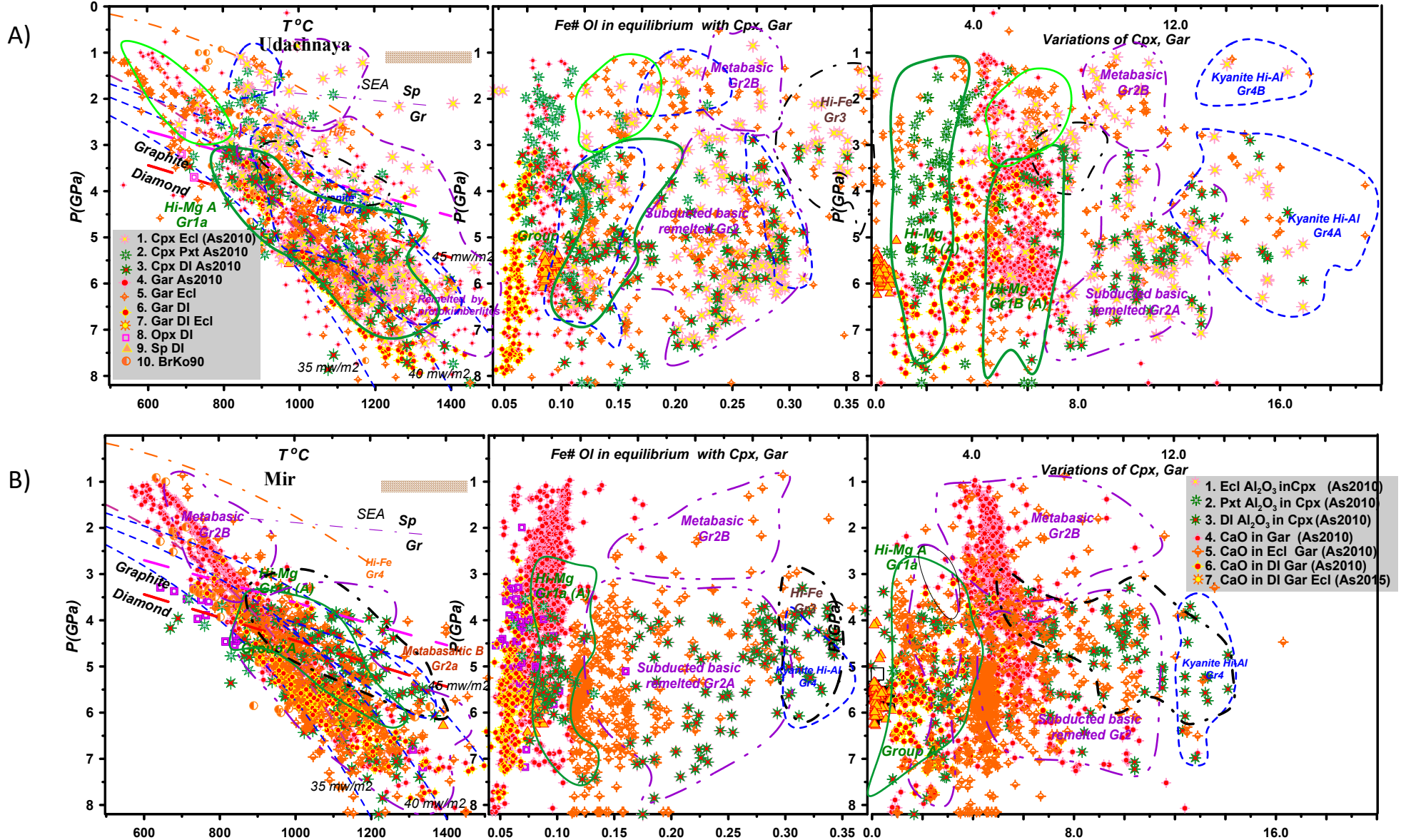


Fig.3. PTX diagram for xenoliths and minerals concentrates from: A) Udachnaya pipe; B) Mir pipe. Symbols: 1. Cpx: T°C Nimis & Taylor, 2000 - P (GPa) Ashchepkov et al., 2010) for common eclogites; 2. The same for pyroxenites; 3. The same for diamond inclusions; 4. Garnet (monomineral): T°C (O'Neill & Wood, 1979) - P (GPa) Ashchepkov et al., 2010); 5. The same for eclogitic diamond inclusions. 6. The same for peridotitic diamond inclusions; 7. The same for eclogitic garnets. 8. Opx for diamond inclusions: T°C (Brey & Kohler, 1990) - P (GPa) (McGregor, 1974); 9. Chromite for diamond inclusions: T°C (O'Neill & Wall, 1987) - P (GPa) (Ashchepkov et al., 2010); 10. Opx- Gar: T°C - P (GPa) (Brey & Kohler, 1990). Position of conductive geotherms are after Pollack & Chapman (1977) and the graphite - diamond transition after Kennedy and Kennedy (1976); the line above after Day (2012). Shaded areas are labeled according to the divisions described in introduction.

Udachnaya pipe

The distribution of eclogites in the SCLM beneath Udachnaya (Fig.3A) is typical for xenoliths from other Upper Devonian pipes in Yakutia. We separated eclogites from pyroxenites which commonly contain relatively low-Al and Na- augites or belong to the Cr-diopside group (Kuligin, 1996).

The PT plot of Udachnaya SCLM shows steps formed by intercalations of hotter and colder parts in mantle section (Fig. 3A) (Ashchepkov et al., 2010;2014; 2017b). Eclogites lie on both hot and cold geotherm branches. The Mg-rich eclogites of Gr1A (with Mg pyroxenites) reflect mainly low temperature conditions. Gr1A –in the lower SCLM partly followed the precipitates from protokimberlites (Ti-rich association) coincide with the high temperature PT conditions for ilmenites and sheared peridotites (Ashchepkov et al., 2013a, b; 2017a,b). The Mg-rich Gr1 pyroxenites (group A) also mostly belong to the middle SCLM level including diamond-bearing varieties which lie on the relatively cold branch of the geotherm, marked by pyrope inclusions in diamonds. This group divides into 2 trends according to the CaO and Al₂O₃ concentrations. The lower in Al groups is closer to pyroxenites but Al-Ti-Ca enriched group is closer to protokimberlites.

Group 2 or B eclogites, together with the pyroxenites, follow the heated branch of the geotherm in the upper SCLM. Groups A eclogites are found in the lower part of SCLM (LSCLM). Many diamond-bearing eclogites in the latter group show signs of reaction with protokimberlites (Shatsky et al., 2006; Stepanov et al., 2008) in the LSCLM and are more frequent near its base. They form typical magmatic trends of ascending Fe# with decreasing pressure trend (AFDP). Fe-eclogites (Gr3A) belong to the 3.0-3.5 GPa interval and corresponds in pressure to the pyroxenite layer. Kyanite grosspydites (Gr4) belong to the 3.0-6.0 GPa pressure interval where they are intercalated with pyroxenites in a pyroxenite layer (Pokhilenko et al., 1999; Ashchepkov et al., 2013a,b), but they are more abundant in the 5.5-6.5 GPa interval. The relatively low pressure estimates corresponds to the Gr 4B.

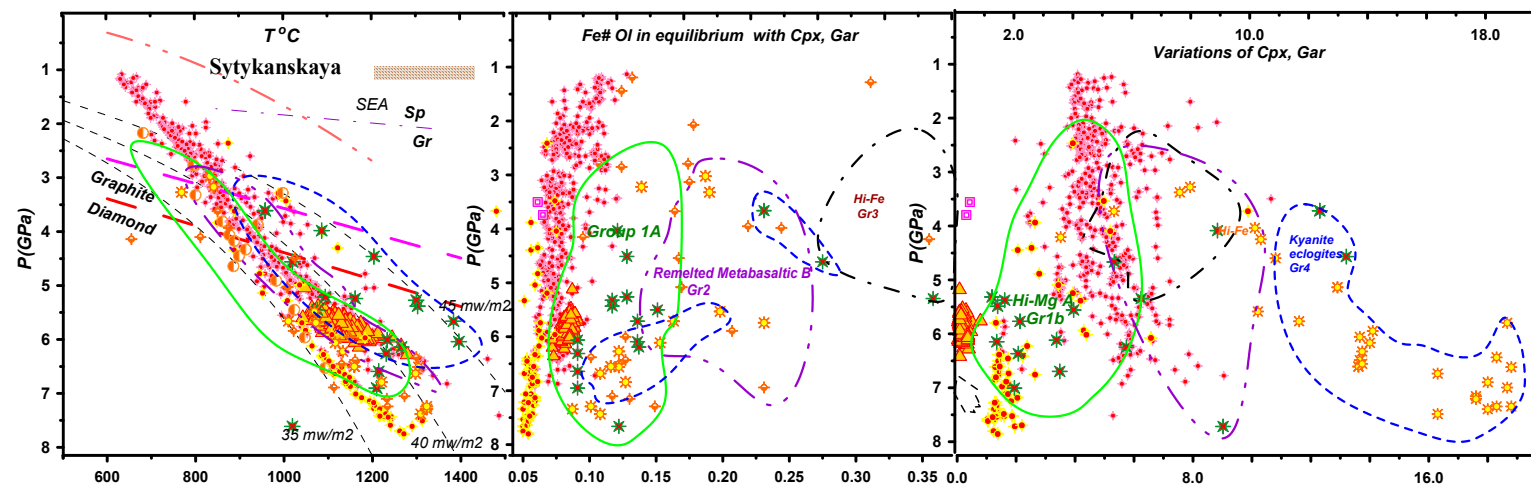
There is rather sharp boundary at 5.0-5.5 GPa which is shown by abundant low-T Mg-rich eclogites, located just above the hottest sheared peridotite ilmenites, and ilmenite eclogites (pyroxenites) with Fe#=0.11-0.515 marking the ascent path of differentiating protokimberlite melts.

