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MAGMATOGENE AND VOLCANOGENIC FACTORS OF KIMBERLITE DIAMOND POTENTIAL

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Petrochemical features of kimberlites from ten Yakut pipes (deposits) with industrial diamond content are described: Internatsionalnaya and Mir – in the Mirnyi field, Botuobinskaya, Maiskaya and Nyurbinskaya – in the Nakyn field, Aykhal, Yubileinaya and Sytykanskaya – in the Alakit-Markha field, Udachnaya-West and Udachnaya-East – in the Daldyn field. Representative geological samples have been selected exclusively from the core of prospecting wells (331 wells, the total length of the studied core column – 88 082 m, maximum depth of sampling – 1 359 m). We used 7 114 chemical analyzes of rocks from diamond deposits, data on the average composition of 83 kimberlite bodies of the studied kimberlite fields, and 1 992 definitions of diamond content (data received by employees of "ALROSA"-company due to the averaging of 6–10-meter intervals of core from prospecting wells). Using all available data the population petrochemical model of kimberlite formation has been established, for which the petrological model of diamondiferous kimberlites of Yakutia has been proposed. It is concluded that the diversity of the material composition and diamond content of rocks is due to the depth of magmatic chamber. At the volcanic stage the chemical composition of rocks is also influenced by xenoliths of host rocks that cause viscosity differentiation of melts.

Key words: kimberlite, chemical composition, population petrochemical model of kimberlite formation, diamond content, petrological model, Yakutia.

Until recently the science related to kimberlites dealt mainly with their accessory minerals, with the diamond standing number one among them. Diamond, garnet and other accessories in kimberlite rocks are well differentiated crystallographically, are easy to extract and identify due to their well-developed crystallographic forms. It seems that the Nature itself has done a favour to the researchers by preparing the items to study. Diamond bearing rocks, kimberlites, are on the contrary formed by a mixture of primary magmatic minerals, products of their post-magmatic transformations, and numerous mantle and crust xenoliths. These rocks are hard to study, and do not offer easy solutions in defining the targets, the study of which could facilitate elaboration of a petrologic judgment.

The above situation was recorded when from a number of genetic hypotheses of diamond formation there was distinguished the xenogenic one, shared by many scientists. This hypothesis turned into the paradigm of the diamond genesis. Its most clear definition is given in the

work of L. Taylor et al.: "Most diamonds are extracted from kimberlites, but this fact reflects merely the way of diamond transportation to the surface. The mantle rocks that actually generate diamonds (peridotites and eclogites) were mostly degraded by the turbulent flow of the fluid in kimberlite magma to release diamonds." [15, p. 960]. But what are kimberlites? As an answer to this question there usually follows the description of the mineral composition, its textural and structural features, the appearance of the rocks, many of these attributes we have already considered in one of our publications [13].

Nevertheless, from the above considerations it does not follow that the kimberlite petrology is absolutely not investigated. A number of research papers written by academicians N. Sobolev, N. Pokhilenko and their colleagues [4, 9–11] dedicated to studying kimberlite minerals provided essential results in exploring the conditions of minerogenesis, mineralogical factors associated with diamond content, as well as in studying the diamond proper. But there still remain a lot of open questions in the theory of genesis and evolution of kimberlites and their accessories, that can be resolved by comparing the quantities of rock forming and accessory minerals for the kimberlites developed under different conditions.

The best solutions for these tasks are found through the study of the elemental composition of the rocks. The established procedure of exploring kimberlites with the use of high throughput methods of chemical analysis helped the authors of this publication to obtain a large number of databases of kimberlite silicate analysis. Processing of a large body of empirical data was made feasible due to the efficient systems concept combined with mathematical statistics.

The systems concept proceeds from the provision that any geologic object with respect to its chemical elements content is markedly delimited from the others and consists of discrete parts, which compositions change in some way distinctive of all the objects of this species. In magmatic rock formations the presence of sharp discontinuities in compositions, e.g. different phases, is accounted for by the fact, that fractional (selective) melting of the mixture of mantle minerals with the heat inflow falls into a number of discrete stages. At each stage there melts the next by temperature mineral cotectic, which determines the discontinuity of particular fractioned portions of the melt, and the variability direction in some melts to follow. In some magmatic formations homogeneous rock groups are visually detected, while in others they can be detected only with the help of mathematical statistic methods. This seems especially important for mapping separate intrusive bodies, where the systems concept, the so-called petrochemical population analysis [1] demonstrated a rather good efficiency. In the formation analysis of magmatic complexes the items under study are separate magmatic massifs and their mean compositions. There is no problem to identify the target of study, but difficulties appear when one tries to provide a reliable description of these objects.

The best efficiency seems to be reached through the combination of a petrochemical population analysis with a statistical description of well visualized magmatic complexes. The present paper studies chemical compositions and the diamond potential of the Yakutian diamondiferous deposits.

