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Composition and origin of kelyphitic rims around garnets in fresh sheared lherzolite from the Udachnaya-East kimberlite pipe, the Siberian Craton

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2020 May

SEM-EDS

Tescan Mira 3 LMU scanning electron microscope equipped with an Aztec Energy X-Max 50+

For mineral grains with size <6 μm

Parameters

10 keV, 1.440 nA, 90 sec of accumulation

For bulk analyses of the kelyphite

Parameters

Rastering the electron beam over a 50-200 μm surface, 20 keV, 1.440 nA, 90 sec of accumulation

EPMA

Jeol JXA-8230

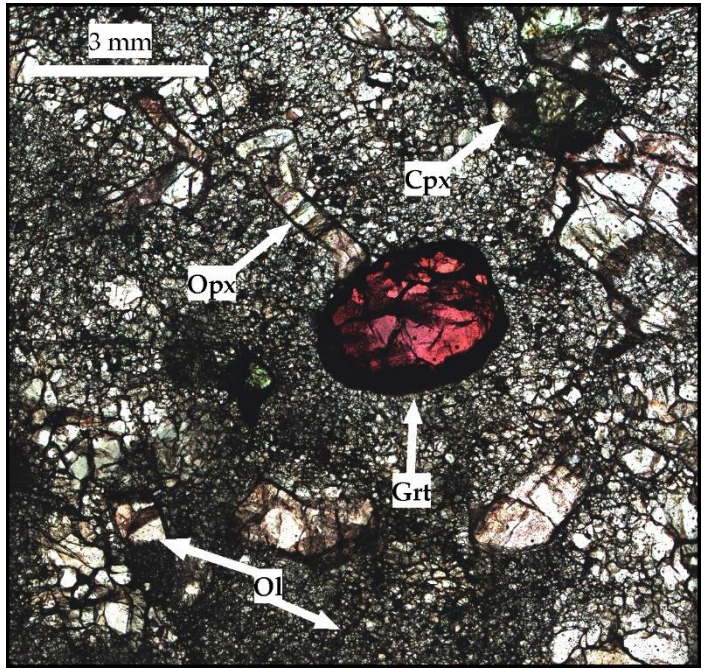
For mineral grains with size >6 μm

Parameters

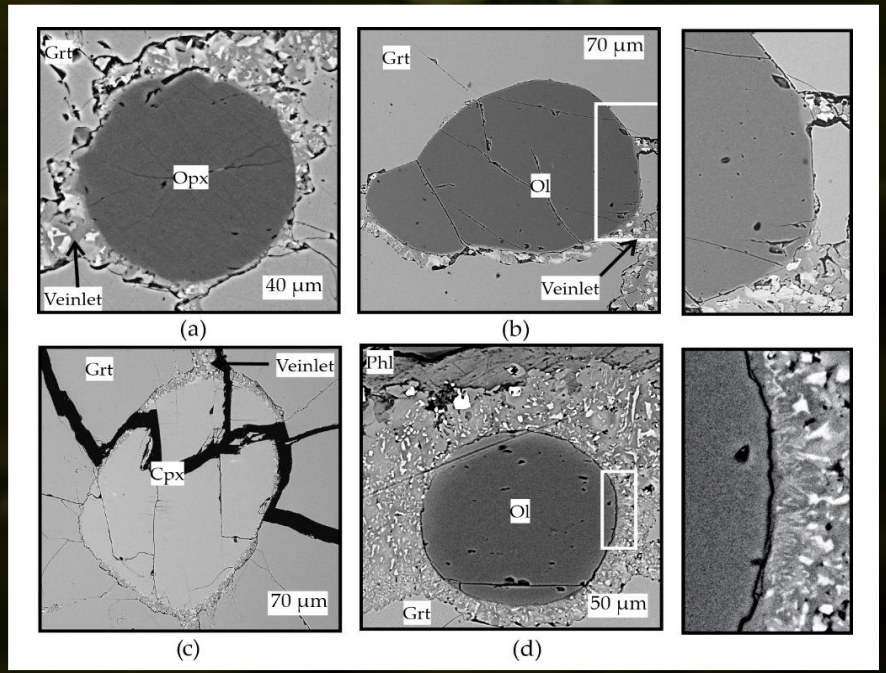
15 keV, 100 nA, 1 μm beam, 20 sec for peak and 10 sec for background