Mir pipe

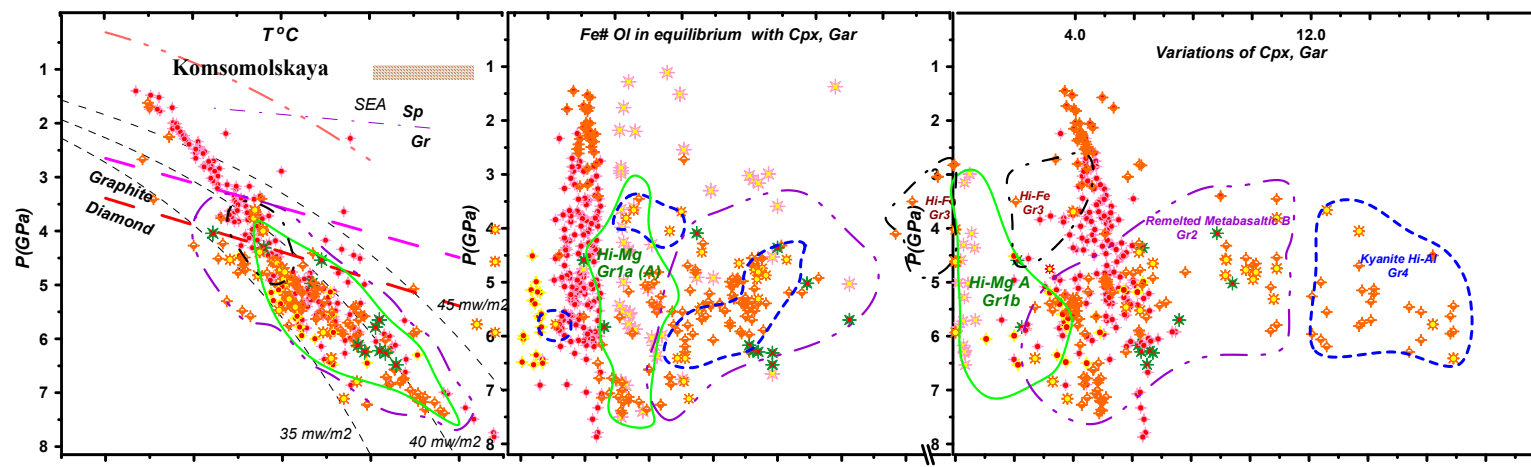
The geotherm (Fig. 3B) determined by Opx-Gar (Brey & Kohler, 1990) and garnet (Ashchepkov et al., 2010) thermobarometry is relatively low temperature near the lithosphere base, e.g. showing 1000 °C at 6.0 GPa. It cuts all conductive geotherms in the upper part and marks the advective PT path starting from the pyroxenite layer located at 3.5-4.0 GPa. Most diamond-bearing eclogites (Sobolev et al., 1970; Beard et al., 1996) of Gr1 and Gr4 trace the diamond-graphite boundary (Kennedy & Kennedy, 1976) and reflect rather high temperature conditions. The location of a rather large group above this may be explained by data after Day (2012) which gives this transition ~2-5 GPa higher, it is shown on the diagram approximately by magenta line at 1.5 GPa above the line determined by Kennedy and Kennedy (1976) . Mg-rich clinopyroxenes in Gr1a eclogites form a dense cluster (5-6 GPa) near the lithosphere base and are slightly more heated than xenoliths and garnet geotherm. The low-Cr varieties form the cloud in P-Fe# diagram in 3.5-4.5 GPa interval. For Gr2 -Gr3 -Gr4 eclogites there are several AFDP trends which characterize rising and differentiating melts. Eclogites of Ca-rich Gr3 are found within a rather wide pressure interval but mainly near the lithosphere asthenosphere boundary LAB and in the middle part of the mantle section. The points for the Fe- and Al-rich Gr4 form a cloud within the 3-5 GPa interval and in the level near 6 GPa. Omphacites in Gr3 and Gr4 eclogites occur on the relatively hot branches >45 mW/m², suggesting the influence of protokimberlites. Several low-Cr Gar and Cpx from Gr1d and Gr2d eclogites with relatively low Fe#~0.15 found in the lithosphere base may have crystallized from protokimberlites. Eclogites with low Fe#~0.11-0.15 found in the lithosphere base may be crystallized from protokimberlites.

Fig.4

A)



B)



C)

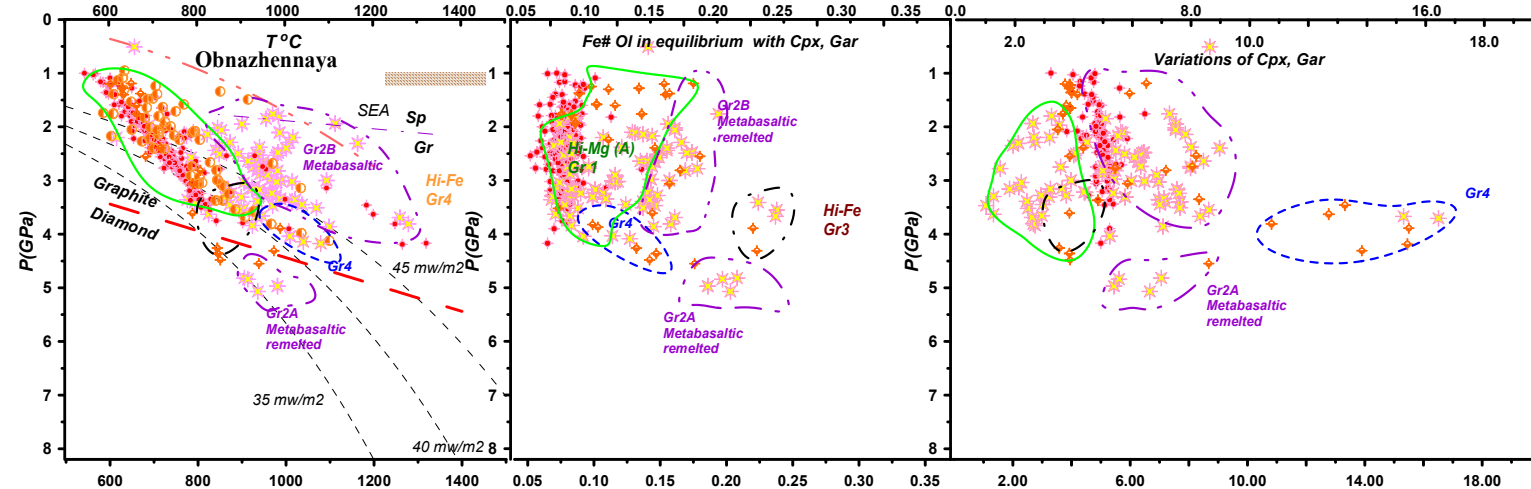


Fig.4. PTX diagram for xenoliths and mineral concentrates from: A) Sytykansкая pipe; B) Komsomolskaya; C) Obnazhennaya pipe.

Symbols are as for Fig.3

Sytykanskaya pipe

In the SCLM beneath this pipe (Fig. 4A) (Ashchepkov et al., 21016), diamond-bearing eclogites often contain kyanite (Spetsius & Koptil, 2008) and even diamond inclusions belong to Ca-Al-rich types. They closely trace the diamond-graphite boundary. Rare diamond inclusions of the Mg-rich Cr-bearing type are found close to 3 and 5 GPa and lie close to the conductive 35 mW/m² geotherm at pressures of 3-4 GPa. Gr1a-1d eclogites reflect hotter conditions (40-45 mW/m²) in the middle SCLM 3-5 GPa near the pyroxenite layer. Common basaltic eclogites are found in the upper part of SCLM (USCLM) (Gr2A,B). Eclogites belonging to the Gr4 are found near the lithosphere base. As is common, the high-Fe diamond inclusions are related to the hottest part of the geotherm at 50 mW/m²

Komsomolskaya pipe.

In the mantle column beneath the Komsomolskaya pipe (Fig. 4B), diamond-bearing eclogites (Pernet-Fisher et al., 2013) rarely belong to the Mg-rich Gr1a which is related to low temperature 35 mW/m² conditions. The Fe-rich group is distributed from 4.0 to 5.0 GPa and relates to the 42 mW/m² geotherm. The metabasaltic melt-metasomatized eclogites Gr2c,d are found in the lithosphere base and mark the 40-42 mW/m² geotherm branches.

Obnazhennaya pipe

In the mantle section beneath this Jurassic pipe, high eclogite population belong to Gr1 (Fig. 4C) (Taylor et al., 2003; Ovchinnikov, 1991). Though Gr2 and 3 are also present (Sun et al., 2020). Most of them belong to the high-Mg Gr1a and represent the middle or upper part of the SCLM. Hybrid low-Cr varieties (transitional between Gr1b and Gr2d) are located in the 4.0-2.5 GPa interval. The new data set allowed us to find eclogites belonging to the melt- (Gr2d) near 5 GPa. As usual, the high-Fe group Gr3 (Sun et al., 2020) is located at the base of the pyroxenite layer in the middle SCLM.

Bumerang and Khardakh pipes

They both belongs to the Jurassic Ary Mastkh pipe at the western margin of the Anabar shield. They contain mainly pyroxenites located at the M-USCLM but a few omphacites are found in the middle part of the mantle section 3-2.5 GPa. The garnets of low-Cr type (with Eu anomalies) should belong to eclogites, but low-Mg pyroxenes are mainly Cr-bearing. The deviation to Gr2 is at Fe# 0.17. The Gr3 Fr garnets are found at 2.5-3 GPa and those from the Gr4 are located near 5. GPa (Fig. 5A). The Kharamai field pipes in general repeats the features of the previous (Fig. 5B) field but Gr2 extends to 5.2 GPa. The Gr 3 is represented mainly by pyroxenes and Gr4 was detected.

