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Petromagnetism and paleomagnetism of kimberlite pipesof the Verkhnemunskoe deposit (Yakutsk diamondiferous province)

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Abstract. The purpose of the studies of kimberlite pipes of the Verkhnemunskoe diamond field is to calculate the Middle Paleozoic paleomagnetic pole to clarify the trajectory of the apparent migration of the pole and reconstructions of the paleogeographic position of the Siberian platform at the time of the manifestation of active tectono-magmatic processes. The Verkhnemunskoye deposit is located within the Verkhnemunskoye kimberlite field of the Yakutsk diamondiferous province and includes five kimberlite pipes (Deimos, Zapolyarnaya, Komsomolskaya-Magnitnaya, Novinka and Poiskovaya), the age of which according to geological and isotopic data is estimated as Late Devonian-Early Carboniferous (372–347 Ma). For the first time scalar and vector physical parameters of kimberlites and captured xenoliths from different structural-material complexes of the Earth's crust, as well as the host terrigenous sedimentary rocks of the Early Paleozoic were obtained, which are necessary for the development of physical-geological models of the Verkhnemunskoe field deposits. A relatively deep level of erosional shearing of the field has been established. The primary (synchronous with the formation of the field) natural residual magnetization was preserved in the kimberlite cohesive mass. The main carrier minerals of natural remanent magnetization vectors of kimberlites are unaltered magnesioferrite and magnetite, which indicates their thermo-sufficient nature. The natural remanent magnetization vectors of captured xenoliths indicate that the influence of hypergenic processes did not strongly affect the NRM vectors of kimberlites. Firing test is positive. The paleomagnetic pole with coordinates Φ = 26.5°N, Λ = 142.2°E, *dp/dm* = 6.2/7.8° was calculated from the obtained clusters of N = 10 vectors of the primary natural remanent magnetization of kimberlite pipes. On its basis, we reconstructed the paleogeographic position of the Siberian Platform, which at the time of the kimberlite intrusion was located in the middle latitudes of the northern hemisphere and was facing north with its southern edge.

Keywords: Yakutsk diamondiferous province, Verkhnemunskoe deposit, kimberlite pipes, Zapolyarnaya, Deimos, Komsomolkaya-Magnitnaya, Novinka, Poiskovaya, kimberlites, Middle Paleozoic, paleomagnetism, magnetites, magnesioferrites

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ГОРНОПРОМЫШЛЕННАЯ И НЕФТЕГАЗОПРОМЫСЛОВАЯ ГЕОЛОГИЯ, ГЕОФИЗИКА, МАРКШЕЙДЕРСКОЕ ДЕЛО И ГЕОМЕТРИЯ НЕДР

Научная статья
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Петромагнетизм и палеомагнетизм кимберлитовых трубок Верхне-Мунского месторождения (Якутская алмазоносная провинция)

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Резюме. Цель проведенных исследований кимберлитовых трубок Верхне-Мунского месторождения алмазов заключалась в расчете среднепалеозойского палеомагнитного полюса для уточнения траектории кажущейся миграции полюса и реконструкций палеогеографического положения Сибирской платформы на время проявления активных тектоно-магматических процессов. Верхне-Мунское месторождение расположено в пределах Верхне-Мунского кимберлитового поля Якутской алмазоносной провинции и включает пять кимберлитовых трубок («Деймос», «Заполярная», «Комсомольская-Магнитная», «Новинка» и «Поисковая»), возраст которых по геологическим и изотопным данным оценивается как поздний девон – ранний карбон (372–347 млн лет). Впервые получены скалярные и векторные физические параметры кимберлитов и захваченных ими ксенолитов из разных структурно-вещественных комплексов земной коры, а также вмещающих терригенно-осадочные породы раннего палеозоя, необходимые для разработки физико-геологических моделей месторождений Верхне-Мунского поля. По данным анизотропии магнитной восприимчивости установлен относительно глубокий уровень эрозионного среза месторождения. Согласно палеомагнитным данным, в связующей массе кимберлитов сохранилась первичная (синхронная становлению месторождения) естественная остаточная намагниченность. Основными минералами-носителями векторов естественной остаточной намагниченности кимберлитов являются неизмененные магнезиоферрит и магнетит, что свидетельствует об их термоостаточной природе. Векторы естественной остаточной намагниченности захваченных ксенолитов указывают на то, что влияние гипергенных процессов не сильно отразилось на векторах естественной остаточной намагниченности кимберлитов. Тест «обжига» вмещающих пород положительный, что указывает на первичную природу характеристической естественной остаточной намагниченности кимберлитов. По полученным кластерам N = 10 векторов первичной естественной остаточной намагниченности кимберлитовых трубок рассчитан палеомагнитный полюс с координатами Φ = 26,5° с. ш., Λ = 142,2° в. д., dp/dm = 6,2/7,8°. Палеомагнитное датирование векторов естественной остаточной намагниченности кимберлитов Верхне-Мунского месторождения соответствует среднему палеозою. На основе рассчитанного палеомагнитного полюса реконструировано палеогеографическое положение Сибирской платформы, которая на момент внедрения кимберлитов находилась на средних широтах северного полушария и была обращена к северу своим южным краем.