Targets of research. Subject to petrochemical description are ten diamond deposits, i.e. ten kimberlite pipes with industrial diamond contents. These are the pipes in the Mirnyi field: Internatsionalnaya and Mir; in the Nakyn field: Botuobinskaya, Maiskaya and Nyurbinskaya; in the Alakit-Markha field: Aykhal, Yubileinaya and Sytykanskaya; in the Daldyn field: Udachnaya-West and Udachnaya-East. Geological samples were taken only from the diamond drill cores. Totally there were studied samples from 331 drill holes, the overall length of the studied core intervals made 88 082 m, the maximum sample depth was 1 359 m, the total num-

ber of chemical analyses of the samples made from diamond deposits amounted to 7 114. In addition there were used mean compositions of 83 kimberlite bodies, located within the margins of the investigated kimberlite fields. The data on the diamond potential of kimberlites was obtained by the research staff of AC "Alrosa" with mean values of 6–10 m drill core intervals. All in all we used 1 992 definitions of the diamond potential. It is worthwhile to mention that the diamond potential of kimberlite deposits was characterized only by the values that were at our disposal. These data do not characterize the deposit reserves.

Preparation of analytical samples consisted in their crushing, removal of mantle and crustal xenoliths, and a further desintegration. The sample analyses were carried out at a VRA 20R X-ray fluorescent analyzer by the same analytical group. The measurement accuracy was under a permanent internal and external control. The statistical description of the chemical elements concentration distribution in mountain rocks has specific features. These include the asymmetry and polymodality of empirical distributions and remain the basic factor hindering the statistical description of chemical elements distributions in geological objects.

Random value distribution models are important for statistical research as a technique of universe estimates of chemical elements content by limited sampling. In the absence of a correct methodological technique standard base, one has to increase the number of surveys for the described objects and using the systems concept to divide them into a number of subpopulations.

This strategy is based on the law of large numbers, which provisions will be cited here in the interpretation of Harold Cramer. When clarifying the law, H. Cramer [3] mentioned in the section "Statistical stability", that "In a sequence of random experiments, it is not possible to predict individual results. These are subject to irregular random fluctuations which cannot be submitted to exact calculation.

However, as soon as we turn our attention from the individual experiments to the whole sequence of experiments, the situation changes completely, and an extremely important phenomenon appears: In spite of the irregular behaviour of individual results, the average results of long sequences of random experiments show a striking regularity" (p. 162). The high accuracy and high throughput analytical equipment, available for the description and classification of geological objects, that furnished a huge amount of sample materials at an affordable price, helped the authors to realize this strategy. As a result, we managed to build such a complicated petrochemical model, as the kimberlite one, as well as of some other formations.

Magmatogene factors. A homogeneous (indivisible) in the petrochemical respect geological object should be characterized by unimodal frequency distributions of rock-forming oxide concentrations. For kimberlites this condition is deemed feasible in two-factor models [1]. In this model the first factor stands for the combination of silicate analyses by TiO_2 content into seven groups. The second one subdivides the above seven groups into subgroups by the content of CaO and MgO. After verification of the obtained model it turned out that the TiO_2 composition groups have the same level of magmatic chamber depths. Thus, they are called populations formed under similar baric conditions. The subgroups were called varieties, reflecting the trend of selective melt temperature growth from calciferous to magnesial ones. The petrochemical population model of kimberlites is given in table 1.

The mean population compositions for the kimberlites of the diamond fields of Yakutiya under consideration are listed in table 2. This table rather vividly reveals the special features of the population model, i. e. the reverse correlation of TiO_2 and K_2O, and the reverse correlation between MgO and CaO.

Table 1

Petrochemical population model of kimberlites

Step 1. Identification of populations. Typochemical indicator – TiO_2							
Population number	1	2	3	4	5	6	7
Boundaries of TiO_2, wt. %	< 0,4	0,41–0,60	0,61–1,00	1,01–1,40	1,41–1,80	1,81–2,20	2,21–3,00

Step 2. Identification of varieties. Typochemical indicator – CaO/MgO				
Name of population variety	Kimberlitic carbonatites (Kcb)	Carbonatitic kimberlites (Ca-kmb)	Kimberlites (Kmb)	Magnesial kimberlites (Mg-Kmb)
Boundaries of CaO/MgO	> 8,20 to 1,76	1,75 to 0,83	0,82 to 0,34	0,33 to < 0,18

Table 2

Mean population compositions for the kimberlites of the diamond fields of Yakutiya

Components	Population number						
	1	2	3	4	5	6	7
SiO_2	28,77	29,04	28,60	28,46	29,62	29,49	29,20
TiO_2	0,34	0,47	0,81	1,19	1,58	2,00	2,46
Al_2O_3	3,36	3,69	2,74	2,13	2,00	1,99	2,15
Fe_2O_3	5,04	5,75	6,48	7,46	8,16	8,57	9,12
MgO	23,59	24,60	25,15	27,96	28,53	28,45	28,73
CaO	14,12	12,90	13,49	11,56	9,92	9,63	8,67
Na_2O	0,27	0,17	0,23	0,20	0,17	0,16	0,13
K_2O	1,12	1,10	0,71	0,54	0,41	0,38	0,40
P_2O_5	0,39	0,53	0,35	0,36	0,34	0,35	0,41
LOI	19,95	21,76	20,58	20,87	21,88	22,84	23,89
Number of analyses *n*	1 430	1 230	1 874	1 335	740	328	93

All the kimberlite bodies of the Yakutian kimberlite province are made of rocks of the distinguished above seven populations. Their distinctive feature is that in each pipe by the number of analyses or by modality there prevail one or two populations. For example, in the Aykhal pipe these are the first and the second populations (table 3).

According to the values of modal populations the kimberlite bodies of the Alakit-Markha and Daldyn fields make a well-marked succession (table 4). This succession is reflected in the change of mean compositions, distinguished among diamond-bearing kimberlites of the Vilyuisko-Markhinskaya zone of the Yakutian kimberlite province, rock formations of the first and the second alkaline type (fig. 1).