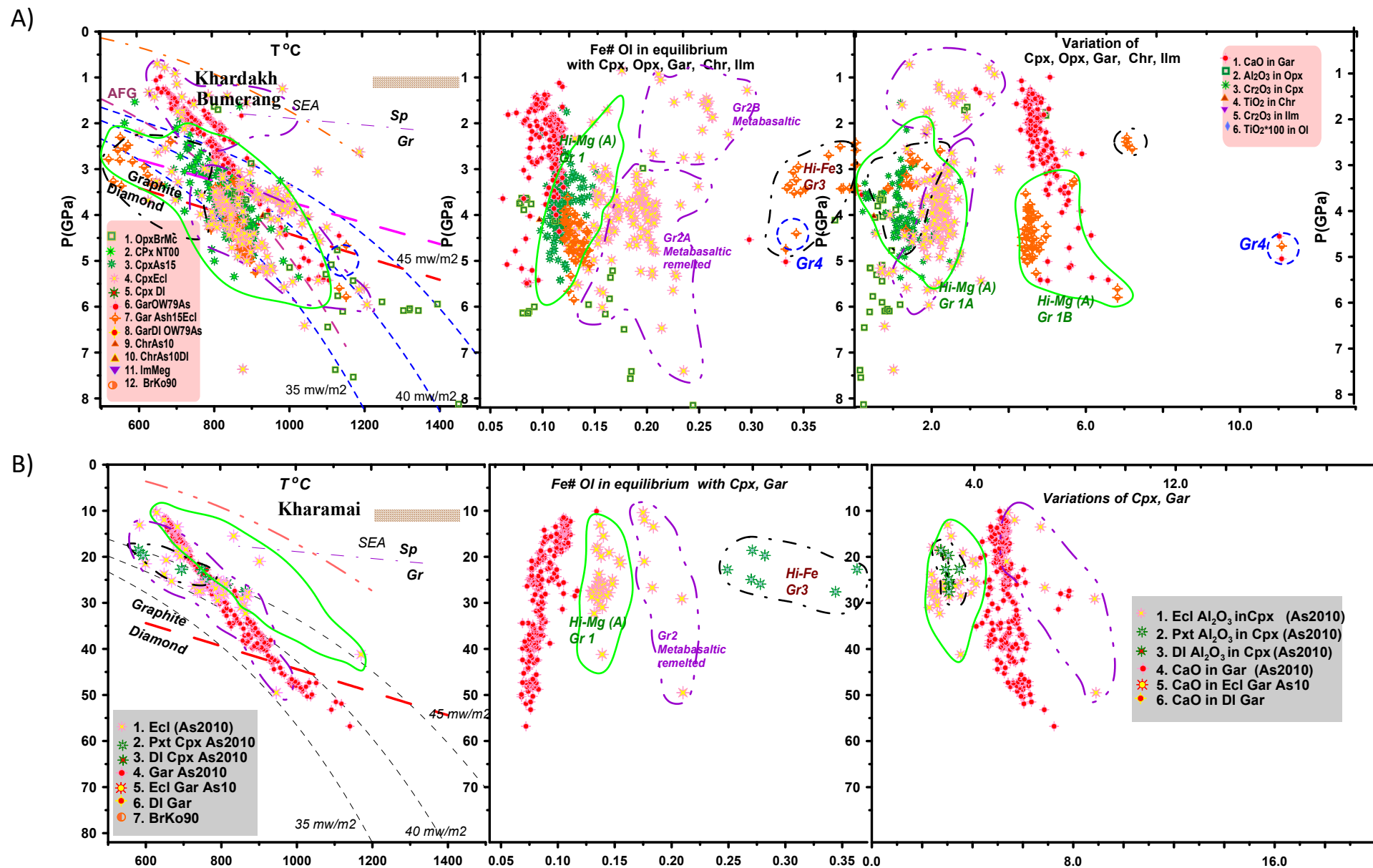


Fig.5. PTX diagram for diamond inclusions and minerals concentrates from A) Ary Mastakh field; B) Kharamai field

Colorado, Wyoming craton Montana

Compared to Yakutia, eclogites from the Sloan kimberlites (Ater et al., 1984; Ashchepkov et al., 2013b) in Colorado, North America are mostly from Gr2. Those from the GR1 are Cr bearing though are high-in Na and Al pyroxenes. These omphacites refer to low-T conditions close to the garnet geotherm. Metabasaltic eclogites Gr2A from the interval 7-3 GPa are typical subduction-related varieties. Eclogites from the lower part of mantle section are of metabasaltic Gr2d affinity reflect heated conditions (plume remelted) with AFDP trend, while the others from Gr2a,b trace the low-T conductive 35 mW/m² geotherm. In the USCLM beneath the Sloan pipe, the Gr2B eclogites are related mainly to the heated geotherm in the 3.5-1.0 GPa interval. The Fe-eclogites (Gr3) from 4.0-3.0 GPa intervals reflect the 45 mW/m² geotherm. High-Ca varieties close to 3.0 GPa show higher temperature conditions (Fig. 6A).

Lac de Gras cluster, Slave craton.

We have calculated the PT parameters for eclogites from the Slave craton (Canada) from the Jericho pipe (Heaman et al., 2006; De Stefano et al., 2009; Smart et al., 2009; Kopylova et al., 1999) and the Lac de Gras kimberlite field (Creighton, 2009; 2010; Davies et al., 2007; Aulbach et al., 2007; Cartigny et al., 2009) (Fig.6B). Mg-rich eclogites from the Jericho kimberlite were captured mainly from the LSCLM.

Eclogites are abundant in the kimberlite pipes of the Lac de Gras cluster (Heaman et al., 2006; Creighton, 2009; 2010) (Fig. 8B) Group A (Gr1a,b) or Mg-rich and Cr-poor varieties in Lac de Gras (Smart et al., 2009) belong to the middle mantle section at 4.0-5.0 GPa.

M. Metabasaltic GR2 varieties form two groups marking a boundary at 3.0 and 4.0 GPa intervals. Fe-rich clinopyroxenes form a trend with the increasing Fe# and decreasing pressure (IFDP) trend from 2.0 to 4.0 GPa. Protokimberlite-derived pyroxenites (Gr2d) which also includes diamond-bearing varieties distributed from the SCLM base to 4.0 GPa. Ca-rich eclogites Gr4 in SCLM beneath the Jericho pipe are found in the lower SCLM from 5.0 to 7.0 GPa. Metabasaltic varieties (Gr2b) dominate in the USCLM together with high-Fe eclogites (Gr4) which reflect higher pressure. The latter are found in the lower part of SCLM also from 5.0 to 6.5 GPa. Melt-metasomatized eclogites (Gr2d) are found in the 7.5-5.0 GPa interval and show an increase in Fe# with decreasing pressures as in the Jericho peridotites. (Fig.8B). The high-Ca varieties (Gr4) are widely distributed in USCLM but also occur near the LAB.

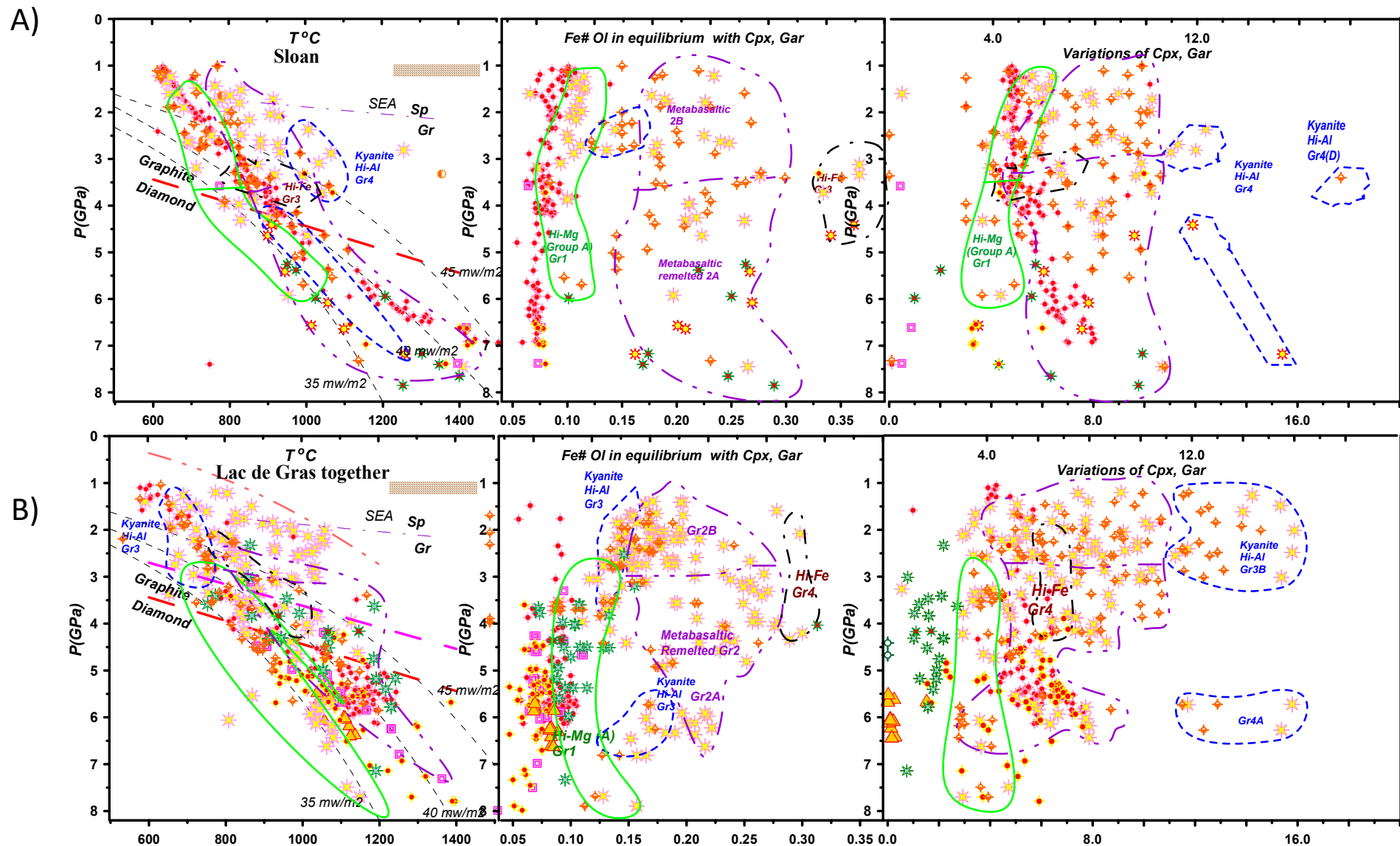


Fig.6. PTX diagram for xenoliths and mineral concentrates from: A) Sloan pipe, Front range field, Wyoming craton; B) For Lac de Gras Field, Slave craton.

