Magnetomineralogy of Botswana Kimberlites

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Received February 20, 2012

Abstract—The magnetic properties and mineralogy of kimberlites from four pipes (BK53, BK56, AK08, and AK06) in Botswana are studied. It is shown that magnetic characteristics of the kimberlites as well as chemical and phase compositions of the oxides from kimberlite groundmass reflect the difference in evolution of kimberlite melts and formation conditions of these bodies and are associated with the grade of these diamoniferous bodies. The relatively low-grade (0.22 carats per ton) kimberlites from the southern lobe of the AK06 pipe contain picrochromites with high chrome and low titanium contents (up to 49.4 wt % Cr₂O₃ with 3.9 wt % TiO₂), which occur in the paramagnetic state at a temperature of $T > -180^{\circ}$ C. Their magnetic properties above room temperature are determined by titanomagnetites with the Curie point at +370to $+ 500^{\circ}$ C, which were formed at the later stages of crystallization as a result of the gradual decline in the PT-parameters. Most spinelides in the Botswana kimberlites from the low-grade pipes (below 0.07 carats per ton) were crystallized at higher PT-parameters than in the southern lobe of pipe AK06, in an environment with highly active titanium. The chromspinelides that were segregated previously turned out to be unstable, which led to the formation of magnesian-chrome and magnesian ulvospinels (15.9–29.7 wt % TiO₂; 12.8–22.8 wt % MgO; 0–11.3 wt % $\bar{C}r_2O_3$; and 1.2–12.4 wt % Al₂O₃) with Curie points $T_C = -50$ to -80° C. These conditions were unfavorable for preservation of chrome-spinelides and diamonds. At lower PT-parameters, a small amount of finely dispersed magnetite with a single-domain and pseudo-single domain structure was formed.

DOI: 10.1134/S1069351313020043

INTRODUCTION

Kimberlites pertain to the deepest magmatic rocks that admit direct investigation. They occur in the craton areas on all continents and, together with lamproites, present the main native sources of diamonds. Within the territory of Russia, there are two kimberlite provinces (the Yakut and Archangelsk), which contain a series of diamond deposits.

Kimberlite and lamproite pipes producing diamonds were formed all over the world in a wide time interval from the Proterozoic (1750 ± 10 Ma, Republic of South Africa) to Cenozoic (18 Ma, Australia) (Kharkiv, Zinchuk, and Kryuchkov, 1998). The Russian diamond-bearing kimberlites are of the Middle Paleozoic age (330-440 Ma ago); many pipes in South Africa were formed in the Mesozoic (less than 90 Ma ago) (Vaganov, 2000).

The studies of kimberlites have a long history. The recent studies increasingly rely on the modern, highly informative methods of rock magnetism. Using the set of magnetomineralogical parameters provided by these methods, it is possible to reconstruct the conditions of the formation and evolution of kimberlites.

Magnetic methods are suitable for solving the problems associated, on one hand, with determination of the phase composition of natural ferrimagnetics that are responsible for the magnetic properties of the rocks and, on the other hand, these methods can be used for establishing the thermodynamical conditions for the formation of these rocks; i.e., they are suitable for studying the genesis of the rocks. In addition, using the temperature dependences of the magnetic characteristics, one can assess the behavior of chemical processes in the ferrimagnetic mineral and in the rock. For example, the shape of the curves $I_{s}(T)$ is controlled by the contribution of different ferrimagnetic minerals that compose kimberlites. The less these minerals are altered by the subsequent metamorphic processes since their formation, the more the behavior of the $I_s(T)$ curves reflects the initial *PT*-conditions and, correspondingly, the closer it can be related to the diamond grade of the kimberlite body (Trukhin et al., 1991). The technique that uses the data on the magnetic parameters of the rocks can be helpful in the search for high-grade pipes. Initially, such studies were intended for providing the correct interpretation of the magnetic measurements above the kimberlite bodies (Savrasov, 1962; 1976; Romanov and Erinchek, 1976).

The widespread occurrence of microcrystalline oxides and, primarily, spinelides in the groundmass of kimberlites, lamproites, and allied rocks causes significant variations in the magnetic characteristics of these rocks.

Chromspinelides and picroilmenites are the main magnetic minerals that compose kimberlites and are the satellite minerals of diamonds. For example, in the kimberlites from the diamondiferous bodies of the Zolotitsa field in Arkhangelsk diamond province, as well as in the kimberlites from several poor-diamondbearing and non-diamondiferous bodies of the Verkhotina field and Kepin group, the satellite magnetic mineral of diamond is chromspinelide (Trukhin et al., 1991; Kharkiv, Zinchuk, and Kryuchkov, 1998; Garanin, 2009). Chromspinelides contained in the rocks of the Arkhangelsk kimberlite province do not possess ferrimagnetic properties above room temperature (T_0).

Most of the kimberlite pipes in Yakutia are rich in picroilmenite (Garanin, 2009; Trukhin, Zhilyaeva, and Safroshkin, 1984; Trukhin et al., 1989; Kharkiv, Zinchuk, and Kryuchkov, 1998). In the Arkhangelsk province, picroilmenite only occurs in some bodies within the Kepin field and in the diamondiferous pipe within the V. Grib's deposit.

Most of the kimberlite samples from the Zolotitsa field exhibit an interesting feature: their saturation magnetization I_s strongly increases in the low-temperature interval (-196 to -150°C) at cooling the sample, and $I_s(-196)/I_s(20) > 2$. It was established that the growth of I_s at cooling from T_0 is due to the presence of chromspinelides with 53 wt % Cr₂O₃ and $T_C < T_0$ (Trukhin et al., 1991).

The kimberlites from the Zolotitsa field also show other types of the $I_s(T)$ curves, which are close to the "magnetite" curves with small tails in the intervals T >500°C. This is most likely to be associated with the processes of serpentinization of olivine, which are widespread in these kimberlites (Trukhin et al., 1991; Kharkiv, Zinchuk, and Kryuchkov, 1998).

The presence of spinelides of titanomagnetite series, which were identified in the kimberlites from the diatrems of the Kepin group, points to the low thermodynamical conditions of crystallization compared to the early chrome spinelides from the kimberlite groundmass.

The comparison of the temperature dependences of saturation magnetization $I_s(T)$ for kimberlites from the North European part of Russia and Yakutia showed that the curves corresponding to kimberlites from lower-grade bodies are closer in shape to the graph of the Brillouin function (Trukhin et al., 1991; Trukhin, 2005). The $I_s(T)$ curves of kimberlites from higher-grade pipes have positive curvature in the interval from -196° C to T_c . These results show that the analysis of the features of $I_s(T)$ curves from the bodies of different diamond-bearing grades can be helpful for estimating the grade of these bodies. This difference can be used for indirect express assessment of the diamond content of kimberlite bodies at the stage of the prospecting evaluation survey.

Overall, the magnetism of kimberlites from the North European part of Russia is determined by a variety of ferrimagnetic minerals. The high-grade pipes mainly contain homogeneous grains of chromspinelides. The grains of the low-grade bodies have a complex composition and zonal structure with the zones represented by ferrispinelides with a varying percentage of iron and the ions of other elements (Cr, Al, Mg, Mn, and Ti) or ferrispinelides of nonstoichiometric composition.

Chromspinelides are also the main ferrimagnetic minerals in lamproites—deep migmatites from Australia, Spain, and Russia (the Aldan Shield) (Garanin et al., 1993). It is shown that, as in the case of kimberlites, the shape of the thermomagnetic curve $I_s(T)$ is indicative of the diamond grade of lamproites: the $I_s(T)$ curves of the samples from diamondiferous pipes are close to linear in the interval $T > 0^{\circ}$ C, while at $T < 0^{\circ}$ C, $I_s(T)$ sharply increases with decreasing temperature. The following relations are valid for nondiamon-diferous lamproites: $I_s(0^{\circ}$ C)/ $I_s(-196^{\circ}$ C) > 0.7 and $I_s(0^{\circ}$ C)/ $I_s(-196^{\circ}$ C) < 0.3, while for diamondiferous lamproites, $0.3 < I_s(0^{\circ}$ C)/ $I_s(-196^{\circ}$ C) < 0.7 (Garanin et al., 1993).