Sample description

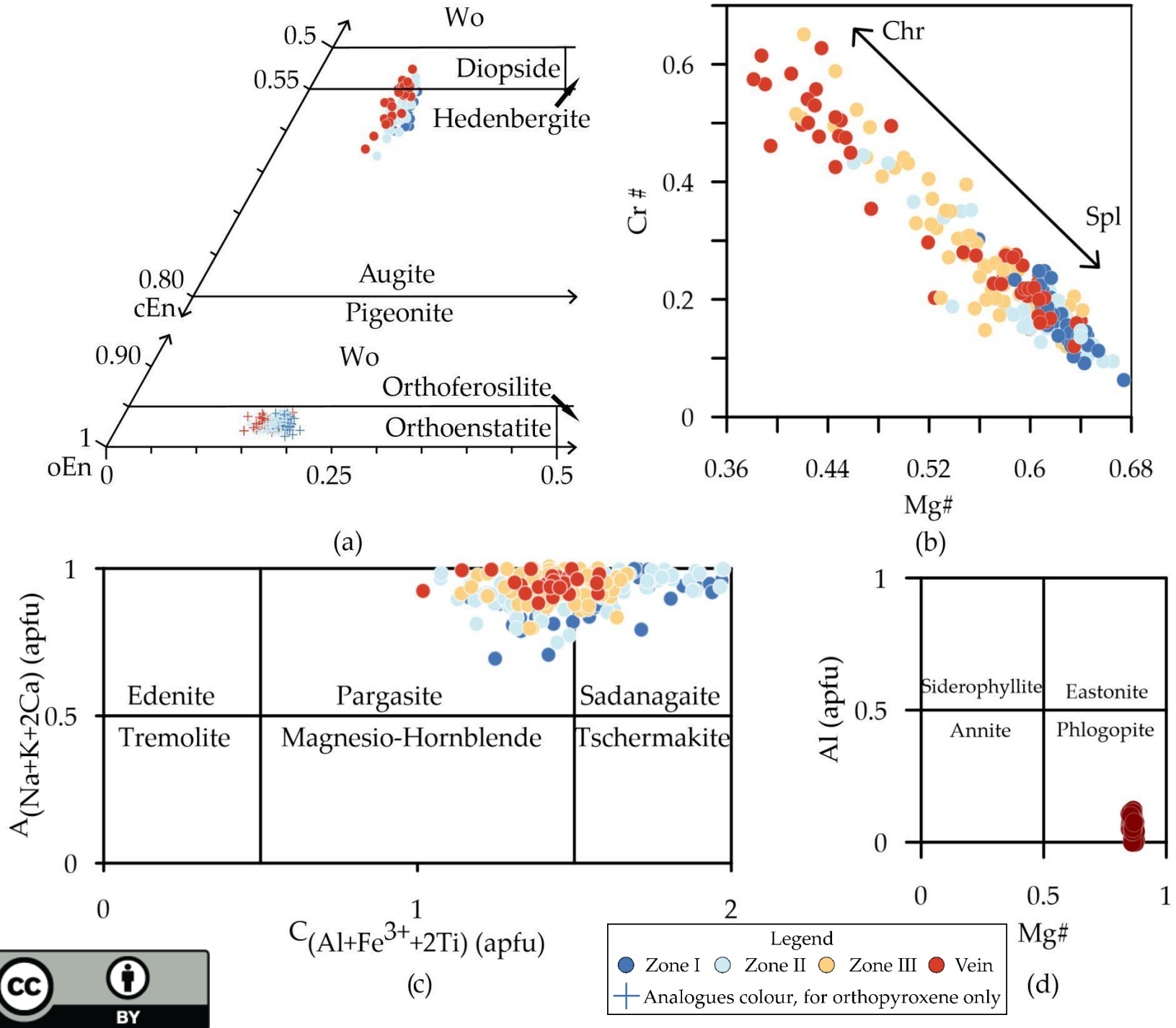
Sheared lherzolite with mosaic-porphyroclastic texture (UV-3/05) from the Udachnaya-East kimberlite has been studied. P-T conditions of equilibration of the xenolith in the mantle are estimated as 63.9 kbar and 1352°C, which correspond to ~ 200 km depth.



The kelyphite has several Zones. Zone I consists of intergrown micron grains of spinel, orthopyroxene, amphibole, and clinopyroxene (b and d). Zone II is represented by micron-sized orthopyroxene and amphibole are associated with submicron-sized spinel (b, c, and d). Zone III is made up of aggregates of amphibole, spinel grains and phlogopite (c). Veinlets in garnets has the same structure and composition (e and f).