Colorado, Wyoming craton Montana

Compared to Yakutia, eclogites from the Sloan kimberlites (Ater et al., 1984; Ashchepkov et al., 2013b) in Colorado, North America are mostly from Gr2. Those from the GR1 are Cr bearing though are high-in Na and Al pyroxenes. These omphacites refer to low-T conditions close to the garnet geotherm. Metabasaltic eclogites Gr2A from the interval 7-3 GPa are typical subduction-related varieties. Eclogites from the lower part of mantle section are of metabasaltic Gr2d affinity reflect heated conditions (plume remelted) with AFDP trend, while the others from Gr2a,b trace the low-T conductive 35 mW/m² geotherm. In the USCLM beneath the Sloan pipe, the Gr2B eclogites are related mainly to the heated geotherm in the 3.5-1.0 GPa interval. The Fe-eclogites (Gr3) from 4.0-3.0 GPa intervals reflect the 45 mW/m² geotherm. High-Ca varieties close to 3.0 GPa show higher temperature conditions (Fig. 6A).

6.2 Lac de Gras cluster, Slave craton.

We have calculated the PT parameters for eclogites from the Slave craton (Canada) from the Jericho pipe (Heaman et al., 2006; De Stefano et al., 2009; Smart et al., 2009; Kopylova et al., 1999) and the Lac de Gras kimberlite field (Creighton, 2009; 2010; Davies et al., 2007; Aulbach et al., 2007; Cartigny et al., 2009) (Fig.6B). Mg-rich eclogites from the Jericho kimberlite were captured mainly from the LSCLM.

Eclogites are abundant in the kimberlite pipes of the Lac de Gras cluster (Heaman et al., 2006; Creighton, 2009; 2010) (Fig. 8B) Group A (Gr1a,b) or Mg-rich and Cr-poor varieties in Lac de Gras (Smart et al., 2009) belong to the middle mantle section at 4.0-5.0 GPa.

M. Metabasaltic GR2 varieties form two groups marking a boundary at 3.0 and 4.0 GPa intervals. Fe-rich clinopyroxenes form a trend with the increasing Fe# and decreasing pressure (IFDP) trend from 2.0 to 4.0 GPa. Protokimberlite-derived pyroxenites (Gr2d) which also includes diamond-bearing varieties distributed from the SCLM base to 4.0 GPa. Ca-rich eclogites Gr4 in SCLM beneath the Jericho pipe are found in the lower SCLM from 5.0 to 7.0 GPa. Metabasaltic varieties (Gr2b) dominate in the USCLM together with high-Fe eclogites (Gr4) which reflect higher pressure. The latter are found in the lower part of SCLM also from 5.0 to 6.5 GPa. Melt-metasomatized eclogites (Gr2d) are found in the 7.5-5.0 GPa interval and show an increase in Fe# with decreasing pressures as in the Jericho peridotites. (Fig.8B). The high-Ca varieties (Gr4) are widely distributed in USCLM but also occur near the LAB.

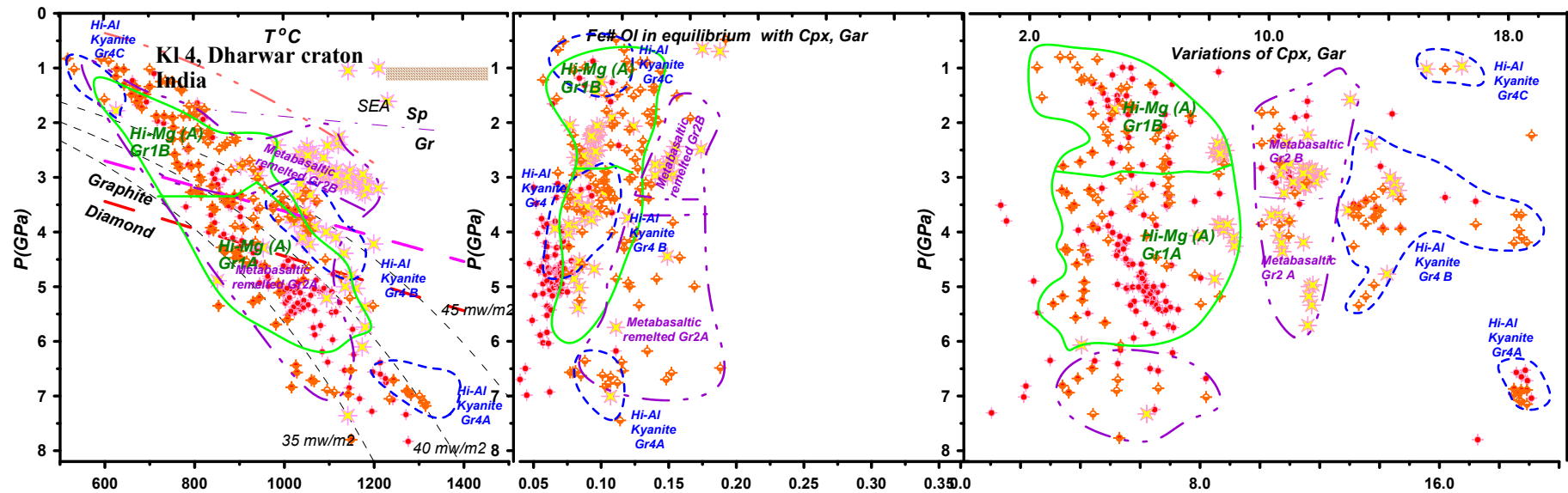


Fig.7. PTX diagram for xenoliths and mineral concentrates from: KL-4 pipe, Wajrakarur field; Dharwar craton. Symbols are the same as for Fig.3

Dharwar craton, India

Proterozoic (1.1Ga) KL-4 pipe in the Dharwar craton of India (Patel et al., 2009) contains mainly kyanite-bearing eclogites or grosspydrites (Fig.7B). The Mg-rich Gr1 is very wide in Al_2O_3 and CaO and distributed from the LAB to Moho. The subduction-related eclogites of Gr2 (Dongre et al., 2015) with pyroxenes also rich in Al are distributed from 6 to 1.5 GPa. Most xenoliths basaltic group and lie on the hot 90-60 mW/m^2 geotherm in the 1.5-3.0 GPa interval. Gr3 is not detected. The kyanite-bearing Gr4 mainly belong to the 3.5-4.5 GPa interval and form a pyroxenite layer which is suggested also by geophysics (Naganjaneyulu & Santosh, 2012). Eclogites contain several generations of pyroxenes and some of them belong to low pressure conditions. Some of them contain Cr but are Ca-rich and look like products of interaction (Gr1b) of Si-Al-Ca fluids with mantle peridotites.

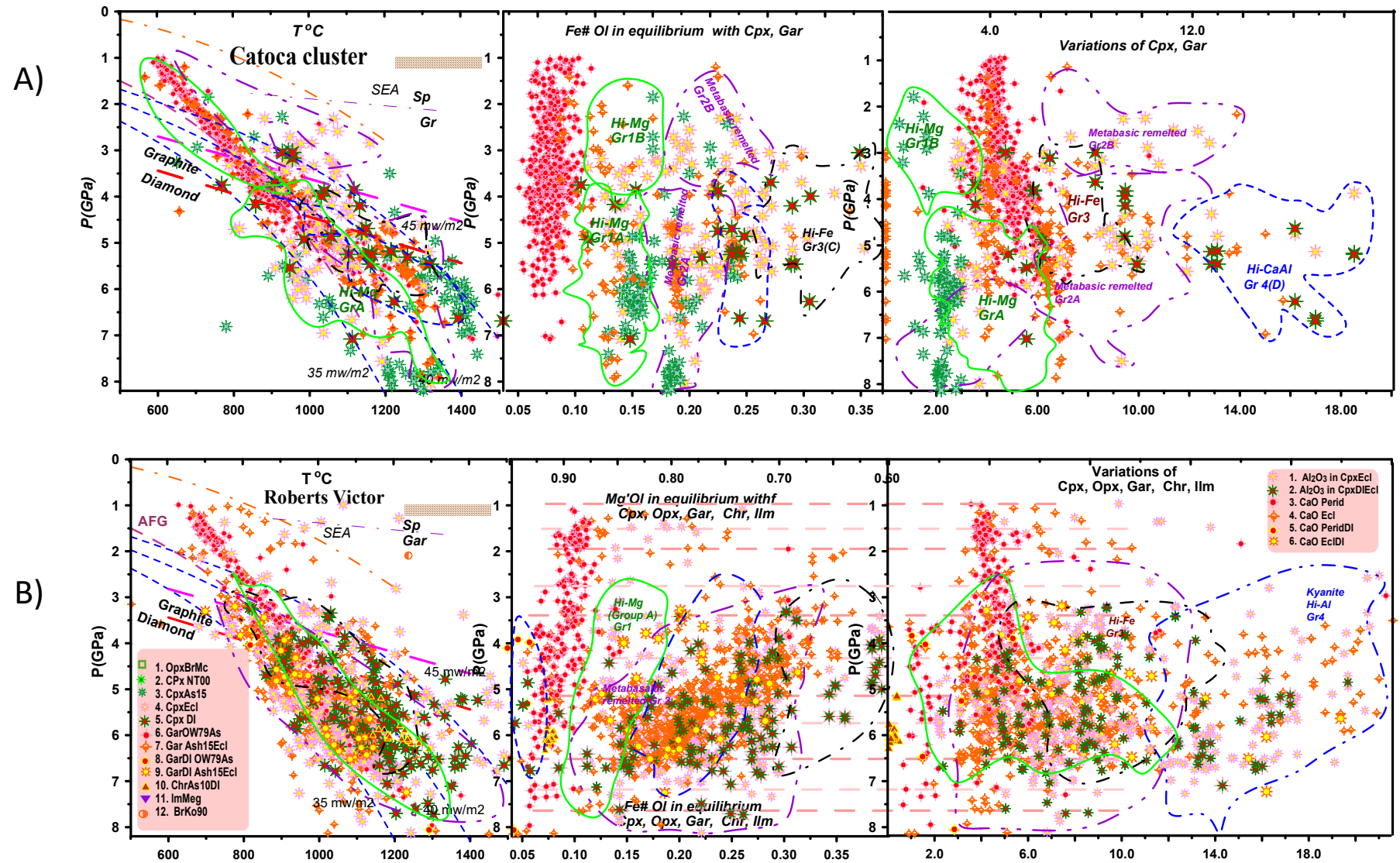


Fig.8. PTX diagram for xenoliths and mineral concentrates from: A) Catoca cluster, Kasai craton. B) The same for Roberts Victor pipe, Slave craton