Thus, the data in the literature show that the magnetic properties of kimberlites of the Yakut and Arkhangelsk diamond provinces are studied quite comprehensively. Picroilmenites and spinelides of a certain composition are the main magnetic minerals that are satellite to diamond. However, the magnetomineralogical properties of kimberlites from Africa, including the Botswana kimberlites are still poorly known. It is unclear which minerals are responsible for the magnetic properties of kimberlites from the Botswana pipes with different diamond content; the relationship between the formation of the magnetic minerals and preservation of diamond in the kimberlite bodies in Botswana is also unclear. As has been noted in (Kharkiv, Zinchuk, and Kryuchkov, 1998), little attention is paid in the literature to the study of the physical properties of kimberlites worldwide.

In order to determine the pattern of magnetic properties and mineral compositions of African kimberlites and to identify the proxies of the diamond content of kimberlite pipes in the magnetic properties of the rocks, in this work, we study the magnetic mineralogy of kimberlite rock from the pipes of the Orapa field (Botswana, South Africa).

THE SAMPLES AND THE PROCEDURE OF ANALYSIS

We studied 23 samples acquired at different depths from four kimberlite pipes pertaining to the Orapa

kimberlite field in Botswana (Fig. 1, table). Samples kv28, kv29, kv30, kv31, and kv32 were taken from pipe BK53; samples kv36, kv37, and kv38, from pipe BK56; and samples kv33, kv34, kv35, kv39, and kv40, from pipe AK08. Samples kv41, kv42, and kv43 were acquired from the central lobe of pipe AK06; and samples kv44, kv45, kv46, kv47, kv48, kv49, and kv50, from the southern lobe of this pipe.

To date, among these bodies, pipe AK06 has been studied best. It is located 25 km southeast of the Orapa pipe and is composed of three contacting bodies (the northern, central, and southern lobes), which have different sizes. According to the zircon U–Pb dating, the age of these lobes is estimated at 88 ± 5 , 93 ± 3 , and 93 ± 2 Ma, respectively (Appleyard, 2005; 2006). In their petrographic and geochemical features and the morphology of diamond crystals, the kimberlites of the central and northern lobes are similar; however, they significantly differ from the kimberlites of the southern lobe (Stiefenhofer and Opperman, 2008). The northern and central lobes are dominated by dodecahedral diamond crystals (among diamonds with a size of above 1.8 mm, 92.6% and 83.1%, respectively), whereas within the southern lobe, the crystals of octahedral habit with a strongly corroded surface texture are most widespread (74.1%) (Chinn et al., 2008).

Pipe AK08 is located between pipes AK06 and Orapa. It consists of two lobes (the southern and the northeastern), which outcrop on the surface over an area of 5 ha overall. Information on the geology of kimberlites AK08, BK56, and BK53 is absent in the literature.

According to the data of African Diamonds PLC (2009), the AK06 kimberlites are highest-grade among the studied bodies (on average, 0.22 carats per ton). The diamond content in the rocks of AK08 pipe is 0.01–0.07 carats per ton. Preliminary sampling indicated the BK56 and BK53 kimberlites to be of a lower grade.

The study of the magnetomineralogical properties of the collection described above included measurements of the natural magnetic characteristics of the samples. The natural remanent magnetization (I_n) and magnetic susceptibility (k_0) were determined on cubic specimens 8 cm³ in volume, and the hysteresis parameters (saturation magnetization I_s , remanent saturation magnetization I_{rs} , coercive force H_c , and remanent coercive force H_{cr}) were measured on 1 cm³ specimens. We carried out thermomagnetic analysis of the ferrimagnetic phase in the specimens from the temperature dependence of saturation magnetization I_s (in the field of 0.24 T) and initial magnetic susceptibility $k_0(T)$ in the temperature interval from -196° C to 600°C and determined the corresponding Curie points T_{C} . We have also studied the formation of ther-



Fig. 1. The layout of kimberlite pipes of the Orapa field (Botswana).

mal remanent magnetization (I_{rT}) in weak (small) fields (about 0.1 mT). The thermomagnetic measurements were conducted on specimens with a volume of 1 cm³ and smaller.

For measurements of remanent magnetization at room temperature, we used the JR-6 spinner magnetometer. The magnetic susceptibility in the temperature interval from -196° C to $+700^{\circ}$ C was measured by the MFK1-A kappabridge with the CS-3 high-temperature furnace apparatus and the CS-L low temperature cryostat apparatus. The measurements of temperature dependence of saturation magnetization $(I_{s}(T))$ and the study of thermal remanent magnetization were carried out using the BMA-1 vibration thermomagnetometer (Maksimochkin et al., 2003). The hysteresis characteristics (coercive force H_c and remanent coercive force H_{cr}) were studied using the spinner magnetometer. For determining the saturation magnetization, we applied the Weiss-Forrer technique (Chechernikov, 1963).

The phase and chemical composition of the oxide minerals was studied using the Jeol-JSM-6480LV raster electron miscroscope equipped with the INCA 350 energy dispersive X-ray microanalysis system, with an accelerating voltage of 15 kV and a direct current of electron beam of 15 nA. The measurements were conducted at the Laboratory of local material testing, Petrology Department of the Faculty of Geology, Moscow State University.

Magneti	c propertie:	s of Botswa	ına kimt	oerlites (
Sample no.	Depth, m	$k_0, 10^{-3},$ SI units	$\stackrel{I_n}{A/m}$	$Q_{ m n}$	I_{s} (fm), kA/m	I_{rs}/I_s	$^{H_{c}}_{ m mT}$	H_{cr}/H_c	$T_{\mathrm{C}}, {}^{\circ}\mathrm{C}$ from $I_s(T)$	$T_{\mathrm{C}}{}^{\circ}\mathrm{C}$ from $k_0(T)$	$I_{s}(-190)/I_{s}(20)$	$T_{ m C[pred]},^{\circ} m C$
								Pipe B	(K53			
kv28-1	44.9	7.2	0.8	2.8	0.55	0.19	7.9	1.80	-120, 610	-185, +580	2.2	
kv29-1	54.9	5.6	2.0	9.2	0.35	0.22	9.2	1.40	-70,600	+540+580	1.65	
kv30-1	62.7	5.7	1.3	5.6	0.35	0.47	9.2	1.48	-70,580	-185, -30, 550	1.8	
kv31-1	77.1	14.9	3.3	5.5	1.22	0.20	8.6	1.51	-50, 500	-110,490	1.82	
kv32-1	91.6	1.9	0.5	7.2	0.07	0.14	3.9	1.44		230, 580	Ι	
	_	_	_	_	_		_	Pipe B	K56	-	_	
kv36-1	160.3	32.8	34.0	26.1	5.55	0.28	29.3	1.57	+540+560	560	1.15	
kv37-1	175.6	26.7	16.4	15.4	4.59	0.25	27.1	1.65	-70, 570	-100, 390, 570	1.40	-200140, 0 +110 470
kv38-1	197.2	12.4	8.0	16.1	1.35	0.27	26.8	1.97	-110,590	-105, +550+580	1.80	·····
		_	_	_			_	Pipe A	K08			
kv33-1	99.7	22.8	31.1	34.2	2.36	0.20	11.5	1.44	-100, 520	-150, 510.	1.77	
kv34-1	138.9	32.9	22.9	17.5	3.00	0.21	15.7	1.66	-80, 410, 570	-175, 420, 570	1.6	
kv35-1	289.5	67.7	8.0	3.0	6.41	0.05	3.7	1.95	520	520	1.06	
kv39-1	95.7	23.7	7.1	7.5	3.26	0.19	9.3	2.17	-50, 610	-170,600	1.36	
kv40-1	119.8	6.1	13.6	56.1	0.61	0.29	15.2	1.47	-60, 310, 500	-160, -80, 310, 480	3.2	≤-170;-12010,
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kv41-1	84	7.3	8.3	28.7	0.53	0.19	8.5	1.73	530, -90	-155, 560	2.15	-70+100
kv42-1	140.7	24.4	24.8	29.1	2.24	0.23	14.7	1.52	550, ~0	560	1.61	
kv43-1	213.8	18.3	21.6	29.6	2.61	0.22	16.2	1.56	490, ~0	-160, -25, 540,	1.65	≤-170; +20+120, +450+500
	_	_	_	_			Pipe /	AK06. So	outhern lobe	_	_	
kv44-1	87.2	27.1	10.0	9.3	3.12	0.09	6.9	1.99	-110,490	-170, -20, +500+560	1.39	-18080; +353+413, 540
kv45-1	153.5	32.2	3.4	2.6	2.80	0.04	3.1	3.45	500, 540	-140, 500, 540	1.28	
kv46-1	239.4	25.0	6.2	6.3	3.00	0.08	7.2	2.00	520	540	1.12	-170, + $310+350.540$
kv47-1	300.5	19.7	2.8	3.6	2.62	0.11	12.9	2.00	+400+580	420, 520, 580	1.26	-10010; + $200+350;580$
kv48-1	339.7	13.9	1.0	1.8	1.65	0.12	11.6	1.77	-110, +380+550	+370+560	1.34	-17020; +100+400
kv49-1	389.9	33.1	4.2	3.2	2.79	0.07	6.9	2.29	400, 540	400, 540	1.18	
kv50-1	445.1	51.4	24.4	11.9	4.11	0.07	6.9	1.99	410, 550	400, 550	1.22	-190150, + $350+410$