The thermodynamic verification of these results, reported in a number of publications [5, 7, 8 etc.] leads us to two important conclusions. First, it helps to plot a population variant of the kimberlite petrological model (fig. 2) (it should be noted, that in the presented model the estimation of the depths of parental melt formations is symbolic, marked as the upper and lower boundaries. All the other characteristics are measured with due accuracy). And second, it shows that the diamond potential of kimberlites is in direct correlation with potassium content

and in reverse correlation with titanium content. In this model the titanium and the potassium serve as depth indicators of parental kimberlite melts formation, while potassium also characterizes the compositions of magma-generating media, at times rich in fragments of ocean crust with high-potassium mountain rocks (e. g. for kimberlites of the second type).

Table 3

Population petrochemical model of the Aykhal pipe

Components	Population and variety					
	1st				2nd	
	Kcb	Ca-kmb	Kmb	Mg-kmb	Kcb	Ca-kmb
SiO_2	12,24	20,01	24,09	28,59	11,85	20,15
TiO_2	0,27	0,29	0,31	0,26	0,48	0,50
Al_2O_3	2,15	2,57	2,36	2,20	2,29	3,48
Fe_2O_3	3,52	3,55	3,78	4,32	3,63	4,42
MgO	9,45	19,74	25,99	29,98	10,29	19,40
CaO	35,49	21,78	14,71	7,34	34,90	21,00
Na_2O	0,32	0,20	0,16	0,24	0,21	0,23
K_2O	0,82	1,06	0,86	0,46	1,01	1,13
P_2O_5	0,47	0,44	0,46	0,53	0,70	0,78
|LOI	29,70	22,70	17,36	15,38	28,66	20,26
$D_{Car/t}$	–	3,01	4,38	4,84	2,30	5,34
Content, %	4,6	14,4	24,2	5,5	3,1	6,1

Components	Population and variety					
	2nd		3rd			
	Kmb	Mg-kmb	Kcb	Ca-kmb	Kmb	Mg-kmb
SiO_2	24,25	28,17	10,47	22,64	25,90	28,83
TiO_2	0,51	0,51	0,72	0,70	0,69	0,65
Al_2O_3	2,15	2,57	2,23	2,46	2,48	2,25
Fe_2O_3	4,82	5,05	3,78	5,04	5,24	6,52
MgO	26,57	29,09	9,60	20,48	26,14	30,00
CaO	14,48	7,80	36,30	21,26	14,06	9,71
Na_2O	0,11	0,18	0,23	0,12	0,12	0,12
K_2O	0,76	0,75	0,75	0,74	0,88	0,59
P_2O_5	0,82	0,74	0,86	0,88	0,94	0,99
|LOI	14,00	10,74	28,24	18,41	12,21	12,65
$D_{Car/t}$	3,83	4,84	–	2,52	5,25	0,40
Content, %	24,5	4,0	1,8	3,4	7,4	0,9

The compositions and correlations of potassium and magnesium in kimberlites are also associated with their diamond content. But in these cases the regressional relationships within each identified population are of a nonlinear form (fig. 3). In one of our publications (Vasilenko et al., 2011) we recommended to use fig. 3 for estimating kimberlite diamond potentials by mean compositions of homogeneous rock groups, which were not altered by secondary processes.

Here it should be noted, that fig. 3 disproves the hypothesis on the allogenic, xenogenic nature of diamonds in kimberlites, related to peridotite xenoliths, since the dependence of the diamond content on magnesium is nonlinear, the high-magnesial kimberlites have low diamond content, or none at all in all populations.

Table 4

Relative distribution of modal populations in kimberlite pipes
(percent of the total number of samples in a pipe)

Pipe	Population					
	1	2	3	4	5	6
Sytykanskaya	–	–	–	–	35,0	39,5
Udachnaya-East	–	–	33,1	47,7	–	–
Udachnaya-West	–	–	68,8	15,3	–	–
Aykhal	49,5	37,7	–	–	–	–

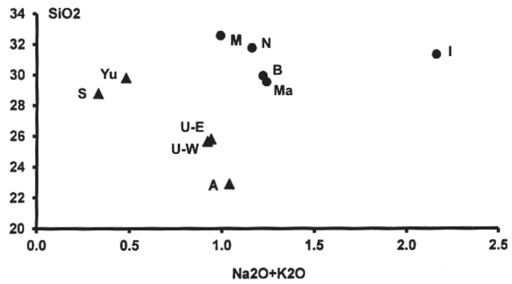

Fig. 1. Imaging points of mean compositions of rock forming oxides.

Triangles are kimberlites of the first type, circles are kimberlites of the second type. Letters stand for pipes designations: S – Sytykanskaya, Yu – Yubileinaya, U-E – Udachnaya-East, U-W – Udachnaya-West, M – Mir, I – Internatsionalnaya, B – Botuobinskaya, Ma – Maiskaya, N – Nyurbinskaya.