Catoca pipe, Congo Kasai craton

Most pipes are located within the “Diamond SW-NE corridor” including diamond-bearing in the Catoca pipe in Angola (Ashchepkov et al., 2012) with abundant eclogitic xenoliths (Nikitina et al., 2014) (Fig.8A). They show a wide range of compositions and two IFDP trends. The high-Mg low-Cr eclogites (Gr1c) are probably ancient arc cumulates and are concentrated in the 3.0-4.0 GPa interval. The high-T trend starting from Fe#~0.12 to 0.18 relates to protokimberlites (Gr2d), whereas the second one is low-T and starts from Fe#~ 0.17 and probably was formed by ancient plume-derived magma. Both Ca-Al-rich (Gr4) and Fe-rich (Gr3) eclogites are found in the 4.0-5.0 GPa interval. A wide range of compositions of basaltic origin is found in the USCLM and probably represents intrusive bodies derived from different magmas.

6.5.2 Roberts Victor pipe, Kaapvaal craton .

This pipe, the most eclogite-rich in Kaapvaal craton, is described in numerous publications (Fig.8B) (Smyth, 1977; Schulze et al., 2000; Jacob et al., 2005; Gréau et al., 2011; Huang et al., 2014 a,b). We also made >380 analyses of minerals from concentrate mostly from eclogitic type. The reconstructed mantle section is similar to that of Udachnaya pipe with the broad IFDP trend. The Gr1 are mostly found in the lower part of the mantle section and are both of Cr-bearing and Cr-free protokimberlitic type often diamond-bearing. The Gr2 formed the inclined complex trend with increasing of Fe# with decreasing pressure in general. The Fe- group 3 is found from 3 to 6 GPa. The kyanite Gr-4 is very wide and located also in the LSCLM forming a gentle trend of pressure and Ca-Al joint decrease.

6.5.3 Premier pipe, Kaapvaal craton .

The Proterozoic kimberlite Premier in South Africa (Phillips et al., 1989) contains different types of eclogites which mostly show a subduction origin (Dludla et al., 2006). Abundant omphacitic diamond inclusions (Tsai et al., 1979; Kovalev et al., 2018) allows reconstruction of the high-T geotherm, very similar to that determined for the lherzolites (Viljoen et al., 2009) and shows a division into three intervals. In the LSCLM the high-Mg (Gr1c) eclogites are relatively depleted in Al. Basaltic eclogites create AFDP trend (APFT). High-Al-Ca (Gr4) eclogites reveal a wide trend in the 6.0-5.0 GPa interval (Fig.9A), whereas Fe-rich (Gr3) ones form a rather dense group within the 3.5-5.5 GPa interval. Some omphacites from diamonds show rather low pressure above the diamond-graphite transition (Kennedy and Kennedy, 1976). But more recent work (Day, 2012) has determined that this line occurs at lower pressures ~2-5 GPa. The influence of the 2 GPa Bushveld plume determines the HT conditions of the whole lithosphere.

6.5.4 Orapa pipe, Limpopo belt

The PTX diagram for this pipe mainly is constructed using diamond inclusion from Orapa pipe (Dludla et al., 2006; Korolev et al., 2018) and separate nodules (Deines & Harris, 2004; Aulbach et al., 2017). The Mg-rich group mostly Cr-free and Cr-bearing are from the MSCLM. The Cpx from the Gr2 are lower in pressure than garnets, opposite to Premier pipe. They also form the IFDP trend. The Fe-group is in 3-5 GPa interval. The Gr4 eclogites are widely distributed in LSCLM and garnets are higher in pressure and lower in temperature than pyroxenes.

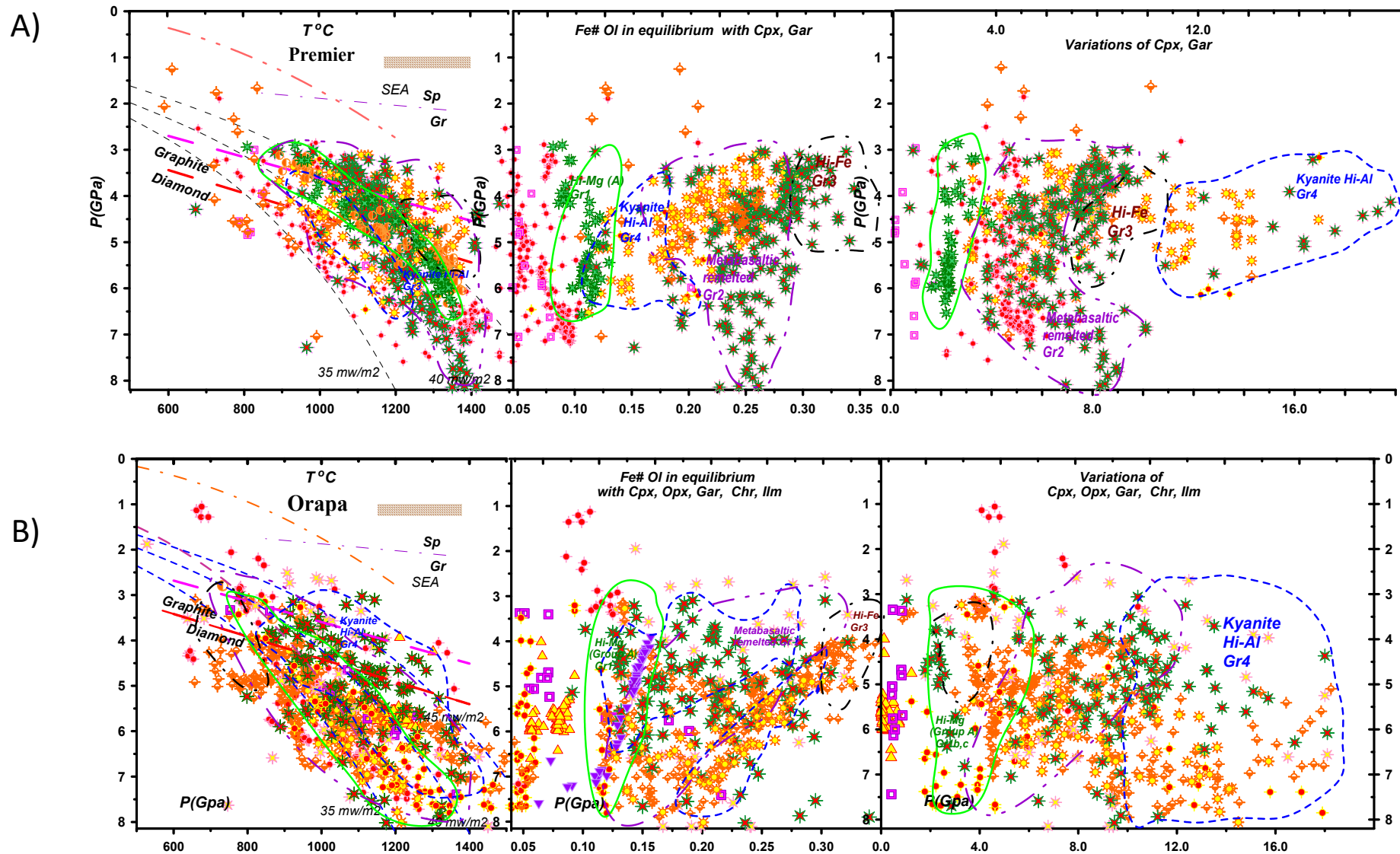


Fig.9. PTX diagram for xenoliths and mineral concentrates from: A) Premier pipe. B) for Orapapite. Symbols the same as for Fig.3