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Fig. 2. The relation between the magnetic susceptibility and natural remanent magnetization of the kimberlite samples from the Orapa field (Botswana). cl stands for central lobe, and sl stands for southern lobe.

MAGNETIC PROPERTIES OF KIMBERLITE SAMPLES FROM THE STUDIED COLLECTION

Isothermal Magnetic Properties

The values of natural remanent magnetization I_n , initial susceptibility k_0 , and the Kenigsberger factor calculated from these values ($Q_n = I_n/k_0H_E$, where $H_{\rm E} = 39.8$ A/m) for the samples of the collection are presented in the table. It can be seen that the I_s of the kimberlites from the studied pipes in Botswana is quite high, varying among the samples from 0.5 A/m to 34 A/m. The I_n of the samples from the BK56 and AK08 kimberlites and from the central lobe of the AK06 pipe ranges within approximately the same interval. The average $I_{n \text{ aver}}$ calculated from the kimberlite samples of the central lobe of AK06 pipe is approximately by a factor 2.5 higher than $I_{n \text{ aver}}$ determined from kimberlite samples from the southern lobe of this pipe and approximately by a factor of 10 higher than $I_{n \text{ aver}}$ calculated from the samples of the BK53 pipe.

The initial magnetic susceptibility k_0 of the samples varies within $(1.9-67.7) \times 10^{-3}$ SI units. The highest magnetic susceptibility was identified in sample kv35 from AK08 kimberlite, and the lowest susceptibility was detected in sample kv32 from BK53 pipe. We did not find a clear correlation between the values of I_n and k_0 of the studied samples and the grade of the pipes from which the samples were taken. However, as can be seen in Fig. 2, which illustrates the relationship between the magnetic susceptibility and natural remanent magnetization, the magnetic characteristics of the studied samples probably show a certain regularity. With a given magnetic susceptibility, the value I_n for the samples from the southern lobe of the AK06 pipe (the highest-grade among the studied pipes) is generally lower than for the samples from the central lobe of the AK06 pipe and pipes AK08 and BK56. The sam-



Fig. 3. The relation between the magnetic susceptibility and saturation magnetization of the kimberlite samples from the Orapa field (Botswana). cl stands for central lobe, and sl stands for southern lobe.

ples from the BK53 pipe have a characteristic feature: their I_n and k_0 values are low (see table and Fig. 2).

The Kenigsberger factor $Q_n = I_n / k_0 H_E$ (where H_E is the intensity of geomagnetic field) of the kimberlites from the Orapa field pipes is above unity and varies from 1.8 to 56.1. This indicates that the induced magnetization $(I_i = k_0 H_E)$ of the studied kimberlites is lower than the natural remanent magnetization; i.e., the contribution of I_n to the total magnetization I = $I_n + k_0 H_E$ in most samples is predominant. Therefore, the anomalous magnetic field above the kimberlite bodies of the discussed pipes is largely determined by remanent magnetization. Considering the fact that the lowest magnetic susceptibility and remanent magnetization were detected in the samples from pipe BK53, the anomalous magnetic field above this pipe should be expected to be lower than above pipes BK56, AK08, and AK06.

It is common knowledge (Trukhin et al., 1983) that the natural magnetic characteristics of rocks, including kimberlites, depend on the concentration of the ferrimagnetic minerals in the rock, the type of ferrimagnetic mineral, the size of ferrimagnetic grains, and other factors, which, in turn, are controlled by the conditions of the rock formation. In order to assess the contributions of different factors to the formation of the magnetic properties of kimberlites, we measured the hysteresis parameters of the samples: the saturation magnetization I_s^{fm} , remanent saturation magnetization I_{rs} , coercive force H_c , and remanent coercive force H_{cr} (table). The saturation magnetization of a rock is proportional to the concentration of the ferrimagnetic phase and the value of its spontaneous magnetization, which is determined by the type of the ferrimagnetic phase. Magnetic susceptibility is also proportional to the concentration of ferrimagnetic grains; it depends on the spontaneous magnetization and grain size of ferrimagnetic minerals. Figure 3 shows a



Fig. 4. The relation between the saturation magnetization and natural remanent magnetization of the kimberlite samples from the Orapa field (Botswana). cl stands for central lobe, and sl stands for southern lobe.

certain correlation between k_0 and I_s^{fm} . In the first approximation, it can be assumed that the magnetic susceptibility of most kimberlite samples is determined by the concentration of the ferrimagnetic phase in them. The scatter in the points is probably due to the difference in the structural and phase state of the ferrimagnetic fraction. I_n is a complex function of the whole set of parameters mentioned above. As seen in Fig. 4, overall, no correlation between I_n and I_s^{fm} is observed. Taking into account the fact that I_s^{fm} of the rock is linearly proportional to the concentration of the ferrimagnetic phase and its spontaneous magnetization, we conclude that the I_n of the studied kimberlites is largely controlled by the type of magnetization and the grain size of ferrimagnetic minerals; i.e., it is determined by the prehistory of the rock and thermodynamic conditions of its formation. Figure 4 also indicates that the largest scatter of the natural magnetic parameters and the lowest correlation between I_n and I_s are revealed in the samples from the AK08 pipe. Therefore, we assume that the kimberlites from this pipe are highly dispersed in terms of composition of their ferrimagnetic grains, their size, and the type of magnetization (table).

Just as the natural magnetic characteristics, the magnetic rigidity of the tested samples (see table) also widely varies throughout the collection: $H_c = 3.1-29.3$ mT, $H_{cr} = 5.6-52.9$ mT. The ratios I_{rs}/I_s and H_{cr}/H_c , which describe the type of domain structure and depend on the size of ferrimagnetic grains, vary within 0.05–0.25 and 1.4–3.45, respectively. According to the Day criterion (Day, Fuller, and Schmidt, 1977), the structure of the magnetic grains of kimberlites sampled from pipes BK53, BK56, AK089, and AK06 mainly corresponds to the pseudo-singledomain (PSD) state $I_{rs}/I_s > 0.1$, $H_{cr}/H_c < 2.5$. The kimberlite samples from the southern lobe of pipe AK06 and sample kv35 from BK35, according to their hys-



Fig. 5. The Day's diagram for the samples of Botswana kimberlites. cl stands for central lobe, and sl stands for southern lobe.

teresis characteristics ($I_{rs}/I_s = 0.04-0.12$, $H_{cr}/H_c = 1.77-3.45$), have larger ferrimagnetic grains (table, Fig. 5). Considering these data, we assume that the smaller values of I_n and Q_n in sample kv35 from pipe AK08 compared to the other samples from this pipe are probably accounted for by the multidomain structure of its ferrimagnetic grains.