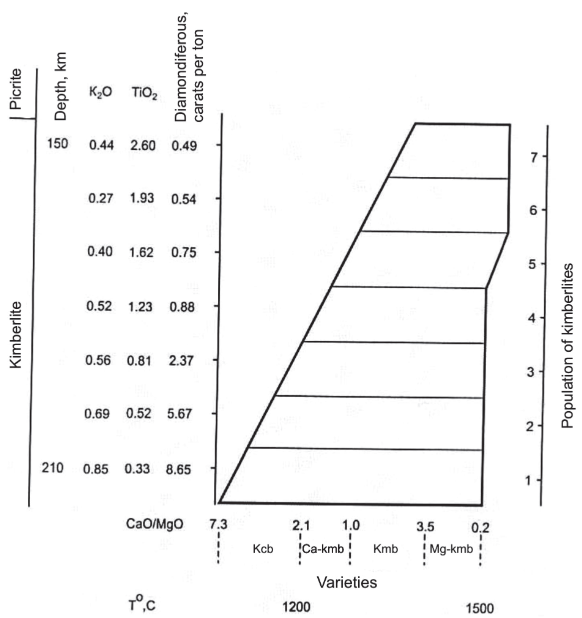

Fig. 2. Population variant of petrological model of kimberlite formation and their diamond potential.

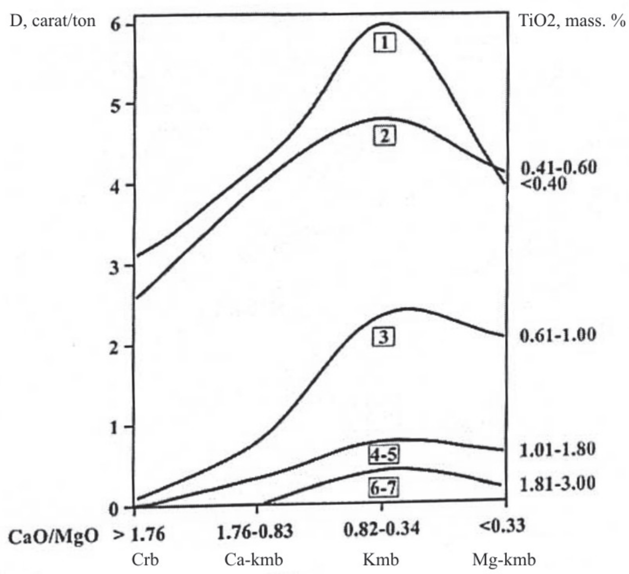

Fig. 3. Diamond potential vs population parameters section showing the petrochemical model.

The correlations of rock-forming oxides and diamond contents in the kimberlite population model are validated by the changes in the mean compositions of kimberlites of the first and the second types (see fig. 1) in the northward direction (table 5). The analysis of this table shows, that in kimberlites of different alkaline types there occurs a regular change in the contents of titanium, potassium, calcium, magnesium, and diamonds. The contents of titanium, magnesium and iron increase, while the contents of calcium, potassium and diamonds decrease northwards. It much resembles the kimberlite population model (see table 1), which demonstrates the change in the chemical composition and in the diamond content of the rocks at the elevation of magma formation zones with trends of changes of mean compositions of kimberlite deposits in the northward direction. Gradual loss of formation depths of kimberlite parental melts for normal or hyperalkalinity rocks tells that the lithosphere bottom (most probable location of selective melts where mantle peridotites meet with thermal plumes) also proceeds in the same upward direction.

Comparing the series of population models of the central and northern parts of the province with the profile of the underlying lithosphere, V. Vasilenko et al. (2000) demonstrated, that in general there is observed a gradual discontinuous ascend of the magma formation zone to the upper part of lithosphere. This conclusion is based on the fact of elevation of the kimberlite and picrite genesis zones, parallel to the relief of the lithosphere bottom (fig. 4). Within the 200 km values of isopachytes we find developed diamond-bearing kimberlites. With the ascend of the lithosphere bottom to the isopachyte value of 150 km the diamond-bearing kimberlites give way to low-diamond and diamond-free kimberlites, while the role of picrites grows progressively.

Thus, the relief of the lithosphere bottom beneath the Yakutian kimberlite province determines the depth of kimberlite melting zones, forms the body distribution trend of ultramafic and alkaline kimberlites, their composition and diamond content.

Table 5

Mean kimberlite compositions of diamond deposits of Yakutiya

Components	Kimberlites of the 1st type, pipes				
	Sytykanskaya	Yubileinaya	Udachnaya-East	Udachnaya-West	Aykhal
SiO_2	28,41	29,93	25,84	25,69	22,92
TiO_2	1,78	0,99	1,15	0,84	0,43
Al_2O_3	1,88	2,06	2,17	2,34	2,44
Fe_2O_3	8,33	7.13	7,07	5,98	4,26
MgO	27,72	27,60	27,61	24,63	23,37
CaO	10,87	10,92	13,76	15,82	17,36
Na_2O	0,11	0,13	0,29	0,20	0,17
K_2O	0,22	0,35	0,66	0,72	0,87
P_2O_5	0,25	0,37	0,33	0,30	0,65
LOI	28,31	20,63	21,31	23,63	27,35
$D_{car/t}$	0,45	0,53	0,61	1,16	4,04
N	267	206	135	71	121
n	542	1 103	824	1 014	329

Components	Kimberlites of the 2nd type, pipes				
	Mir	Internatsio-nalnaya	Nyurbinskaya	Botuobin-skaya	Maiskaya
SiO_2	32,62	31,41	31,81	29,98	29,57
TiO_2	1,40	0,42	0,53	0,42	0,42
Al_2O_3	2,50	2,78	5,11	3,83	4,10
Fe_2O_3	8,26	5,95	6,54	5,37	5,40
MgO	27,45	28,77	20,90	23,55	21,13
CaO	8,47	7,29	12,70	14,06	15,68
Na_2O	0,29	1,21	0,10	0,01	0,09
K_2O	0,29	0,95	1,06	1,22	1,15
P_2O_5	0,35	0,40	0,45	0,44	0,44
LOI	17,91	20,85	20,77	21,13	22,10
$D_{car/t}$	1,99	3,27	6,68	8,11	5,56
N	180	119	352	481	60
n	725	400	1 025	1 001	151

N o t e. *N* – number of estimated diamond contents in a pipe; *n* – total number of analyses in a pipe.