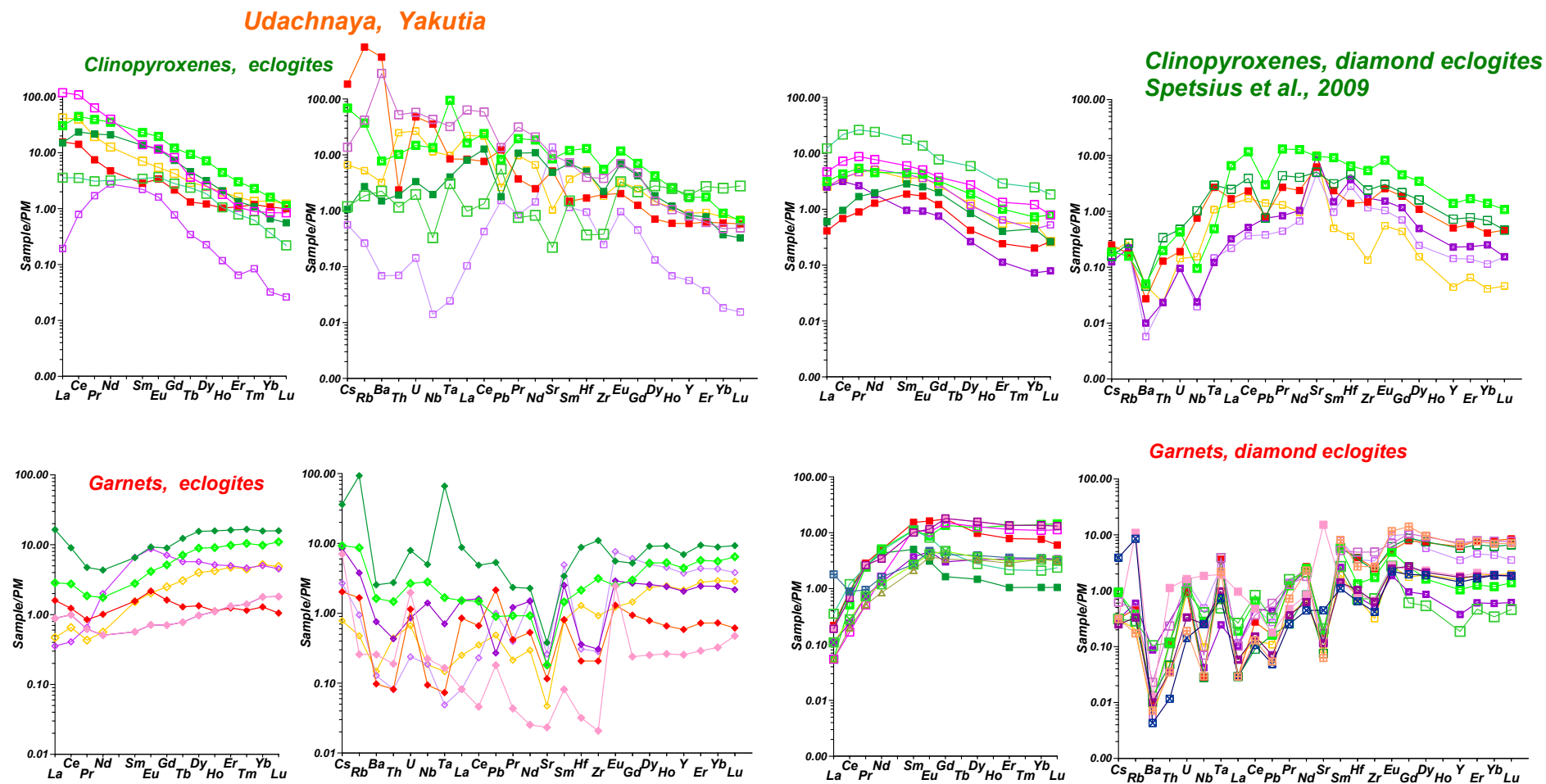


Fig.10. REE patterns and trace elements spider diagrams patterns for garnets and clinopyroxenes from eclogite xenoliths: A) Udachnaya pipe B) Udachanaya pipe, diamond-bearing eclogites (Spetsius et al., 2009).

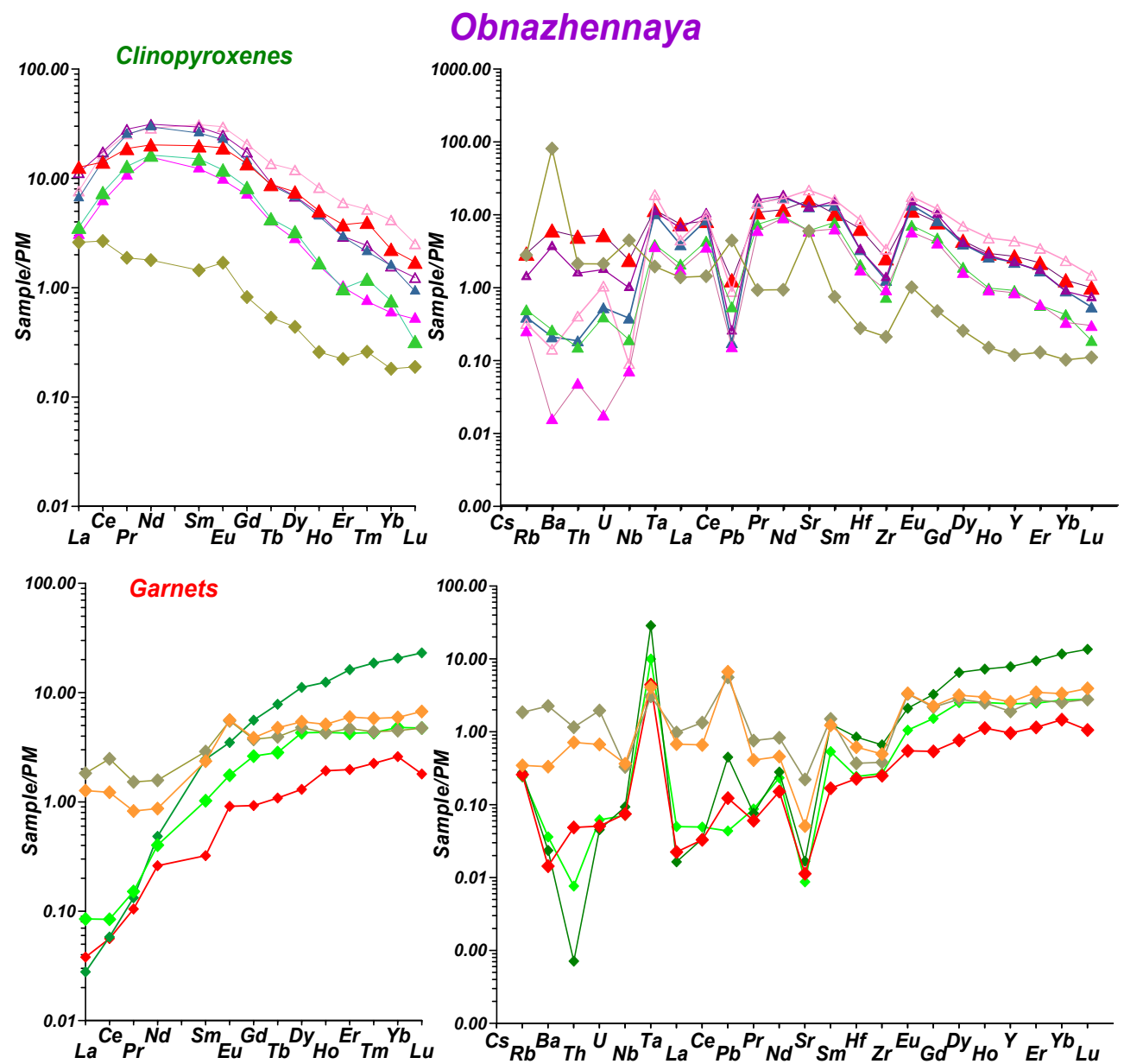


Fig.11. REE patterns and trace elements spider diagrams for garnets and clinopyroxenes from eclogite xenoliths from Obnazhennaya pipe, Siberia.

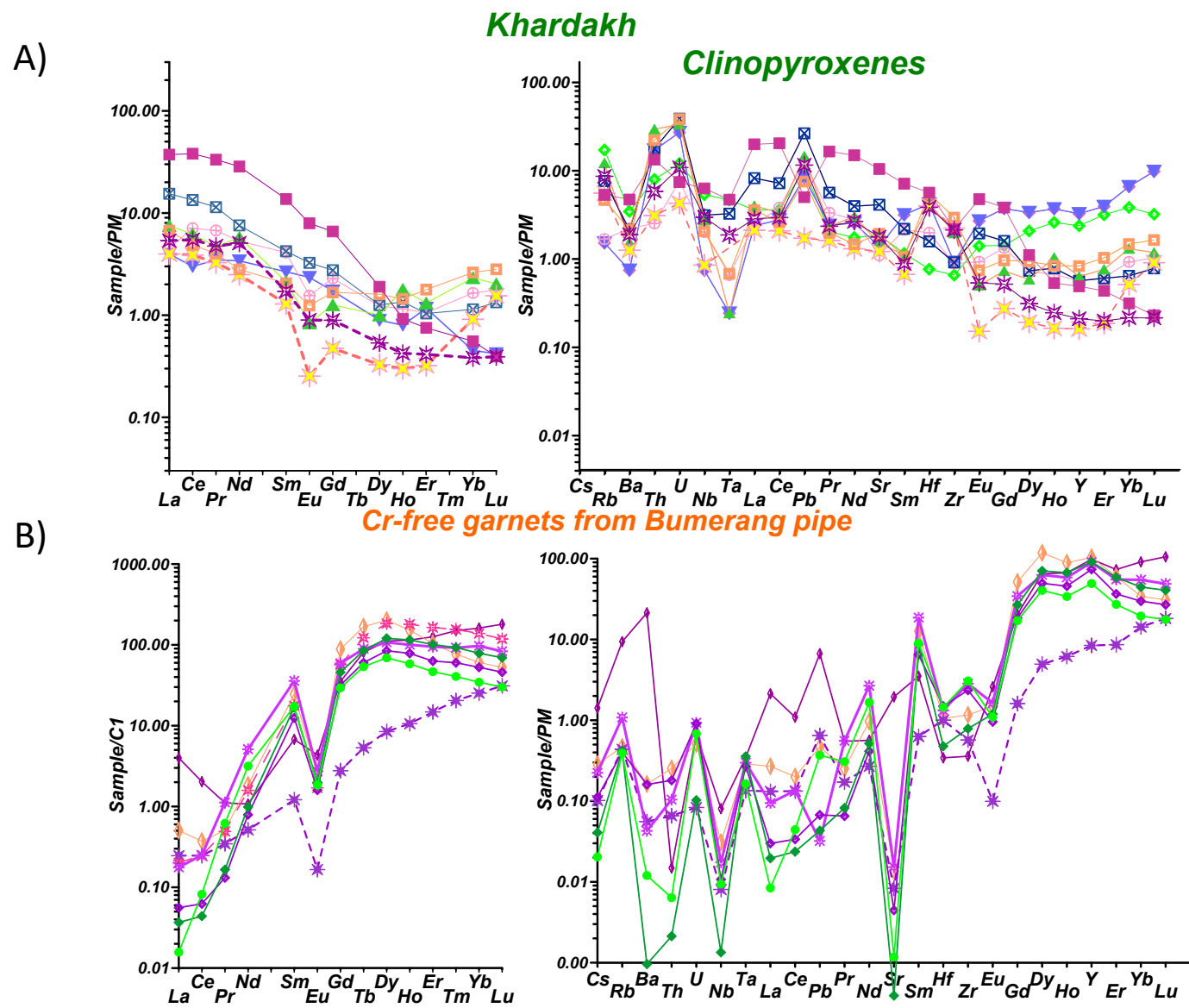


Fig.12. A) REE patterns and trace elements spider diagrams for garnets and clinopyroxenes from omphacite from, Ary - Mastakh field, Siberia