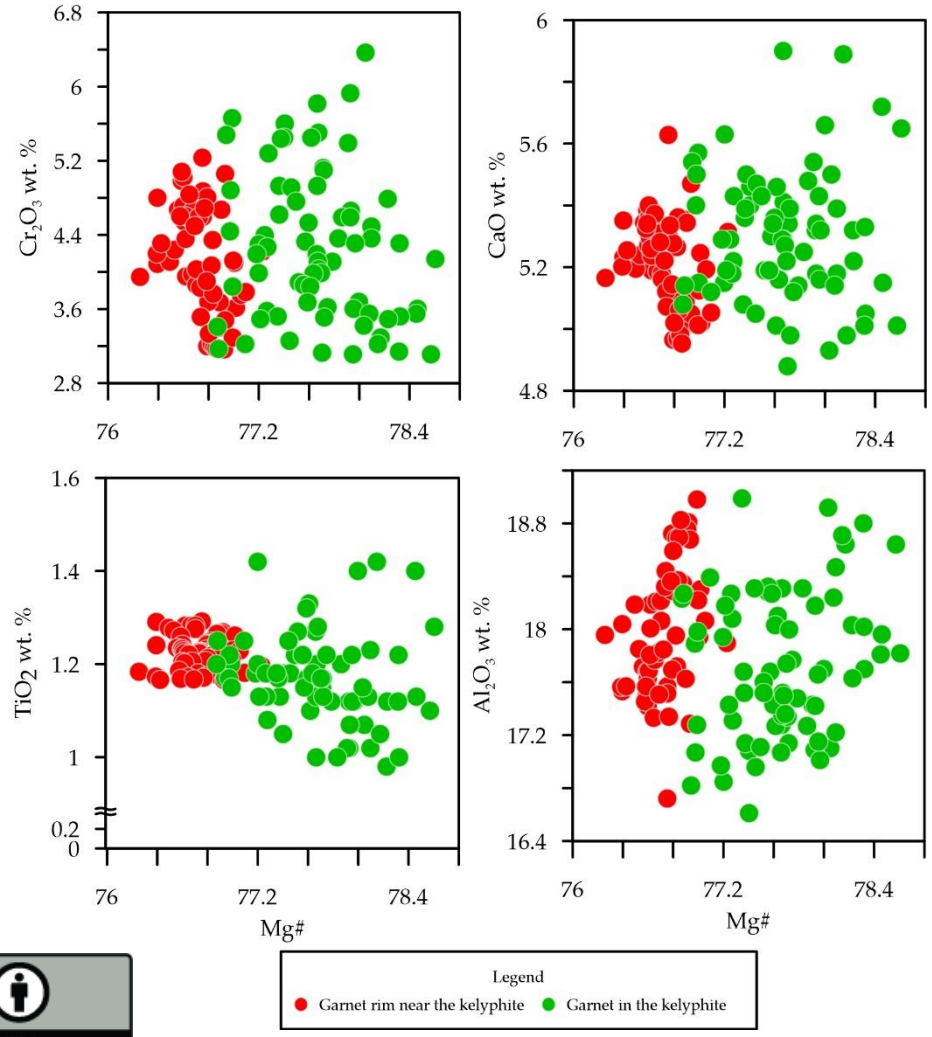
The kelyphite is not formed on the boundary between garnet and its inclusions of pyroxenes and olivine, except case when the veinlets travers the inclusions.