The presented material provides an evident proof, that the diamond content in kimberlites is not random, but completely correlates with the compositions of rock forming oxides.

The content of volatile components in the rocks can also be associated with magmatic factors of the diamond potential. This aspect in the petrochemistry of kimberlites was first investigated through the case study of the selected by us picritic and alkali-gabbro complexes of one of the northern kimberlite fields (the investigated collection belongs to OJSC “Almazy Anabara”) of the Yakutian kimberlite province. The chemical compositions of the rock formations of the complexes under study (table 6) are rather similar and differ in the alkali-to-silica ratio, one of the basic criterion of magmatic complexes discrimination [2, fig. 1]. In this aspect it is interesting to consider the volatile components ratio in both complexes under study to check them for diamond content.

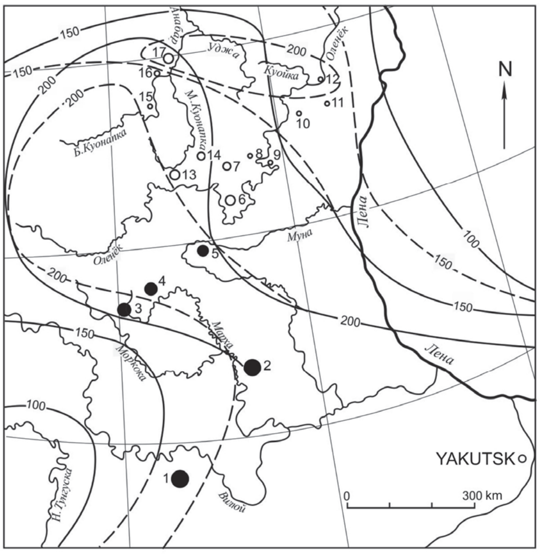

Fig. 4. Location of kimberlite magmatism main manifestations.

Isopachytes of lithosphere, thickness in km: solid line – according to V. Epifantsev and R. Rodin (1998), dashed line – our data; the numbers indicate kimberlite fields: *1* – Mirnyi, *2* – Nakyn, *3* – Alakit-Markha, *4* – Daldyn, *5* – Verkhne-Muna, *6* – Chomurdakh, *7* – West Ukukit, *8* – East Ukukit, *9* – Ogoner-Yuryakh, *10* – Merchimden, *11* – Molodo, *12* – Kuoik, *13* – Kuranakh, *14* – Luchakan, *15* – Ary-Mastakh, *16* – Starorechenskoe, *17* – Orto-Yargin.

Table 6

Mean contents of rock formations of the picritoid and alkaline-gabbroid complexes of the Orto-Yargin field

Components	Group			
	1	2	3	4
1	*2*	*3*	*4*	*5*
SiO_2	35,79* 51,39	25,33 32,01	15,47 18,59	8,63 12,18
TiO_2	0,61 1,22	0,46 0,60	0,60 0,67	0,54 0,32
Al_2O_3	5,67 15,08	5,65 8,04	4,08 4,26	2,77 2,76
Fe_2O_3	6,95 11,52	7,82 10,58	8,06 8,28	8,68 6,40
MgO	16,90 4,44	12,25 8,70	9,34 12,96	5,32 14,06
CaO	11,56 5,73	18,57 14,93	27,30 23,04	36,14 28,02
Na_2O	0,82 4,61	0,51 0,82	0,06 0,24	0,01 0,13
K_2O	1,44 1,12	2,11 2,65	1,13 1,61	0,41 1,00

End of table 6

1	2	3	4	5
P_2O_5	0,39 / 0,56	0,80 / 1,68	1,02 / 0,90	1,48 / 1,57
$(Na_2O+K_2O)/SiO_2$	0,063 / 0,112	0,103 / 0,108	0,077 / 0,100	0,053 / 0,093
n	15 / 2	19 / 18	13 / 15	8 / 8
CO_2	6,42 / 1,76	15,06 / 10,91	17,39 / 15,84	19,61 / 18,33
H_2O	2,36 / 1,42	1,19 / 1,16	1,22 / 1,40	1,17 / 1,27
H_2	0,020 / 0,001	0,029 / 0,020	0,020 / 0,019	0,016 / 0,017
N_2	0,001 / 0,001	0,004 / 0,009	0,005 / 0,002	0,002 / 0,002
CO	0,081 / 0,052	0,873 / 0,910	1,342 / 0,545	1,695 / 0,466
CH_4	0,001 / 0,000	0,001 / 0,002	0,002 / 0,001	0,000 / 0,002
n	15 / 2	19 / 18	13 / 15	8 / 8

*In the numerator – the rocks of picritoid complex, in the denominator – of alkaline-gabbroid.