1. Geochemistry of trace elements of studied eclogites.

Trace elements patterns for minerals in eclogites are rather specific for each group and very often there is a dominant type in some of the investigated pipes like Obnazhennaya (Taylor et al., 2003; Sun et al., 2018) or KL4 in Dharwar craton. Compared to the crustal eclogites which reveal often very inflected patterns with decreasing LREE for both clinopyroxenes and garnet (Condie et al., 2004; Bebout, et al., 2007; Xiao et al., 2014), all mantle eclogites show the opposite inclination of the Cpx and garnet patterns regulated by the partition coefficients between cpx, garnet and melt. This supports the data that all mantle eclogites were melted or were subjected to intense fluid influence.

Udachnaya eclogites trace element distributions for pyroxenes and garnets

The most variable of the studied samples are those from Udachnaya pipe (Fig.11, Sf 2). During earlier work (Ashchepkov et al., 2008) a restricted amount of eclogites was analyzed which did not cover all types (Misra et al., 2004; Sobolev & Sobolev, 1993; Sobolev et al., 1994; Snyder et al., 1997; Stepanov et al., 2008; Shatsky et al., 2008; Spetsius et al., 2009). Clinopyroxene from carbonated basaltic eclogites (Gr2) reveals bell-like asymmetric REE patterns with very low incompatible trace elements, a strong Sr and small U peaks, and a trough in Zr; these are probably strongly metasomatized subducted MORB (Fig.10A) (Snyder et al., 1997; Jerde et al., 1993). They differ from the diamond-bearing eclogites (Fig.11B). Low-Cr type A- to B (Spetsius et al., 2009) eclogites also show humped REE patterns which are divided into two groups. Those with lower concentrations have less LREE and show troughs in Nb and Zr, a high peak in Pb and a smaller peak in U. The others have round smooth trace element pattern with small troughs in Pb and Ba.

Diamond-free eclogites show inclined REE patterns with rather high LREE and other incompatible trace elements and a trough in Ba. Those with lower concentrations also show a Zr-Hf trough. Clinopyroxene from the corundum-bearing eclogite shows REE pattern with an inflection in Eu and also a general increase in incompatible elements with a high peak in LILE, a small one in Sr and a trough in Th.

Garnets from Udachnaya eclogites show HREE-enriched patterns with spoon-like LREE patterns, typically resulting from metasomatic processes. Some of them show troughs in both HFSE and Th-Ba, others even have peaks in Zr-Hf and Ta that are controlled by rutiles. Some garnets have depressions in HFSE and incompatible elements except for Sr and could be derived from (or have reacted with) rather primitive mantle melts like undifferentiated protokimberlites.

Obnazhennaya pipe.

Most eclogites from Obnazhennaya are related to the relatively magnesian Cr-bearing group 1 with a minor amount of Gr2 transitional eclogites described by Taylor et al. (2003). They reveal similar asymmetric bell-like REE patterns for clinopyroxenes which are common for partial melts (Fig.12). But the left part of the trace element pattern is mildly depleted or flat. Varieties with lower REE concentrations show Zr troughs typical for H₂O-bearing melts and a trough at Pb because of separation of sulfides which are abundant in eclogites. Omphacite from a corundum-bearing eclogite (Fig.12 marked by rhombs) reveals a pattern with an inflection in Eu and lower HREE relative to a similar sample from Udachnaya. It also reveals high peaks in Ba and Sr but Hf-Zr troughs and higher enrichment in LREE.

Most garnets have rounded trace element patterns with high HREE, low LREE, a peak typically at Pb and a Sr trough. The incompatible elements in general repeat the tendencies of pyroxenes. Garnets from corundum eclogites display greater REE enrichment.

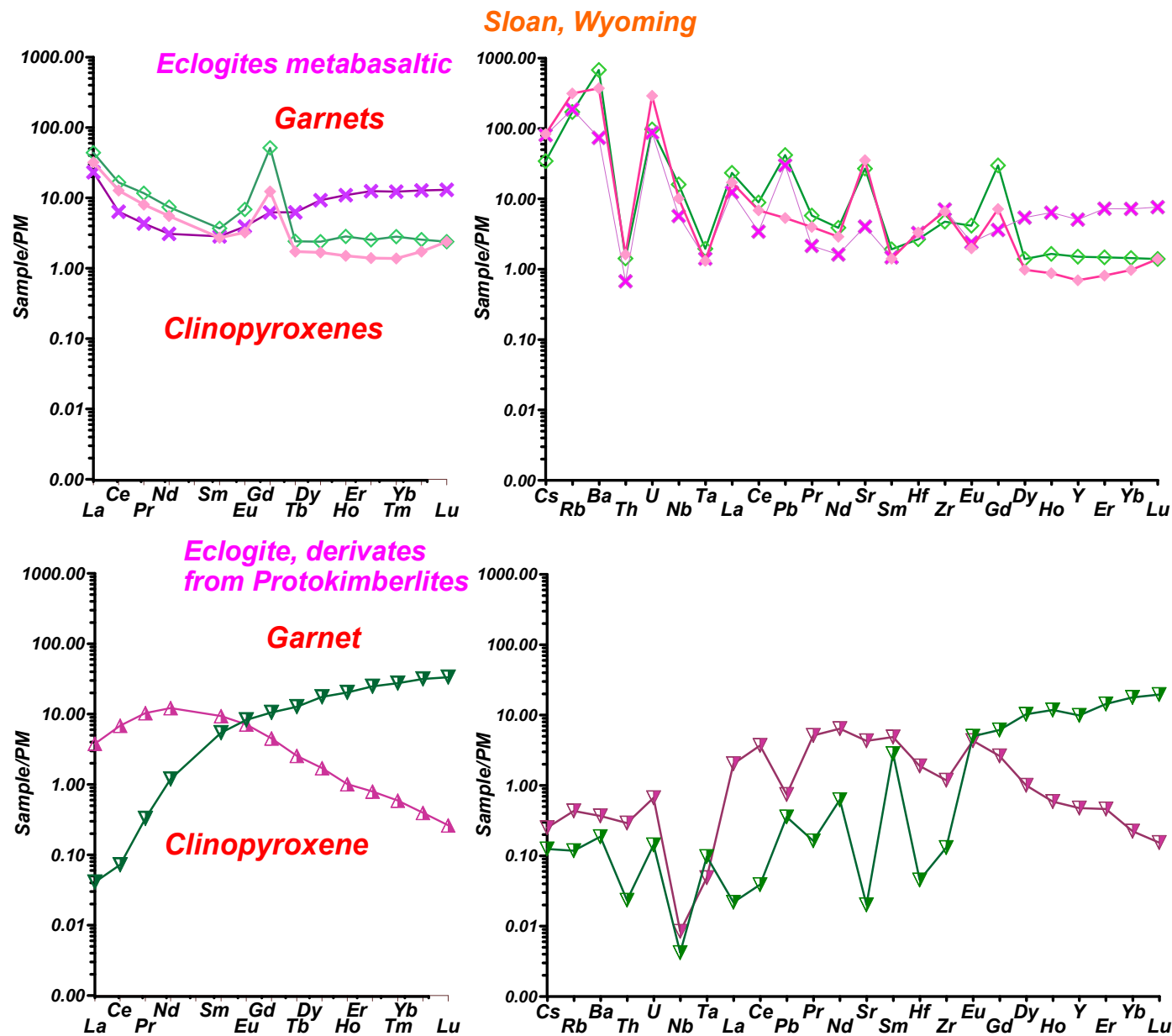


Fig.13. REE patterns and trace elements spider diagrams for garnets and clinopyroxenes from eclogite xenoliths from Sloan pipe, Wyoming craton, USA.