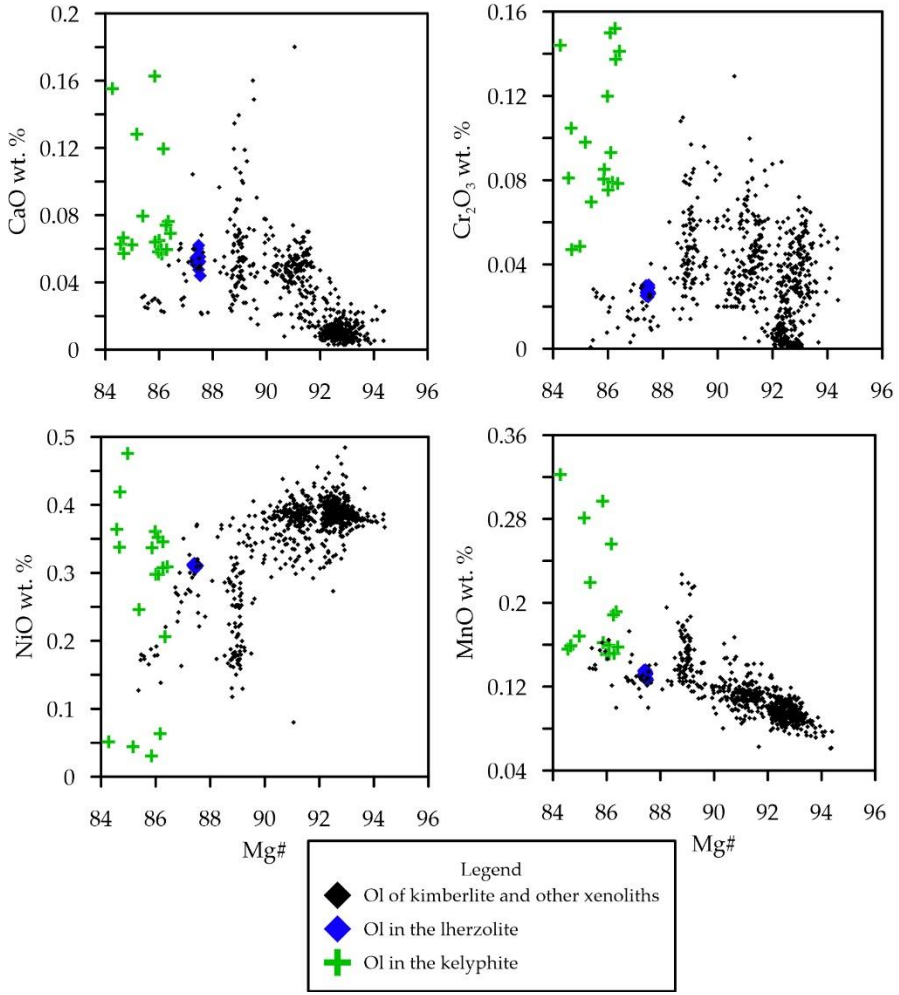


Compositions pyroxenes (a), spinel (b), amphibole (c) and mica (d) from the kelyphitic rims.
Nomenclature of minerals
a) Pyroxenes [Morimoto, N., 1988], b) spinel [Bosi, F. et al., 2019], c) amphibole [Hawthorne, F.C. et al., 2012], d) mica [Rieder, M. et al., 1998].

Spinel has the widest range of Cr#. As can be seen in the figure b, first, maximum value of Cr# is decreasing from Zone III to Zone I (toward garnet interface), second Cr# interval of Zone III include Cr# interval of Zone II, which include Cr# interval of Zone I. Width of Cr# interval of veinlets is equal to this of Zone III.

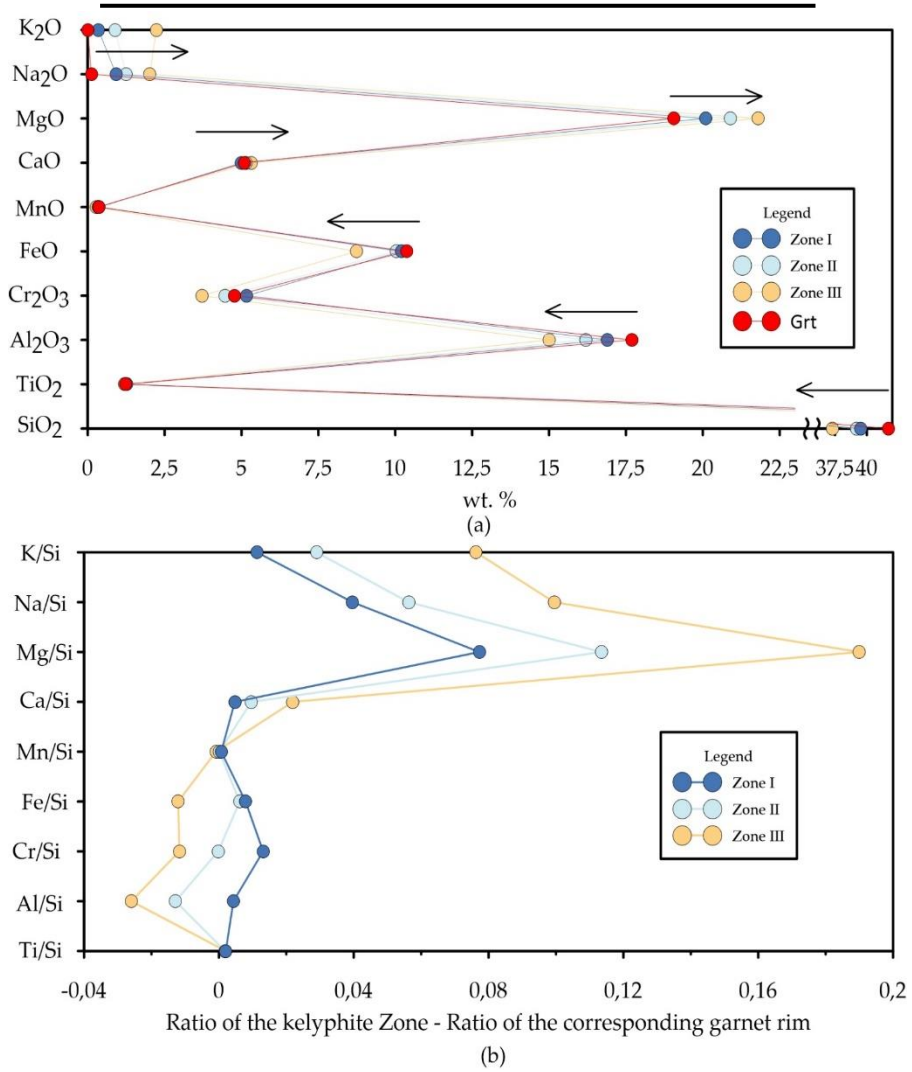
Relics of garnet grains in the kelyphite has equal composition as the corresponding garnet rims besides Mg#.