The authors in this case have applied the contents of volatile components in rocks to predict probable diamond potentials of rocks for the first time in petrological practice. Model presentations on the role of volatiles in magma formation favor to this prediction. In [16, 17] (quoted according to [12]) the authors propose a model of diamond formation based on the experiments for melting mafic and ultramafic compositions in the presence of reduced fluid base. According to their presentations, the fluids separated from the deep mantle below the astenospheric level in equilibrium with buffer W have an abruptly reductive character: $CH_4 > H_2O > H_2 > C_2H_6$. A melting effect under the reduction conditions (redox-nelting) could manifest itself in the interaction between the fluids reduced and more oxidized lithosphere. As a result of this interaction, the ash content grows progressively in the fluid, thus decreasing the solidus temperature rapidly and stimulating the partial pressure. The diamond separation takes place simultaneously as a result of methane oxidation (p. 228). The astenospheric melt layer becomes a membrane conducting predominantly more active hydrogen and light noble gases. The hydrogen flow produces a series of gas reactions of the following type, which lead to diamond crystallization [12, p. 232]:

$$2CO_2 + 6H_2 \rightarrow CH_4 + C + 4\,H_2O; \quad (1)$$

$$2CO + 4H_2 \rightarrow CH_4 + C + 2H_2O; \quad (2)$$

$$3NO + 6H_2 \rightarrow 2NH_3 + N + 3H_2O. \quad (3)$$

According to L. Perchuk and V. Vaganov [6], the presence of diamonds in kimberlites indicates very high pressure of their generation (P_{fl} > 40 kbar). But at the same time, diamonds could be the indicators of the fluid mode defined by the reactions:

$$2CO = C + CO_2; \quad (4)$$

$$CH_4 + CO_2 = 2C + 2H_2O; \quad (5)$$

$$C + ½\,O_2 = CO; \quad (6)$$
$$C + O_2 = CO_2. \quad (7)$$

It is evident that the fugitiveness increase CO_2 (f_{co2}) could lead to both diamond dissolution (under other conditions, reaction (4), and its stabilization (reactions (5 and 7).

Hence, at greater depths (over 120 km) the reaction (5) is leading and it is displaced to the right. If a diamond would be transported upwards and the rate of kimberlite magma penetration becomes higher than the rate of reaction (5) displacement to the left, then this diamond would restore under rapid melt crystallization. Otherwise, the diamond would dissolve (oxidize), which should be manifested in the correlation of H_2O and CO_2 in kimberlites.

From the equations reduced, hydrogen reduction reaction (5) is of greater importance for the reconstruction purposes. A negative correlation of H_2O + C and CH_4 occurs when this reaction displaces to the right. The water formation correlates with the presence of reduced hydrogen.

Since the definition of free carbon is missing in the experiment in question, let us consider that the conditions favoring to diamond crystallization took place in rock formation, if a negative correlation of CO and water occurs. The correlation sequence (fig. 5) based on the data of table 7 shows the positive relation of CH_4 and CO in picritoids and negative correlation of this correlation complex with H_2O.

The empirical material shows the reality of reaction (5) displacement to the right and hence, the possibility of free carbon formation, which could result in diamond formation, if the required external conditions are satisfied.

Table 7

Correlation matrices of volatile components in rock associations of the Orto-Yargin field

Picritic association, n = 55, r_{01} = 0,34						
	CO_2	H_2O	H_2	N_2	CO	CH_4
CO_2		–0,05	0,02	0,18	**0,50**	0,14
H_2O	–0,05		–0,06	–0,21	**–0,45**	–0,23
H_2	0,02	–0,06		0,06	–0,03	0,18
N_2	0,18	–0,21	0,06		**0,62**	**0,75**
CO	**0,50**	**–0,45**	–0,03	**0,62**		**0.52**
CH_4	0,14	–0,23	0,18	**0,75**	**0,52**	
Alkali-gabbro association, n = 43, r_{01} = 0,39						
	CO_2	H_2O	H_2	N_2	CO	CH_4
CO_2		–0,06	0,28	–0,22	0,06	0,20
H_2O	–0,06		0,26	0,18	0,01	–0,03
H_2	0,28	0,26		0,09	0,43	–0,04
N_2	–0,22	0,18	0,09		0,09	0,13
CO	0,06	0,01	0,43	0,09		**0,51**
CH_4	0,20	–0,03	–0,04	0,13	**0,51**	

The compositions of carbonatite-containing alkaline gabbro in their correlations show only the presence of positive correlation of CH_4 and CO. The correlations with H_2O are absent, which means the reaction (5) displacement to the left and absence of the conditions for free carbon formation. This circumstance should be considered as negation of diamond formation possibility.

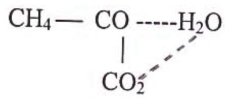

Fig. 5. Correlation sequence for picritoids.

The features of interrelations between the rock-forming oxides and diamonds presented above could lead to erroneous conclusions on the fact that all kimberlite manifestations could be described by these regularities. This is not entirely true. The diamondiferous kimberlites are characterized by the values of contents of rock-forming oxides, which are appropriate only to them. Figure 6 demonstrates the interrelation between the compositions of kimberlites in diamond fields and other rocks of this type using 83 bodies of non-diamondiferous kimberlites and the kimberlites in diamond fields of the area under investigation. As is evident, the more diamondiferous kimberlites contain more MgO and less TiO_2. We recommend the imaging points of kimberlite manifestations relating to calcite varieties of kimberlites located left to the point of kimberlite fields. This drawing is proposed to reveal potentially diamond containing rocks in kimberlite manifestations.