Our study of the isothermal magnetic properties shows that kimberlite samples from the poorly diamondiferous pipe BK53 are characterized by low concentration of fine ferrimagnetic inclusions (which is indicated by low I_n , I_s , and k_0), whose magnetic structure corresponds to PSD.

Kimberlites sampled from the southern lobe of pipe AK06, whose diamond grade averages 0.22 carat per ton, have a higher concentration of ferrimagnetic grains whose magnetic structure corresponds to the multidomain state; i.e., these grains are larger than in the samples from the lower-grade pipes.

The Results of Thermomagnetic Analysis

The temperature dependences of saturation magnetization $I_s(T)$ and magnetic susceptibility $k_0(T)$ for the studied collection of kimberlite samples are shown in Figs. 6 and 7. The Curie points T_C derived from these curves are presented in the table.

The thermomagnetic analysis $(I_s(T) \text{ and } k_0(T))$ shows that in the high-temperature interval $(T > T_0 = 20^{\circ}\text{C})$, kimberlite samples from BK53 (Fig. 6a and 7a) mainly contain one magnetic phase whose Curie point varies among different samples from 500 to 580°C. These curves show that kimberlites from this pipe also contain the magnetic phases with T_c below room temperature, because the magnetization in the field of 0.24 T strongly increases at cooling, while the ratio of magnetization at the boiling temperature of liquid nitrogen to that at room temperature



Fig. 6. The temperature dependence of magnetization in the field H = 0.24 T for the kimberlite samples: (a) pipe BK53: 1 sample kv28, 2 sample kv29, 3 sample kv30, 4 sample kv31; (b) pipe BK56: 1 sample kv36, 2 sample kv37, 3 sample kv38; (c) pipe AK08: 1 sample kv33, 2 sample kv34, 3 sample kv35, 4 sample kv39, 5 sample kv40; (d) pipe AK06 (central lobe): 1 sample kv41, 2 sample kv42, 3 sample kv43; (e) pipe AK06 (southern lobe): 1 sample kv44, 2 sample kv45, 3 sample kv46, 4 sample kv47, 5 sample kv48, 6 sample kv49, 7 sample kv50.

 (I_s^{-190}/I_s^{20}) varies among the samples from 1.65 to 2.2. For example, according to the data for $k_0(T)$, the Curie point of this phase in the kimberlite sample kv28 is $T_C = -185^{\circ}$ C (curve 1 in Fig, 7a, table), whereas, according to the $I_s(T)$, $T_C = -100$ to -120° C (curve 1 in Fig. 6a). The magnetic phases with the most probable Curie points at -50 to -110° C and -185° C, -30° C (curves 3 and 4 in Figs, 6a and 7a, respectively) are revealed in the samples kv31 and kv30. In addition to the high-temperature phase with $T_C = 580^{\circ}$ C, sample kv32 is likely to contain also a small amount of ferrimagnetic phase with $T_C = 230^{\circ}$ C, which was detected from the dependence $k_0(T)$ (curve 5, Fig. 7a). We failed to measure the temperature dependence of sat-

uration magnetization I_s because of the low values of this parameter.

Overall, the maximal Curie point determined from the dependence $I_s(T)$ of kimberlite samples from pipe BK53 is higher than that derived from $k_0(T)$ (table). The ferrimagnetic inclusions in sample kv31 probably have a highly dispersed phase composition because the maximum in $k_0(T)$ is observed at about 270°C, while the major drop in magnetic susceptibility only occurs at T = 550°C (curve 3 in Fig. 7a).

The values of T_C determined from the dependences $I_s(T)$ (Fig. 6b) and $k_0(T)$ (Fig. 7b) for the samples from pipe BK56 are close to each other (see table). According to thermomagnetic analysis (TMA), kimberlites



Fig. 7. The temperature dependence of the initial magnetic susceptibility for the kimberlite samples: (a) pipe BK53: *1* sample kv28, *2* sample kv29, *3* sample kv30, *4* sample kv31, *5* sample kv32; (b) pipes BK56 and AK06 (central lobe): *1* sample kv36, *2* sample kv37, *3* sample kv38 from pipe BK56; *4* sample kv41, *5* sample kv42, *6* sample kv43 from pipe AK06; (c) pipe AK08: *1* sample kv33, *2* sample kv34, *3* sample kv35, *4* sample kv39, *5* sample kv40; (d) pipe AK06 (southern lobe): *1* sample kv44, *2* sample kv45, *3* sample kv46, *4* sample kv47, *5* sample kv48, *6* sample kv49, 7 sample kv50.

from this pipe contain ferrimagnetic phases with the Curie points $T_c = +540$ to $+590^{\circ}$ C close to the magnetite Curie points. The dependence $I_s(T)$ at $T > 20^{\circ}$ C is convex. In the temperature interval from -196 to 0° C, the curves $I_s(T)$ of samples kv37 and kv38 are concave, and the ratios I_s^{-196}/I_s^{20} for these samples are 1.4 and 1.8, respectively (table). The Curie points of the low-temperature phases vary from -110° C to -70° C (curves 2 and 3 in Figs. 6b and 7b).

Thus, the TMA of the samples from pipes BK53 and BK56 indicates that very low-grade kimberlites mainly contain two ferrimagnetic phases. One phase has its Curie point close to the Curie point of magnetite $T_c = +550$ to $+600^{\circ}$ C, and the Curie point of the other phase varies among the samples from -50° C to -110° C. Sample kv28 probably contains a phase with $T_c < -185^{\circ}$ C.

The kimberlites from AK08 pipe of grade 0.01– 0.08 carat per ton exhibit Curie points to broadly scatter among the samples. For example, sample kv32 was found to contain a single magnetic phase with the Curie point at 520°C (curves 3 in Figs. 6c and 7c). Samples kv33 and kv39 contain two ferrimagnetic phases with Curie points $T_{C1} = 520$ °C and $T_{C2} = -100$ to -500°C and $T_{C1} = 600$ °C and $T_{C2} = -50$ to -170°C, respectively (table).

The dependence $k_0(T)$ for the sample kv34 reveals two phases with the Curie points $T_{C1} = 420^{\circ}$ C and $T_{C2} = 570^{\circ}$ C (curve 2 in Fig. 7c) at $T < 0^{\circ}$ C and the phase with $T_{C3} = -175^{\circ}$ C at $T < 0^{\circ}$ C. However, the dependence $I_s(T)$ at $T < 0^{\circ}$ C shows the ferrimagnetic phase with $T_{C3} \approx -80^{\circ}$ C (curve 2 in Fig. 6c).

Four ferrimagnetic phases are detected in sample kv40. The Curie points of these phases are $T_{C1} = 310^{\circ}$ C, $T_{C2} = 480^{\circ}$ C, $T_{C3} = -160^{\circ}$ C, and $T_{C4} = -60$ to -80° C (curves 5 in Figs. 6c and 7c). This fact points to the significantly heterogeneous composition of ferrimagnetic minerals in these rocks.

The high ratio $I_s^{-196}/I_s^{20} = 3.2$ and low $I_s^{20} = 0.61$ kA/m, compared to the other kimberlite samples from this pipe (table), suggest a lower concentration of ferrimagnetic phases with the Curie points above 20°C relative to the concentrations of the phases having their Curie points at negative temperatures. Thus, the kimberlite samples from the AK08 pipe feature a broad scatter of their phase compositions and ratios of concentrations of ferrimagnetic phases with the Curie points above and below room temperature (20°C).

Kimberlites from the central lobe of the AK06 pipe were found to contain ferrimagnetic phases with the Curie points ranging from 490°C to 550°C in the temperature interval T > 20°C. The $I_s(T)$ curves at negative temperatures reveal ferrimagnetic phases with $T_C \approx -90$ °C (curve 1 in Fig. 6d) in sample kv41 and $T_C \approx 0$ °C in the samples kv42 and kv43 (curves 2 and 3 in Fig. 6d). The Curie points of these phases derived from the dependence $k_0(T)$ are $T_C = -155$ °C for kv41 and $T_C = -25$ °C for kv43. Sample kv41 containing a low-temperature component ($T_C \approx -90^{\circ}$ C) has quite low I_s and k_0) (see table), which directly depend on the concentration of ferrimagnetic grains with the Curie point above room temperature, and quite a high ratio $I_s^{-196}/I_s^{20} = 2.15$ compared to the other samples from the central lobe of pipe AK06. This means that here we see again the same trends as those revealed in most samples from the low-grade diamon-diferous pipes.