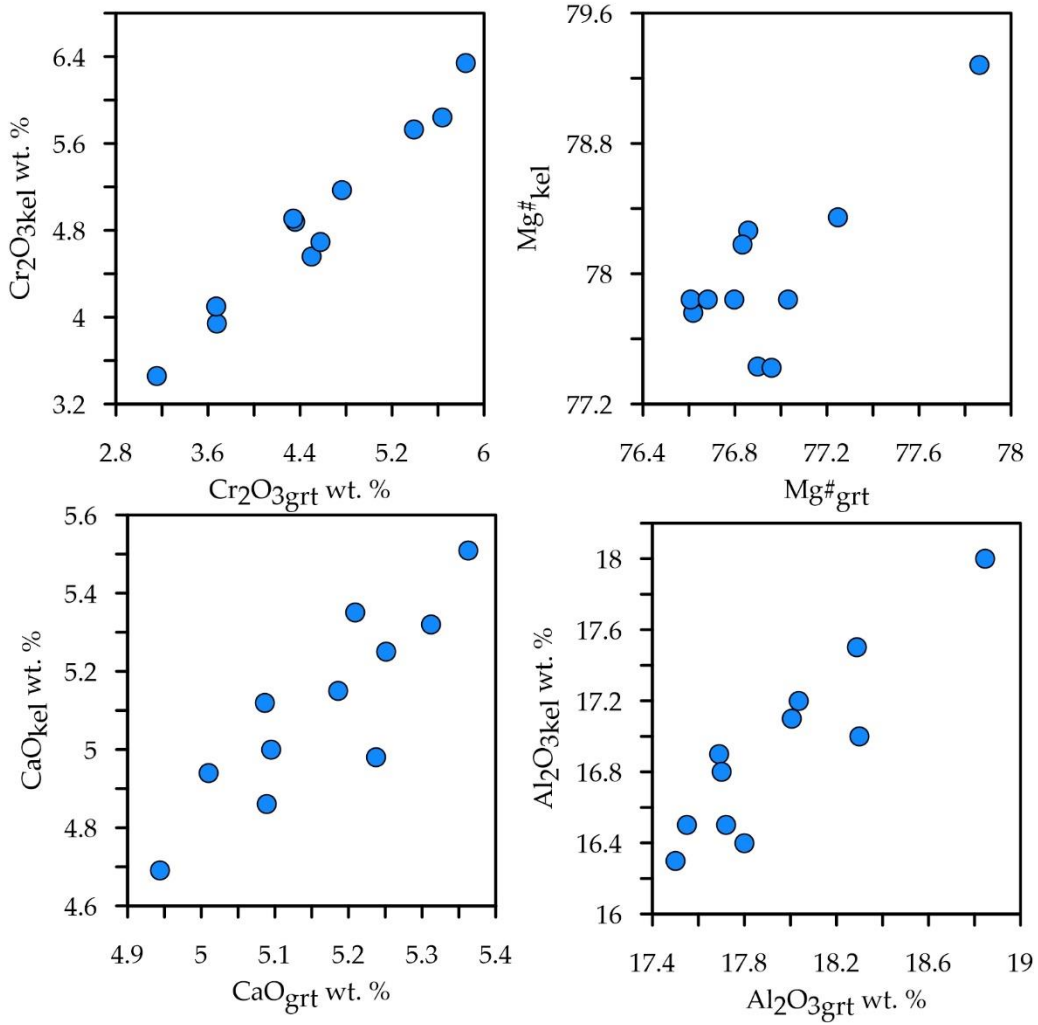




Relics of olivine grains in the kelyphite and in the lherzolite have different compositions. Olivine in lherzolite and isolated inclusion of olivine in garnet have the same composition.

Bulk compositions of the kelyphite Zones (a) show that bulk composition of Zone I (near the garnet) is very similar to garnet rim composition. Graph of normalized atomic ratios of the Zones to those of the corresponding garnet rims (b) yield us information about real changes of element values in respect to Si.





Correlations between composition of the garnet rims and the corresponding Zone I. Ca, Cr, and Al of Zone I are correlated with those of garnet rim, whereas Mg# not.

Mass-balanced reactions

Si is chosen as a reference frame and bulk composition of the kelyphite is considered as garnet rim plus/minus some values of different components.
Normalized ratio Al/Si of the Zone I is zero (previous slide), so we can assume no differential movement of Si and Al in Zone I. So, it is reliable reason to choose Si as a reference frame.
Reactions below is written for the particular area of the kelyphite and garnet rim (slide 2, figure b).