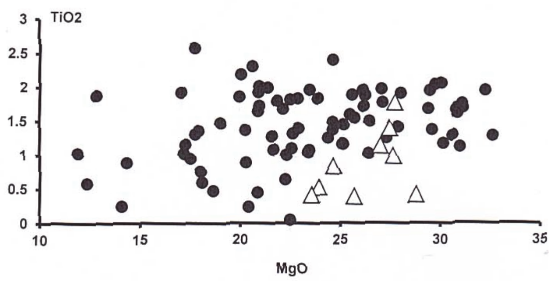

Fig. 6. Imaging points of compositions of kimberlite bodies in Vilyuiskaya sub-province.

The points indicate the compositions of non-diamondiferous kimberlites or kimberlites with low diamond potentials and related calcite carbonatites (Vasilenko et al., 2006), the triangles indicate the compositions.

Volcanogenic factor. At volcanogenic stage, the kimberlite magma penetrates into the diatreme and crystallizes within it. This penetration is accompanied by blasting phenomena due to a diabatic release of volatile components. Large and small fragments of enclosing rocks, including the kimberlites of previous penetration stages enter decrystallized kimberlite melts and become the reason of their viscous differentiation (Vasilenko et al., 2000). The kimberlite structural and textural characteristics diversify by these processes. A porphyritic kimberlite from the Udachnaya-East pipe, where the olivine crystals are cemented by the aggregate of calcite lath-like crystals and other minerals, is shown in fig. 7. The autoliths of previously solidified kimberlites form a specific spheroidal rock structure (fig. 8) in the kimberlites of the Internatsionalnaya pipe.

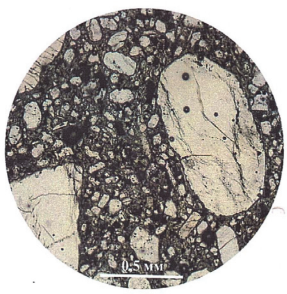

Fig. 7. Photomicrography of a porphyritic kimberlite from the Udachnaya-East pipe.

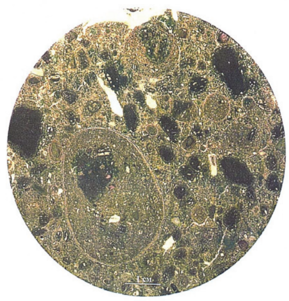

Fig. 8. Spheroidal rock structure in the Internatsionalnaya pipe.

Autholitic kimberlite breccia occurs during the change in composition of kimberlite melt sections containing the xenoliths of enclosing rocks. An abrupt viscosity increase in the *melt* + *xenolith* system and significant energy losses due to melting are caused by the xenoliths. The xenoliths entry to the kimberlite melt leads to decreasing the solidus temperature. As a consequence, the melt crystallization in the *melt* + *xenolith* system starts earlier than the melt crystallization without xenolith inclusions. When the volume concentration of crystals and xenoliths ≥ 30 %, the melt discontinuity takes place due to yield limit manifestation in shear flow, which finally leads to the formation of autholitic kimberlite breccia. This process stipulates an increase in the values of magnesia and diamond contents in the autholitic kimberlite breccia (table 8).

Table 8

Relative increase in diamond contents in the autholitic kimberlite breccia of the Aykhal pipe

Rock	Populations, varieties					
	n	The first, Ca-kmb, %	*n*	The first, Kmb, %	*n*	The second, Mg-kmb, %
PK	4	100	9	100	22	100
AKB	18	129	23	128	8	127

Some authors absolute the increase in diamond contents in breccia, they point to the fact that the upper parts of the pipes are always enriched with diamonds. This is not always true, since the amount of xenoliths is different in different penetrations of kimberlite melts. At a close hypsometric level, each subsequent penetration stage contains a lesser amount of autholitic breccia, than the previous one. For example, in the Aykhal, Udachnaya-West and Udachnaya-East pipes, the distribution of autholitic breccia reduces in subsequent magmatic phases (table 9).

Table 9

Correlation of frequencies of KB and PK occurrence in the kimberlites of different penetration stages, %

Rock	Pipe, phase					
	Aykhal		Udachnaya-West		Udachnaya-East	
	1st	2nd	3rd	4th	3rd	4th
PK	17	82	32	75	27	73
AKB	82	19	69	25	79	20

The increase in diamond contents in autholitic kimberlites is associated not with chemical properties, but with physical properties of enclosing rock xenoliths.

Viscous differentiation of melts can also result in the change of diamond crystallographic type. In this regard, V. Shkodzinsky remarked [14, p. 268] that, in consequence of “common origin of diamonds and kimberlite melts enclosing them, there should be a relation between the kimberlite composition and composition of the diamonds containing in kimberlite melts.” This relation should be implemented, first of all, through the influence of melts viscosity on the diamonds crystallomorhism, since the latter is defined by the degree of oversaturation of medium crystallization with carbon. The degree of oversaturation depends to a greater extent on the diffusion rate of chemical components and, consequently, on the viscosity and composition of melts (p. 268). Using the references, V. Shkodzinsky created a special database on chemical compositions of melts and prevailing crystallographic shapes of diamonds [14, pp. 445–451] to

check the statement on the relation between the crystallographic features of a diamond and the compositions of enclosing kimberlites empirically. Our statistic testing of dependence of the diamond crystallographic shapes on the content of SiO_2 in enclosing kimberlites, the main factor defining the melt viscosity showed that the fraction of rounded crystals enhances, as the content of SiO_2 increases in the melts (table 10). This is evident, since diffusion is complicated in viscous melts.