The main contribution to the magnetic properties $I_s(T)$ and $k_0(T)$ of kimberlite samples from the southern lobe of pipe AK06 is provided by the ferrimagnetic phases with the Curie points ranging from 380 to 520°C (Figs. 6e and 7d), which is a distinctive feature of these samples. These samples were also found to contain a small amount of ferrimagnetic phases with the Curie points from 540 to 580°C, which provide an insignificant contribution to the saturation magnetization and magnetic susceptibility. The dependence $k_0(T)$ for sample kv47 recorded the presence of three phases with $T_c = 420$, 520, and 580°C in this sample.

Ferrimagnetic phases with Curie points below room temperature in kimberlites from the southern lobe of the AK06 pipe were only revealed in two samples (kv44 and kv45). The curve $k_0(T)$ for sample kv44 (curve 1 in Fig. 7d) clearly shows the phases with the Curie points T_c at -170 and -20° C. The Curie point derived from $I_s(T)$ at $T < 0^{\circ}$ C is observed at $T_c = -100^{\circ}$ C. The kv45 kimberlite is found to contain also a small amount of ferrimagnetic phase with $T_c = -140^{\circ}$ C, which is indicated by a small peak in the curve $k_0(T)$ and the ratio $I_s^{-196} / I_s^{20} = 1.28$. Sample kv48 also features a high ratio $I_s^{-196}/I_s^{20} =$ 1.34 (table); however, the curves $k_0(T)$ do not have any peculiarities in the temperature interval from -190 to $+20^{\circ}$ C (curve 5 in Fig. 7d). The shape of the curve $I_s(T)$ at $T < 20^{\circ}$ C (curve 5 in Fig. 6e) suggests the presence of a phase with $T_C = -110^{\circ}$ C in this sample.

THE RESULTS OF MINERALOGICAL ANALYSIS

The mineralogical analysis of the studied kimberlites was carried out for 11 samples from different pipes. We tested five samples (kv44, kv46, kv47, kv48, and kv50) from the southern lobe and two samples (kv41 and kv43) from the central lobe of a relatively higher-grade pipe AK06; two samples (kv40 and kv 34) from the low-grade AK08 pipe; and samples kv37 and kv30 from the barren BK56 and BK53 pipes, respectively.

Our mineralogical analysis shows that the groundmass of the studied Botswana kimberlites contains spinelides, which are probably responsible for natural magnetization of kimberlites, and picroilmenites. The triangular graphs in the coordinates of the main minals shown in Figs. 8a–8i reflect the key features of the chemical composition of the spinelides from the kimberlites of the studied bodies.

Idiomorphic zonal grains ranging from 10 to 80 µm are widespread in the kimberlite groundmass in all samples from the *southern lobe of AK06 pipe*. The central and marginal parts of these grains are composed of chromspinelides and ferrispinelides, respectively (Fig. 9). The chromspinelides are typically represented by chrome-rich Ti-bearing picrochromites (40.4–49.4 wt % Cr₂O₃; 9.1–13.3 wt % MgO; 6.5– 13.6 wt % Al_2O_3 ; 3.9–7.5 wt % TiO₂) and rarer, by the intermediate- and low-chrome picrochromites with a higher Ti content (23–38 wt % Cr₂O₃; 9.6–13.9 wt % MgO; 5.8-6.7 wt % Al₂O₃; 7.5-14.7 wt % TiO₂). Many samples contain larger (up to 600 µm) clasts of xenograins of chromites (52-66 wt % Cr₂O₃; 2.1-11.3 wt % Al_2O_3 ; 0.5–1.9 wt % TiO₂) and aluminum chromites (33.8-34.5 wt % Cr₂O₃; 35.7-35.9 wt % Al_2O_3 ; 0–0.34 wt % TiO₂), which are the products of the disintegration of mantle rocks.

Besides forming the outer rims around the chrome spinelides, ferrispinelides also occur as independent grains, intergrowths with perovskite, or replacement rims around numerous xenocrysts of picroilmenite. The composition of ferrispinelides in the groundmass of kimberlites differs among the samples. Ferrispinelides in samples kv44 and kv50 are mainly composed of magnesian titanomagnetite (5.2-7.9 wt % MgO; 6.8–10.4 wt % TiO₂ rich in magnetite minal (65– 74 mol % FeFe₂O₄) with a moderate content of ulvospinel minal and its magnesian counterpart $(17.8-27 \text{ mol }\% \text{ Fe}_{2}\text{TiO}_{4} + \text{Mg}_{2}\text{TiO}_{4})$. Samples kv46, kv47, and kv48 are dominated by magnesian titanomagnetite with a higher Ti content (5-10.7 wt % MgO; 10.2-17.3 wt % TiO₂) (compared to samples kv44 and kv50), in which the amount of magnetite minal is reduced (44.5-64 mol % FeFe₂O₄) and the sum $Fe_2TiO_4 + Mg_2TiO_4$ makes up 27.5–45 mol %. Some samples (kv44, kv47, and kv48) contain rare inclusions of ferrispinelides (7-10.5 wt % MgO; 17.4-21.4 wt % TiO₂) with an even higher concentration of ulvospinel components (45.3-4 mol % Fe₂TiO₄ + $Mg_{2}TiO_{4}$). Typically, these inclusions are confined to the rims of the picroilmenite xenocrysts, make intergrowths with perovskite, or form exsolution bodies in picroilmenite.

The broadest compositional diversity of ferrispinelides is revealed in sample kv48, in which the microcrystalline spinelides show almost continuous crystallization trend from the chrome-rich picrochromite to the low-Ti titanomagnetite (Fig. 8d). The groundmass of the samples kv44 and kv46 also contains Mg-bearing magnetite (3–4 wt % MgO; 0–3.5 wt % Cr_2O_3 ;



Fig. 8. The compositional diagrams in the coordinates of the main minals for spinelides from the groundmass of Botswana kimberlites: (a)–(e) pipe AK06 (southern lobe); (f), (g) pipe AK06 (central lobe); (h) pipeAK08; (i) pipe BK56. Notations: 1, 2 the center and margin of zonal patches, respectively; 3 inclusions in olivine phenocrysts; 4 xenocrysts; 5 separate homogeneous grains, sometimes intergrowths with perovskite; 6 rims surrounding picroilmenite; 7 exsolution textures in picroilmenite.

92–98 mol % FeFe₂O₄); sample kv47 contains pure magnetite without admixtures.

Large (typically, from 200 um to 6 mm, rarely up to 1 cm) xenograins of Cr-bearing magnesian ilmenite from deep ilmenite-bearing rocks are detected in all samples from the southern lobe of the AK06 pipe. Almost all grains of magnesian ilmenite are, to a different extent, replaced by perovskite-ferrispinelide aggregates (Figs. 9d-9f). The replacements either occur in the form of a narrow rim framing the grain at its edge, or occupy almost the entire grain volume. The unaltered segments of such grains in some cases have a homogeneous structure and are represented by picroilmenite (8.2–12.5 wt % MgO; 2–3.5 wt % Cr₂O₃; 46.2–48.5 wt % TiO₂) with 12.2–13.6 mol % of hematite minale. In other cases, they contain fine exsolution textures (Figs. 9e and 9f). The matrix of heterogeneous segments of magnesian ilmenite contains 6.78.2 wt % MgO; 1.9–2.6 wt % Cr_2O_3 ; 44.8–47 wt % TiO₂; and 14.7–16.2 mol % Fe₂O₃. The exsolution bodies are composed of Cr-bearing magno-titanomagnetite (2.1–8.9 wt % Cr_2O_3 ; 5.9–6.3 wt % MgO; and 7–12.8 wt % TiO₂) containing 60.9–66 mol.% of magnetite minal (FeFe₂O₄), or, more rarely, Cr-bearing magno-ulvospinel (5 wt % Cr_2O_3 ; 6.9 wt % MgO; and 20.4 wt % TiO₂) with 54 mol % Mg₂TiO₄ + FeMg₂TiO₄. Fine grains of ilmenite (about 50 µm), which probably were directly crystallized from kimberlite melt, feature a higher percentage of magnesium and chrome and minor amount of hematite minal (13.5–15.2 wt % MgO; 2.6–3.4 wt % Cr_2O_3 ; 52.1– 52.6 wt % TiO₂; 6.4–6.8 mol % Fe₂O₃).