$$100Grt + 0.11TiO_2 + 0.2Al_2O_3 + 0.69Cr_2O_3 + 0.39FeO + 0.03\mathrm{MnO} + 0.18\mathrm{CaO} + 2.2\mathrm{MgO} + 0.85Na_2\mathrm{O} + 0.37K_2\mathrm{O} + 0.2(F, Cl, H_2O) \rightarrow 105.1\mathrm{Zone\ I}$$

$$100Grt + 0.10TiO_2 + 0.31FeO + 0.01\mathrm{Mn} + 0.37\mathrm{Ca} + 3.2\mathrm{Mg} + 1.21Na_2\mathrm{O} + 0.94K_2\mathrm{O} + 0.3(F, Cl, H_2O) \rightarrow 105.5\mathrm{Zone\ II} + 0.5Al_2O_3$$

$$100Grt + 0.11TiO_2 + 0.85\mathrm{Ca} + 5.3\mathrm{Mg} + 2.13Na_2\mathrm{O} + 2.48K_2\mathrm{O} + 2.4(F, Cl, H_2O) \rightarrow 109.2\mathrm{Zone\ III} + 0.9Al_2O_3 + 0.62Cr_2O_3 + 0.60FeO + 0.04\mathrm{MnO}$$

After skipping values being comparable with error and summing.

$$300Grt + 1.4CaO + 10.6\mathrm{MgO} + 4.2Na_2\mathrm{O} + 3.8K_2\mathrm{O} + 3.2(F, Cl, H_2O) \rightarrow 105\mathrm{ZoneI} + 106ZoneII + 109ZoneIII + 1.2Al_2O_3$$

In total, there are gains of CaO, MgO, Na_2O, K_2O, F, Cl, H2O and lose of Al_2O_3. Due to these reaction interesting behave of Cr_2O_3 is revealed. Cr_2O_3 is a constant for the kelyphite at all, but there is flow of Cr_2O_3 from Zone III to Zone I. It leads to higher Cr# of Zone I in respect to garnet rim.