India, Wajrakarur, K14

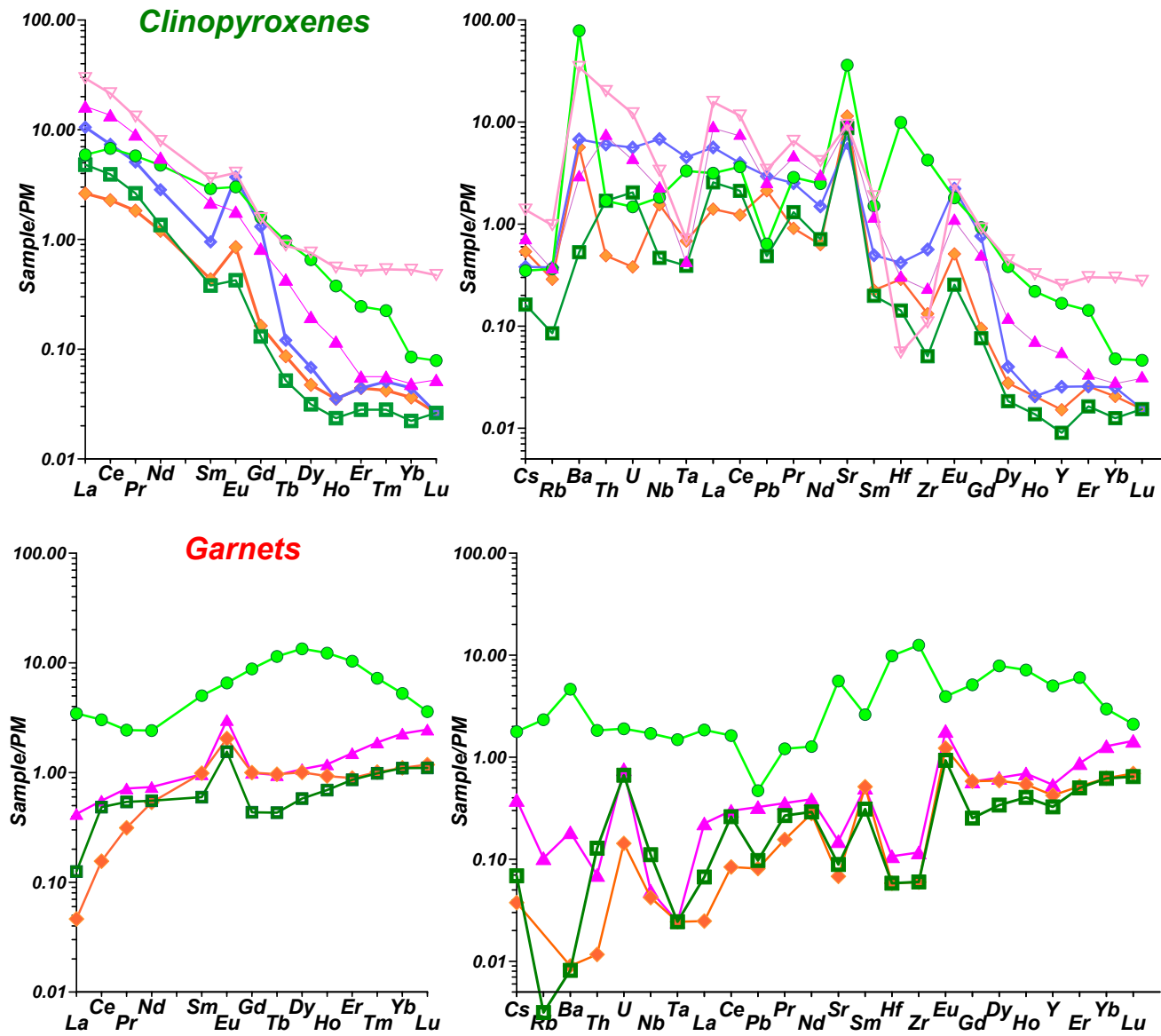


Fig.14. REE patterns and trace elements spider diagrams for garnets and clinopyroxenes from eclogite xenoliths from K14 pipe Dharwar craton, India.

Kharamai and Ary Mastakh field.

The only Mg-rich eclogite from this locality shows an inclined W-shaped REE pattern consisting of two branches, divided by the Eu minimum. The spider diagram shows a smooth pattern, with increasing content of incompatible elements, a peak in Pb and a small trough at Nb (Fig. 12A). The Fe-rich but low-Na “pyroxenitic” eclogites also show inclined sometimes W-shaped REE patterns typical of plagioclase. But the spider diagram displays rather strange enrichment in all HFS elements (Fig. 12B).

Wyoming craton, Sloan pipe

One type of omphacite from the Sloan pipe displays a high Eu peak and has high concentrations of LILE and U, Sr and Pb and deep troughs at Th and Nb, which suggest an origin from a silicic plagioclase-bearing protolith (Fig.13A). One strange clinopyroxene with a flattened spoon-like REE pattern has a spider diagram very similar to previous types.

Some eclogites display common rounded patterns for garnets and clinopyroxene without Eu anomalies. Spider diagrams for clinopyroxene are also rounded with common negative anomalies in HFSE, deeper for Nb, Ta and Pb. Spiderdiagrams for garnets show lower HFSE troughs and a Pb peak (Fig.13B).

Dharwar craton, Wajrakarur field, Kl-4 pipe.

Trace elements for eclogitic Cpx from India reveal mostly similar REE patterns and spider diagrams, with high La/Yb_n ratios, Eu peaks and flattened HREE. This proves that the kyanite-bearing eclogites and grospydites are cogenetic. The Cr-bearing Ca-rich eclogites indicate either interaction of peridotitic mantle with carbonate fluids or that carbonatite melt reacted with enriched material of former eclogites (Fig.14). The most Mg- and Cr-rich varieties have lower trace element concentrations, a smaller Eu trough and a Ba peak. Clinopyroxene from the grospydite has the most enriched REE pattern but is depleted in general in incompatible elements except for a very strong peak in Ba. Garnet REE are not equilibrated and highly inclined. Spider diagrams for garnets show a U peak but are low in Sr. They show depletion in HFSE (Ta>Nb), the most depleted sample displays a deep Y trough. For the other Cpx, peaks in both Ba and Sr are typical.

Melts in equilibrium with clinopyroxenes

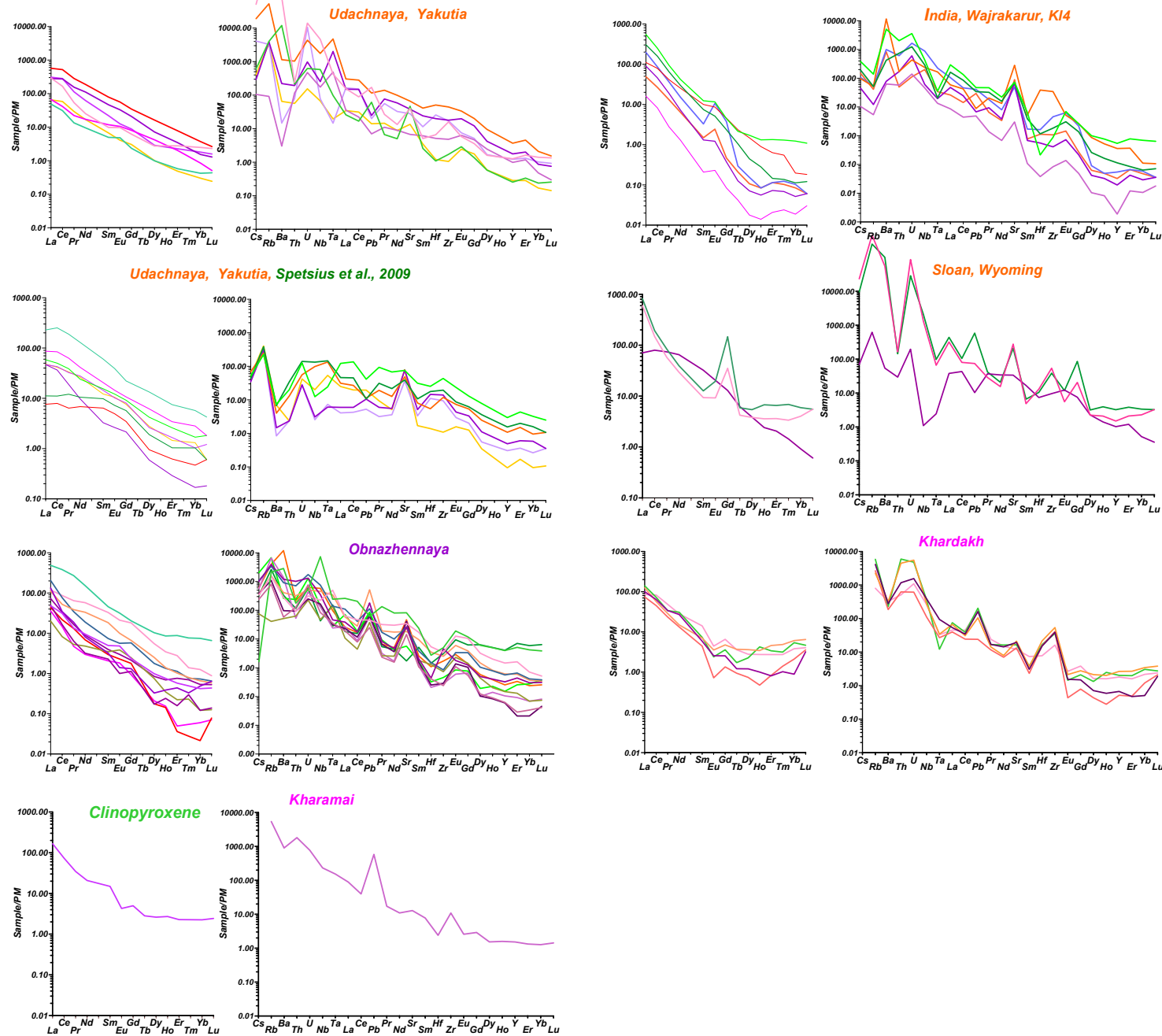


Fig.15. REE patterns and trace elements spider diagrams for the melts parental for the clinopyroxenes from eclogites xenoliths from different cratons.

Conclusions.

1. Eclogite thermobarometry for clinopyroxenes and garnets allows us to determine the position of eclogites in mantle sections beneath kimberlite pipes in some detail, showing high-T conditions for protokimberlite-related and melt-metasomatized eclogites and low-T for subducted eclogites.
2. Most eclogites have been remelted during subduction and later plume events.
3. The division of the sub-cratonic mantle lithosphere into an upper and lower part is probably marked by the presence of Fe-rich eclogites.
4. Ca-rich kyanite eclogites are common in the middle part of SCLM in the Precambrian kimberlites and became more frequent in the LSCLM beneath Phanerozoic kimberlites.
5. Different group of eclogites commonly have individual positions and geothermal gradients in the mantle section beneath kimberlites from different cratons and terranes.
6. Trace elements for Fe-rich and high-Ca eclogites commonly demonstrate their derivation from a silicic LILE-enriched substrate. MORB basalt-like protoliths show derivation from a HFSE- and LILE-depleted source. Common type B (metabasaltic) protoliths show the strong influence of volatile-rich melts and fluid produced by different types of magmatic differentiation. MgO-rich eclogites show Nb anomalies and participation of rutile in the source rocks.

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