Table 10

Correlation dependencies between average contents of SiO_2 and diamond morphotypes of kimberlite and lamproite pipes

Function		Argument	Correlation index i	Limit values i_{01}	Regression equation
Content ratio of	octahedrons, $n = 56$	Content of SiO_2	–0,40	0,34	$-247{,}68 + 22{,}15\ SiO_2 - 0{,}57\ SiO_2^2 + 0{,}004\ SiO_2^3$
	dodecahedrons, $n = 45$		–0,45	0,41	$183{,}13 - 10{,}49\ SiO_2 + 0{,}16\ SiO_2^2$
	rounded crystals, $n = 42$		+0,68	0,40	$175{,}26 + 7{,}21\ SiO_2 - 0{,}02\ SiO_2^2$

Thus, the statistic testing showed the correlation between the melt viscosity and crystallographic shapes of diamonds in kimberlites.

The material presented clearly demonstrates that the history of diamonds origination is closely related to the evolution of the kimberlite chemical composition. As opposed to the xenogenetic paradigm, this enables us to put forward a paradigm of the evolution of rock chemical compositions in the formation of diamondiferous provinces.

The empirical petrochemical model of petrogenesis of diamondiferous kimberlites assuming, that the different kimberlites were generally formed at different depth levels. The petrochemical feature of this formation is a directed change in the titanium, potassium and diamond contents. At each magma formation level we observed selective melting at the temperatures higher, than the initial melting stage temperatures. The distribution of mean values of kimberlites chemical compositions in the province area also confirms the idea of ascending order of magma formation zones, which corresponds to the geodynamic characteristic of the province.

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МАГМАТОГЕННІ ТА ВУЛКАНОГЕННІ ЧИННИКИ АЛМАЗОНОСНОСТІ КІМБЕРЛІТІВ

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Описано петрохімічні особливості кімберлітів із десяти трубок (родовищ) Якутії з промисловим умістом алмазів: у Мирнинському полі – це Інтернаціональна і Мир, у Накинському – Ботуобінська, Майська та Нюрбинська, в Алакіт-Мархінському – Айхал, Ювілейна і Ситиканська, у Далдинському – Удачна-західна та Удачна-східна. Представницькі геологічні взірці відібрано винятково з керна розвідувальних свердловин (331 свердловина, загальна довжина дослідженого керна – 88 082 м, максимальна глибина опробування – 1 359 м). Використано 7 114 хімічних аналізів порід алмазних родовищ, дані щодо середнього складу 83 кімберлітових тіл, а також 1 992 визначення алмазоносності (дані отримано співробітниками АК "АЛРОСА" унаслідок усереднення 6–10-метрових інтервалів керна розвідувальних свердловин). З використанням усіх наявних даних створено популяційну петрохімічну модель кімберлітоутворення, на підставі якої запропоновано петрологічну модель алмазоносних кімберлітів Якутії. Зроблено висновок, що розмаїття речовинного складу й алмазоносності порід зумовлені глибиною залягання магматичного осередку. На вулканічному етапі на хімічний склад породи впливають також ксеноліти вмісних порід, які спричиняють в'язкісну диференціацію розплавів.

Ключові слова: кімберліт, хімічний склад, популяційна петрохімічна модель кімберлітоутворення, алмазоносність, петрологічна модель, Якутія.

МАГМАТОГЕННЫЕ И ВУЛКАНОГЕННЫЕ ФАКТОРЫ АЛМАЗОНОСНОСТИ КИМБЕРЛИТОВ

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Описано петрохимические особенности кимберлитов из десяти трубок (месторождений) Якутии с промышленным содержанием алмазов: в Мирнинском поле – это Интернациональная и Мир, в Накынском – Ботуобинская, Майская и Нюрбинская, в Алакит-Мархинском – Айхал, Юбилейная и Сытыканская, в Далдынском – Удачная-западная и Удачная-восточная. Представительные геологические образцы отобраны исключительно из керна разведочных скважин (331 скважина, общая длина исследованной колонны керна – 88 082 м, максимальная глубина опробования – 1 359 м). Использовано 7 114 химических анализов пород алмазных месторождений, данные по среднему составу 83 кимберлитовых тел из исследованных кимберлитовых полей, а также 1 992 определения алмазоносности (данные получены сотрудниками АК "АЛРОСА" при усреднении 6–10-метровых интервалов керна разведочных скважин). С использованием всех имеющихся данных создано популяционную петрохимическую модель кимберлитообразования, на основании которой предложено петрологическую модель алмазоносных кимберлитов Якутии. Сделано вывод, что разнообразие вещественного состава и алмазоносности пород обусловлено глубиной залегания магматического очага. На вулканическом этапе на химический состав породы влияют также ксенолиты вмещающих пород, которые вызывают вязкостную дифференциацию расплавов.

Ключевые слова: кимберлит, химический состав, популяционная петрохимическая модель кимберлитообразования, алмазоносность, петрологическая модель, Якутия.