ALL PREVIOUS HYPOTHESES ABOUT THE KELYPHITE ORIGIN AROUND GARNET OF THE XENOLITHS FROM KIMBERLITE

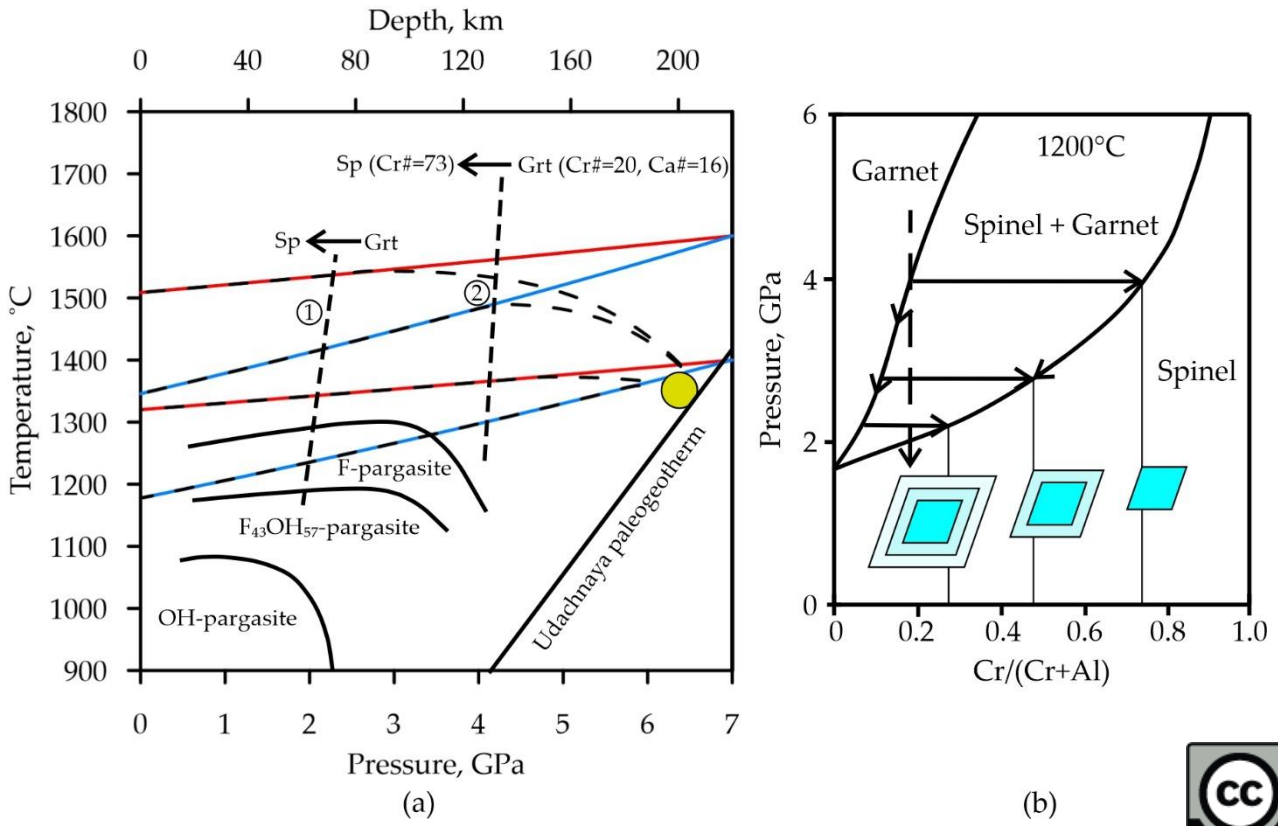
ORIGINS

Formation during the kimberlite magma ascent

1) an isochemical retrograde reaction between garnet and olivine during the ascent followed by hydration reactions between the former mineral association and alkali-H_2O rich fluid exsolved from kimberlite melt [e.g., Franz, L. et al., 1996].
2) a reaction between garnet and fluid (H_2O or alkali-H_2O rich) exsolved from kimberlite melt percolating into the xenolith during the ascent [e.g., Vishnevsky, A.A., 1991].
3) a reaction between garnet and kimberlite melt percolating into the xenolith during the ascent [e.g., Sharygin, I.S., 2014].

Due to mantle metasomatism

1) mantle metasomatism *in situ* [e.g., Spetsius, Z.V.&Taylor, L.A., 1982].
2) a formation in the upper mantle *in situ* followed by a transformation of the previous assemblage with a replacement of spinel by magnetite, silicate minerals by phlogopite under influence of kimberlite melt [e.g., Pokhilenko, L., 2019].



a) The P-T-paths of the lherzolite and kimberlite melt. Thermal properties of the lherzolite and kimberlite melt from [Miao, S. et al., 2014 and 2019; Liu, T.L. et al., 2017]. Calculated magma paths are for assumed carbonatitic (blue) and basaltic composition (red) (after [Kavanagh, J.L&Sparks, R.S-J., 2009]. Calculations are given for two cases: hot and cold source of kimberlite magma. The yellow filled circle is the position of the xenolith prior to the entrainment. Line 1 is a line of first appearance of spinel in lherzolite system without Cr, whereas line 2 is a line of first appearance of spinel in lherzolite system with Cr#=0.2 and Ca#=14 [Grutter, H. et al., 2006; Girnis, A.V.& Brey, G.P., 1999; Nickel, K.G., 1986; O'Neill, H.S.C., 1981].

b) Stability of garnet and spinel in the CMAS-Cr system (Ca#=14). Vertical line is the maximum Cr# of the garnet rims (Cr#=0.2). Scheme for growth of spinel grains is shown [Grutter, H. et al., 2006].

First spinel occurs at least at 120 km (4 GPa), and pargasite and phlogopite form near the surface (figure a). Hence, we can conclude that mantle metasomatism group of hypotheses of the kelyphite origin is not acceptable.

Source of components for pargasite and phlogopite can be kimberlite melt or fluid form the melt. We believe that it was kimberlite melt, because garnets are traversed by the veinlets which has the same max Cr# of spinel. So, the veinlets began to from at the same time with the kelyphite. Due to [Sharygin, I.S. et al., 2017], fluid from kimberlite melt cannot exsolved at pressure greater than 3 GPa (first spinel formed at 4 GPa). So, the kelyphite formed in the presence of kimberlite melt.