The groundmass of kimberlites from the *central lobe of the AK06 pipe*, in contrast to the southern lobe, does not contain Cr-rich microcrystalline picro-



Fig. 9. Oxide minerals from the groundmass of kimberlites from the southern lobe of pipe AK06: (a)–(c), (e) zonal spinelides with picrochromite cores and titanomagnetite rims; (d), (f) resorbed picroilmenite grains with titanomagnetite (\pm perovskite) rims and exsolution textures ((e),(f)). (a), (b), (e) sample kv44; (c) sample kv47; (d) sample kv48; (f) sample kv46. *Chr* picrochromite, *Ti-Mag* titanomagnetite, *Mag* magnetite, *Ilm* picroilmenite, *Per* perovskite. Backscatter electron images are shown.

chromites. Low-Cr picrochromites with up to 20-29.2 wt % Cr₂O₃ with 10.8–12.4 wt % TiO₂ are identified in sample kv41. These picrochromites form the inclusions in the olivine phenocrysts and the grains with sphene rims (CaTi(SiO₄)O). The kimberlite

chromspinelides themselves are not detected in sample kv43; however, the grains of xenogenic chromespinelides with a size up to 150 μ m, which contain 55– 62 wt % Cr₂O₃; 8–12.4 wt % MgO; 1–1.8 wt % TiO₂; and 1.1–8.9 wt % Al₂O₃, are identified.

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In addition, kimberlites of both studied samples from the central lobe of the AK06 pipe differ from the rocks of the southern lobe by the abundance of Ti-rich spinelides: the magnesian-chrome (12.8-14.2 wt %)MgO; 7.4–11.3 wt % Cr₂O₃; 15.9–17.8 wt % TiO₂; 5.9-7 wt % Al₂O₃) and magnesian (14.4-18.4 wt % MgO; 0.7–2.2 wt % Cr₂O₃; 20.9–24.9 wt % TiO₂; 5.5–7.7 wt % Al_2O_3) ulvospinels. The percentage of ulvospinel minal and its magnesian equivalents $(Fe_2TiO_4 + Mg_2TiO_4)$ in the mentioned ulvospinel varieties is 39.7-43.5 and 51-58 mol %, respectively. Ulvospinels form the cores of numerous zonal patches with the sphene rims (Fig. 10); magnesian ulvospinel occurs in the form of inclusions in perovskite, independent grains, and rims around numerous xenograins of picroilmenite and rare xenograins of chrome-spinelides.

In sample kv34, besides ulvospinels, magnesian titanomagnetite is also abundant (11.4–17.3 wt % MgO; 0–0.6 wt % Cr₂O₃; and 4.2–5.6 wt % TiO₂), in which the sum of magnetite and magnesian-ferrite minal (FeFe₂O₄ + MgFe₂O₄) makes up 80.5–85.7 mol %. It forms separate grains and capsule-like outer rims around the ulvospinel-sphene segregations (Fig. 10b).

Ilmenite in the kimberlites of the central lobe of pipe AK06 occurs in the form of large (from 150 µm to 3 mm) xenograins (Fig. 10d) with varying composition (7.7–13.9 wt % MgO; 0–3.83 wt % Cr₂O₃; 45.2– 52.9 wt % TiO₂; 5.7–14.3 mol.% Fe₂O₃) and microcrystalline (typically, 15-50, more rarely up to $100 \,\mu\text{m}$) segregations of Cr-bearing picroilmenite (13.7-17.3 wt % MgO; 2–3.9 wt % Cr₂O₃; 50.2–53.7 wt % TiO₂; $3.3-8.2 \text{ mol } \% \text{ Fe}_2\text{O}_3$), which often form inclusions in the olivine phenocrysts. The grains of magnesian (7.9–15.8 wt % MgO) ilmenite up to 100 µm in size with a manganese admixture (up to 4.3 wt % MnO) are present. The margins of picroilmenite grains are frequently replaced by magnesian ulvospinel, sphene, and perovskite. Single grains of magnesian ilmenite contain exsolution bodies. It is remarkable that sphene, which is rare in the samples from the southern lobe, is abundant in the kimberlites of the central lobe of the AK06 pipe (Fig. 10).

In terms of their composition and structure, spinelides from the groundmass of kimberlites from the **AK08 pipe** (sample kv40) are generally quite similar to the spinelides from the central lobe of the AK06 pipe described above. The absence of microcrystalline Crrich picrochromites is common; the maximal Cr content in the identified chromspinelides is 17.5-28.6 wt % Cr₂O₃ with 9.3-12.1 wt % TiO₂. Sometimes, the finest relics of xenogenic chrome-spinelides (56-63.5 wt % Cr₂O₃; 2-2.9 wt % TiO₂; 0.9-1.1 wt % Al₂O₃) are detected in the central parts of picrochromites, which probably served as the seeds for the growth of kimberlite chrome-spinelides themselves. The spinelide segregations are strongly altered. They form complex structures in which the chrome-spinel nuclei are encapsulated in the magnesian ulvospinel envelope surrounded by rutile-perovskite aggregates and the outer casing-like magnetite rim (Fig. 11b). Magnesian ulvospinel (15.7–20 wt % MgO; 1.2–2.9 wt % Cr₂O₃; 16.2–23.5 wt % TiO₂; 4.9–12.4 wt % Al₂O₃) occurs as numerous separate grains and, together with perovskite, forms the rims around picroilmenite segregations (Figs. 11a and 11b). The content of Fe_2TiO_4 + Mg_2TiO_4 in it is 46.6–56 mol %. We note that microspinelides of the groundmass of kimberlites from the AK08 pipe differ from the spinelides from the other bodies by a higher aluminum content (typically, 10.9–15.4 wt % Al₂O₃).

Picroilmenite in kimberlites from the AK08 pipe (samples kv40 and kv34) occurs as fine $(5-80 \ \mu m)$ segregations, probably exsolved from kimberlite melt, and large (100 μm to 5 mm) xenograins from typhonic rocks. Fine picroilmenite is rich in magnesium and chrome (13.4–18.8 wt % MgO and 2.5–5 wt % Cr₂O₃) and poor in hematite minal (5.4–7.7 mol % Fe₂O₃).

Picroilmenite xenograins also contain an admixture of chromium $(2-4.9 \text{ wt }\% \text{ Cr}_2\text{O}_3)$ and widely vary in the contents of magnesium and ferric iron $(7.6-18.4 \text{ wt }\% \text{ MgO} \text{ and } 6.1-14.2 \text{ mol }\% \text{ Fe}_2\text{O}_3)$. Typically, the largest grains (0.8-5 mm) are richer in hematite minal (above 11 mol %). These are most abundant in sample kv34. Picroilmenite grains with exsolution bodies are not detected.

Microcrystalline spinelides in the groundmass of kimberlites from **BK56 pipe** (sample kv37) are mainly represented by picrochromite and magnesian ulvospinel. Picrochromites form segregations 5- $20 \,\mu m$ in size, which compose the cores of zonal patches rimmed by magnesian ulvospinel (Fig. 12a), and rare inclusions in olivine phenocrysts. They are rich in chromium and have a relatively low Ti content (41.8-49 wt % Cr₂O₃; 5.5-7.7 wt % TiO₂; 11.9-13.9 wt % MgO). The presence of Cr-rich picrochromites indirectly indicates that these rocks are potentially diamondiferous, although, according to the preliminary sampling, this pipe is of a very low grade. Chromspinelides are detected (up to 59.9 wt % Cr_2O_3), whose segregation size (100-300 µm) and composition correspond to xenospinels from typhonic rocks.