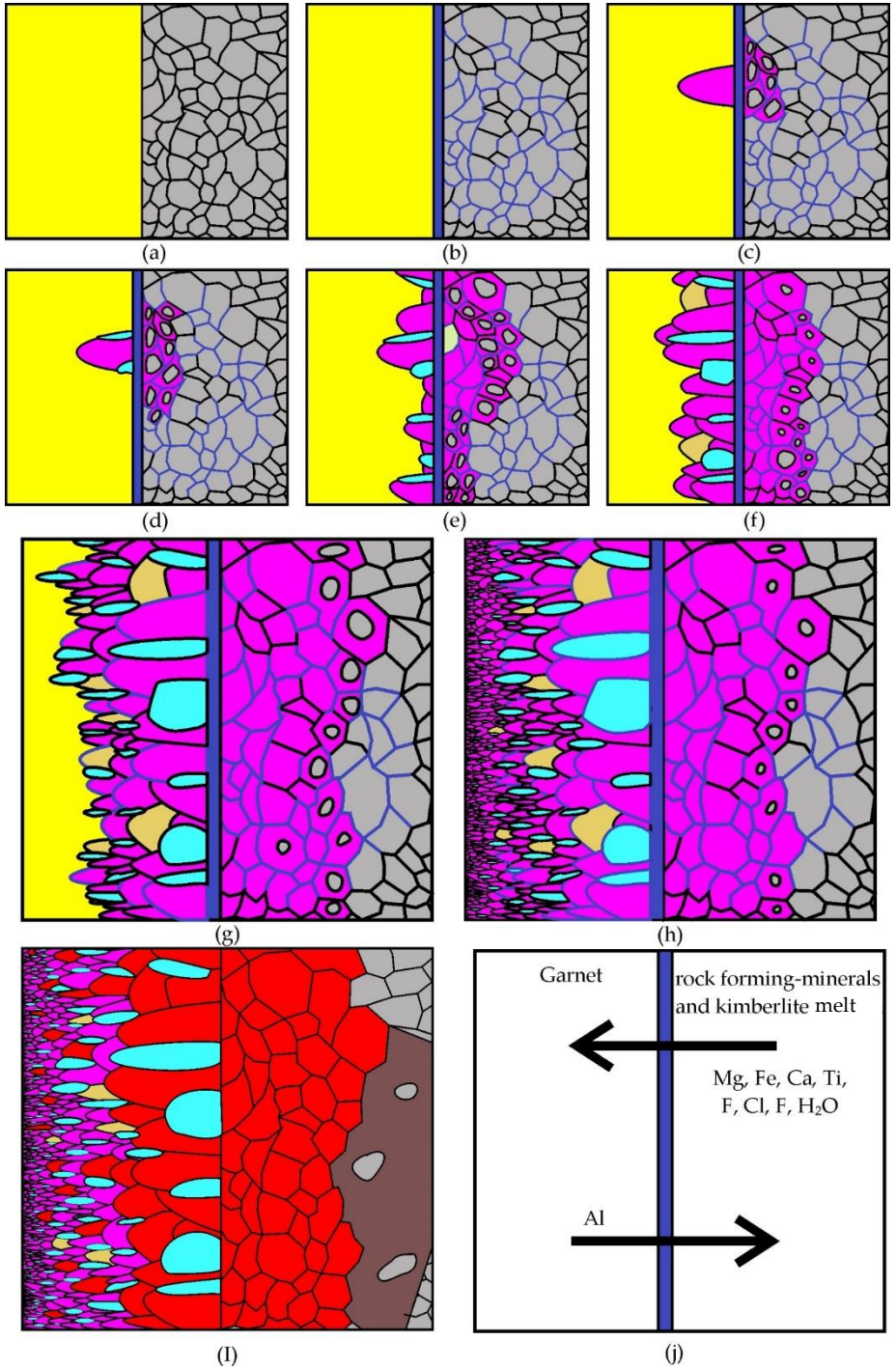
Decreasing of max Cr# of spinel from Zone III to Zone I suggests that kelyphite was forming throughout the ascent of kimberlite magma. Width of spinel Cr# interval indicates that Zone III was forming when Zone I began to form, and that Zone II was forming when Zone I began to form.

Olivine relics in that kelyphite which compositions is not equal to olivine lherzolite assume that olivine was reactant. However, it can be also a product.

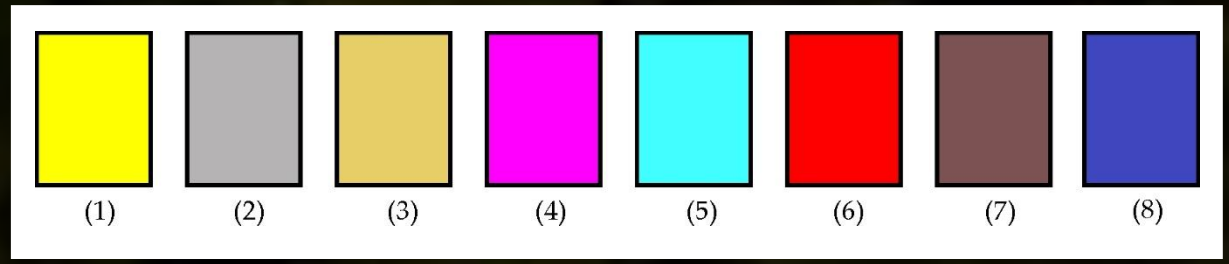
Absence of the kelyphite on the boundary of isolated from the veinlets inclusions in garnets gives evidence that without kimberlite melt formation of the kelyphite do not take place.

STEPS OF KELYPHITE FORMATION

a) before entrainment
b) melt infiltration
c) beginning of reaction between garnet and olivine
d) first spinel grain occur
e) – f) formation of Zone III
g) formation of Zone II
h) formation of Zone I
i) alteration of kelyphite by the kimberlite melt
j) general schematic direction of migration of elements during the kelyphite formation



It was very possible that absolute concentration of Si was not a constant, but as we choose Si as a reference frame, Si do not show in the figure j.



1 is garnet; 2 is olivine, 3 is clinopyroxene, 4 is orthopyroxene; 5 is spinel; 6 is amphibole, 7 is phlogopite, 8 is kimberlite melt.

CONCLUSION REMARKS

1) The kelyphite forms as result of the reaction among garnet, kimberlite melt, and, possibly, rock-forming minerals (olivine and pyroxenes) during the kimberlite magma ascent.

2) Such genesis give us possibility to estimate of composition of kimberlite melt before the eruption.

3) Given this we can use mass-balanced reactions for estimation of ratios of elements which was extracted from the kimberlite melt. For example, Na:K:Ca is about 57:32:11. It is almost equal to estimation using inclusions in olivine made by [Golovin, A.V. et al., 2019].

THANK YOU FOR YOUR ATTENTION