Magnesian ulvospinels (16.4–22.8 wt % MgO; 0– 9 wt % Cr₂O₃; 19.8–24 wt % TiO₂; 4.3–10.7 wt % Al₂O₃) form separate grains and rims around chromespinelides and xenograins of picroilmenite; they contain 46.3–55 mol % Fe₂TiO₄ + Mg₂TiO₄. In the reaction, rims of the aggregate structure around picroilmenite, magnesian ulvospinel with higher Ti content (up to 29.7 wt % TiO₂ and 69 mol % Fe₂TiO₄ +



Fig. 10. Oxide minerals from the groundmass of kimberlites from the central lobe of pipe AK06: (a)–(c) magnesian-chrome and magnesian ulvospinels with the rims of sphene and magnesian titanomagnetite (sample kv43); (d) picroilmenite replaced by sphene and magnesian ulvospinel on the margin (sample kv41). *Ulv-Spl* ulvospinel; *Ti-Mag* titanomagnetite; *Ilm* picroilmenite; *Sph* sphene; *Per* perovskite. Backscatter electron images are shown.

 Mg_2TiO_4) and magnesian titanomagnetite (17 wt % MgO; 4 wt % TiO₂; 1.2 wt % Cr₂O₃) are present. The tiniest outer rims of these structures are probably formed by magnetite.

The picroilmenite segregations identified in the sample are 100–500 μ m in size, contain exsolution textures, and are surrounded by thick reaction rims, which have complex structures and are composed of magnesian ulvospinel, perovskite, magnesian titanomagnetite, sphene, and magnetite (Fig. 12b). The bulk composition of picroilmenite with the lamellae of ferrispinelides measured for the site is characterized by very high Mg content (22–23.4 wt % MgO) and broadly varying percentage of chromium and hematite minal (1.4–5.9 wt % Cr₂O₃ and 6.6–15.5 mol % Fe₂O₃).

In the groundmass of kimberlites from BK53 pipe (sample kv30), oxide minerals are far less abundant than in the samples from the other bodies. Chromspinelides are not identified; and fine (20–

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 $50\ \mu m$), strongly resorbed segregations of Ti-rich ferrispinelides rimmed by sphene are present.

Xenograins (up to 550 μ m) of Cr-bearing picroilmenite (12.8–18.3 wt % MgO; 1–4.8 wt % Cr₂O₃; 5– 12.2 mol % Fe₂O₃), typically containing the finest exsolution bodies presumably represented by ferrispinelides, occur. The margins of picroilmenite grains are replaced by magnesian ulvospinel (up to 18.5 wt % MgO; 23.6 wt % TiO₂; 0.95 wt % Cr₂O₃), which contains about 55 mol % Fe₂TiO₄ + Mg₂TiO₄, and sphene. The tiniest outer rim around the sphene, which, in turn, surrounds ferrispinelides and picroilmenite, is composed of magnetite, which also forms small separate grains.

CORRELATION OF THE MAGNETIC AND MINERALOGICAL RESULTS

Using the data of microprobe analysis, we calculated the Curie points of ferrispinelides identified in eight samples (kv50, kv48, kv46, kv44, kv43, kv41,



Fig. 11. Oxide minerals of the kimberlite groundmass from pipe AK08: (a), (b) zonal patches of complexly structured spinelides with picrochromite-ulvospinel cores and perovskite-rutile rims; (c), (d) picroilmenite replaced by magnesian ulvospinel and perovskite. (a)–(c) sample kv41; (d) sample kv34. *Chr* picrochromite; *Ulv-Spl* ulvospinel; *Mag* magnetite, *Ilm* picroilmenite; *Per* perovskite; *Rut* rutile. Backscatter electron images are shown.

kv40, and kv37) from the compositions of the minals. The Curie points were estimated from the dependence of the composition on the Curie point for the solid solution $(1 - x)Fe_3O_4xFe_2TiO_4$ (Lattard et al., 2006), assuming that the content of magnesian equivalent of ulvospinel (Mg₂TiO₄) in spinelide reduces the Curie point to the same extent as ulvospinel (Fe₂TiO₄) and from a similar dependence for solid solution yFe_3O_4 $(1 - y)FeCr_2O_4$ (Robins et al., 1971). Here it was assumed that the presence of the MgCr₂O₄ minal reduces the Curie point to the same extent as the presence of the FeCr₂O₄ minal. The Curie points of more complex mineral compositions were determined as a superposition of the states $T_C = f(x)$ and $T_c = f(y)$.

The comparison shows that the Curie points derived from TMA for kimberlite samples from the southern lobe of the AK06 pipe quite well agree with the Curie points predicted from the data of mineralogical analysis (see table). For example, the Curie points measured in samples kv50 (T_c = +400 to +410°C) and

kv48 ($T_c = +370^{\circ}$ to 380°C) fall well within the interval of their predicted values ($T_{C \text{ pred}} = +350 \text{ to } +410^{\circ}\text{C}$ and +100 to +400°C, respectively, for the margins of zonal patches and separate spinelide grains (Figs. 8d and 8e). The wider interval of the expected Curie points for sample kv48, compared to sample kv50, is due to the presence of the almost continuous crystallization trend of ferrispinelides in the composition of this sample, as revealed by TMA (Fig. 8d). This accounts for the more intense decrease in $I_s(T)$ in the temperature interval from +100 to +350°C (curve 4 in Fig. 6e) and the slower decrease in $k_0(T)$ in the interval from 300 to 560°C (curve 5 in Fig. 7d).

According to TMA, the kimberlite samples from pipe AK06 contain a minor amount of the material that is compositionally close to magnetite ($T_{\rm C} = +540$ to 580°C). The mineralogical analysis, indeed, identified the inclusions of pure magnetite in the samples kv44 and kv47. Magnetite with small Mg content (3–4 wt % MgO) is detected in sample kv46. In



Fig. 12. Oxide minerals of the kimberlite groundmass from pipe BK56 (sample kv37): (a) zonal patch with picrochromite core, intermediate rim of magnesian ulvospinel and outer rim of magnetite; (b) picroilmenite with exsolution textures and polymineral rim composed of magnesian ulvospinel, sphene, magnesian titanomagnetite, perovskite, and magnetite. *Chr* picrochromite; *Ulv-Spl* ulvospinel; *Ti-Mag* titanomagnetite; *Mag* magnetite; *Ilm* picroilmenite, *Per* perovskite; *Sph* sphene. Backscatter electron images are shown.

the latter case, according to the relation $C_{\rm wt\%MgO} = 85 - 0.149 \times T_{\rm C}$ (Kudryavtseva, 1982), the predicted Curie point is +540 to +550°C, which nearly coincides with $T_{\rm C\ meas} = +520$ to +540°C. According to TMA, samples kv41, kv48, and kv50 (Figs. 8d, 8e, and 8f) also contain a small amount of ferrispinelides with the Curie points close to $T_{\rm C}$ of magnetite. The absence of mineralogical data for these samples is probably due to the fact that these sites were not selected for the collection intended for mineralogical analysis.

As noted above, the TMA data for some kimberlite samples from the southern lobe of pipe AK06 (samples kv44, kv45, and kv48) and its central lobe (samples kv41-kv43) suggest that these samples contain a ferrimagnetic phase with the Curie point below room temperature $T_{\rm C} = -20$ to -170° C (see table). This feature is most prominent in samples kv41 and kv44 (Figs. 6d and 7d). Ferrimagnetic phases with $T_{\rm C} = -170$ to -90° C, which are contained in the kimberlites from the southern lobe of AK06 pipe, are probably Mg-rich picrochromites, which, according to mineralogical analysis, are located at the center of the zonal patches (Fig. 8 and Figs. 9a, 9b, and 9e), because the predicted Curie points $T_{\rm Cpred} = -180$ to -80° C for these samples are rather close to the measured values.

The Curie points -25° C to 0°C in samples kv43 and kv44 probably correspond to spinelides with 39.7 to 58 mol % of Fe₂TiO₄ + Mg₂TiO₄, which form the cores of numerous zonal patches and are present in the form of inclusions in perovskite, separate grains, and rims surrounding the abundant xenograins of picroilmenite. Their predicted Curie points fall in the interval from 0°C to approximately 120°C.

The phase with the Curie point $T_{\rm C} = +490$ to $+540^{\circ}$ C, which is detected in kimberlite sampled from

the central lobe of the AK06 pipe, is determined as magnesian titanomagnetite with 80.5–85.7 mol % of FeFe₂O₄ + MgFe₂O₄, because their measured Curie points almost coincide with the predicted values $T_{C \text{ pred}} = +450$ to 500°C.

Considering the higher ratios $I_s(-190)/I_s(20) = 1.61-2.15$ in these samples, we can state that the contribution of the low-temperature phases with the Curie points $T_C < 20^{\circ}$ C to the magnetic properties of kimberlites from the central body of pipe AK06 is larger than in the kimberlites from the southern body of this pipe, for which this ratio is $I_s(-190)/I_s(20) < 1.4$.

As mentioned above, the magnetic properties of the samples from pipes BK53, BK56, and AK08 differ from those for the samples from the AK06 pipe by the lower concentration of the ferrimagnetic phases with the Curie points above room temperature, compared to the phases with $T_{\rm C} < 0^{\circ}$ C.

The comparison of the magnetic and mineralogical data indicates that, e.g., the ferrimagnetic phase with $T_{\rm C} = -60$ to -80° C in sample kv40 is composed of chromspinelides from the center of zonal patches with 17.5–28.5 wt % of Cr₂O₃, because their $T_{\rm C \ pred} = -10$ to -120° C. The Curie point $T_{\rm C} = -160^{\circ}$ C is probably due to xenogenic chromspinelides with 80–89 mol % of the minals FeCr₂O₄ + MgCr₂O₄ ($T_{\rm C \ pred} \le -170^{\circ}$ C).

The Curie point $T_{\rm C} = 310^{\circ}{\rm C}$ detected in sample kv40 is probably associated with the grains and the rim around picroilmenite with 46.6–56 mol % of the minals (Fe₂TiO₄ + Mg₂TiO₄), because their $T_{\rm C\ pred} = 0$ to +240°C. The phases with the Curie points at +480 to +500°C were probably not included in the collection for the mineralogical analysis due to their low concentration, as indicated by the large ratio

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 $I_s(-190)/I_s(20) = 3.2$. The significant discrepancy between the measured and predicted Curie points in this sample is probably accounted for by the strongly dispersive composition of spinelides and, perhaps, by the increased Al content (10.9–15.4 wt %).

An even stronger discrepancy between the measured and predicted Curie points was observed in the sample kv37 from poorly diamondiferous pipe BK56. As mentioned above, TMA revealed two magnetic phases mainly present in this sample. $T_{C1} = 570^{\circ}$ C corresponds to the finest magnetite rims that surround picroilmenite and magnesian ulvospinel. We failed to identify the Curie point $T_{C2} = -70$ to -110° C, since magnesian ulvospinel with 55–69 mol % of Fe₂TiO₄ + Mg₂TiO₄ should provide the Curie points in the interval from approximately 0°C to 100°C, whereas the predicted Curie point of picrochromite $T_{C pred} = -140$ to -200° C.

CONCLUSIONS

The study of the magnetic and mineralogical properties of kimberlites from four pipes in Botswana shows that the pattern of their magnetic characteristics, as well as the chemical and phase composition of oxides from the groundmass reflect the differences in the evolution of kimberlite melts and the formation conditions of the studied bodies.

Microcrystalline (<100 µm) spinelides in all samples from the southern lobe of pipe AK06 are represented by picrochromites and magnesian titanomagnetite. Picrochromites from the earliest stages of crystallization of kimberlite melt have high Cr and low Ti content (up to 49.4 wt % Cr₂O₃ with 3.9 wt % TiO₂), which indicates that the pipe-forming melts originate from a region of thermodynamic stability of diamonds deep in the Earth's interior and present an indirect evidence of the body to be potentially diamondiferous (Garanin, 2009). The distinctive feature of picroilmenite in these kimberlites is that they reside in the paramagnetic state at $T > -180^{\circ}$ C.

The composition of titanomagnetite varies among the samples; however, the high content of admixtures is characteristic overall. Spinelides with increased Ti-content (17.8–21.4 wt % TiO₂), whose compositions are dominated by ulvospinel species (22.9– 37.3 mol % Fe₂TiO₄ and 16.8–22.3 mol % Mg₂TiO₄), are very rare; their formation is mainly associated with the alteration and replacement of picroilmenite.

These data indicate that the late crystallization of kimberlites from the southern lobe of pipe AK06 occurred in the conditions of high oxidation with the relatively passive behavior of titanium. The high oxygen activity in this system probably resulted in the formation of the signs of etching and corrosion on the surface of diamond crystals. The almost continuous crystallization trend of spinelides from Cr-rich picrochromite to titanomagnetite with low Ti content, which is shown in some samples (kv48 and kv47), suggests that separate portions of the kimberlite melt slowly ascended towards the surface, and this process was accompanied by the gradual decrease in the *PT*-parameters and increase of oxidation potential in the mineral-forming medium.

Overall, we can say that due to the slowly decreasing *PT*-conditions, titanomagnetites with a high content of magnetite minal (mainly 65–74 mol % FeFe₂O₄ (17.8–27 mol % Fe₂TiO₄ + Mg₂TiO₄) with the Curie points at 370–500°C and rarer 44.5– 64 mol % FeFe₂O₄ (27.5–45 mol %. Fe₂TiO₄ + Mg₂TiO₄)) were formed in the kimberlites from the southern lobe of the AK06 pipe. The ferrimagnetic grains have rather large sizes, which correspond to the multidomain structure. This also accounts for the low remanent magnetization and low Kenigsberger parameter against relatively high saturation magnetization.

The characteristic feature of the assembly of microcrystalline spinelides of the kimberlite groundmass from the central lobe of the AK06, AK08, and BK56 pipes, which sharply distinguishes them from spinelides of the southern lobe of AK06 pipe, is the predominance of Ti-rich spinelides (15.9-29.7 wt % TiO₂; 12.8–22.8 wt % MgO; 0–11.3 wt % Cr₂O₃; and 1.2–12.4 wt % Al₂O₃), namely, magnesian–chrome and magnesian ulvospinels. In the composition of these spinelides, the sum $Fe_2TiO_4 + Mg_2TiO_4$ makes up 39.7-69.8 mol %, and the content of ulvospinel minal $(1.9-26.4 \text{ mol }\% \text{ Fe}_2\text{TiO}_4)$ is typically far lower than the content of the magnesian equivalent of ulvospinel (25.1-52.7 mol % Mg₂TiO₄). The Curie points of these ferrispinels mainly fall in the interval from -50 to -80° C and, probably, closer to 0° C. Their magnetic properties above room temperature are determined by the presence of minor amounts of finely dispersed magnetite with a single-domain and pseudo-single-domain structure.

Thus, the main portion of ferrispinelides of these bodies was crystallized at higher PT-parameters than in the southern lobe of AK06 pipe in the environment with very high Ti activity. In this situation, the chrome-spinelides that were segregated previously turned out to be unstable and were actively replacedinitially by ulvospinels and then by perovskite, sphene, and sometimes rutile. This resulted in the formation of complex polymineral aggregates in which chromspinelides are almost not preserved or present in the form of small relics. These conditions are highly unfavorable for the preservation of chromspinelides and diamonds and, probably, they could have been the cause of the intensive dissolution of diamonds. We note that the abundance of ulvospinels among the microcrystalline oxides in the groundmass of kimberlites from Yakut province is mainly peculiar to the kimberlites of low-grade diamondiferous and barren pipes (Garanin et al., 2009).

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ACKNOWLEDGMENTS

The work was supported by the Russian Foundation for Basic Research (grant no. 11-05-00740).

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