Ключевые слова: Якутская алмазоносная провинция, Верхне-Мунское месторождение, кимберлитовые трубки, Заполярная, Деймос, Комсомольская-Магнитная, Новинка, Поисковая, кимберлиты, средний палеозой, палеомагнетизм, магнетиты, магнезиоферриты

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Introduction

Apparent polar wander paths (APWP) [1] are dynamic physical geological models (PhGM) of continental drift [2], characterizing the features of the development of the Earth's lithosphere, patterns of location of endogenous and exogenous mineral deposits on it, etc. On their basis, various geological problems can be solved, for example, dating of barren geological processes, geodynamic reconstructions of blocks of the Earth's crust (terranes), orogeny (*Greek*, "óros" is a mountain and <...> "genesis" is origin, occurrence), minerageny. There are several different APWP for the Siberian platform [3–5, etc.], which require clarification. One of such important segments of the APWP of the Siberian Platform belongs to the Middle

Paleozoic era, when active tectonic-magmatic events, determining the manifestations of kimberlite and basite magmatism, happened [6]. Diamond deposits on the Siberian platform are associated with the first tectonic-magmatic events. In this regard, the clarification of the APWP (dynamic PhGM) The Siberian platform is an urgent problem, the solution of which determines our understanding of the processes of kimberlite formation, which will contribute to the prediction of new deposits of diamonds and other minerals in Eastern Siberia. To clarify the APWP, you need to know:

1. Age of the paleomagnetic research object.
2. The average direction of the vectors of characteristic natural remanent magnetization[1] (NRM, In^{ch} is the most stable component of the NRM isolated during magnetic cleaning, goes to 0 on the Zijderveld vector diagram) with high statistical indicators.
3. Nature In^{ch} (to date and assess the nature of the characteristic remanent magnetization, a set of additional studies is required, which includes three groups of features: geological, physical and geophysical features).

Practically all kimberlite bodies of the Yakutsk diamondiferous province (YaDP) of the Siberian platform are promising objects for achieving this goal, since they are quite well studied in geochronological terms [7]. For their dating, age-related reference points of a geological nature are used, such as the age of the erupted and overlapping sediments, xenoliths of sedimentary rocks with certain faunal remains, isotopic dating (for example, U-Pb, K-Ar, Rb-Sr methods). According to these data, modern geological ideas about the age of the YaDP kimberlites fit into a wide time range. For example, up to seven geological epochs of kimberlite formation can be allocated for the Siberian platform [8, 9]. Due to U-Pb and Sr-Nd isotopic studies of perovskite and zircon from the kimberlites of the YaDP, four stages of kimberlite volcanism/magmatism have been reliably established: Silurian-Devonian (429–1408 Ma); Devonian-Carboniferous (376–344 Ma); Triassic (231–215 Ma); Jurassic (175–147 Ma) [10, 11]. All known diamond deposits in Russia are associated with the Devonian-carbon stage [8, 12].

The purpose of petro- and palaeomagnetic studies of kimberlites of YaDP is to calculate for each site (kimberlite type, exocontact of host rocks) virtual geomagnetic poles (VGP is the position of the geomagnetic pole determined by the elements of the geomagnetic field, for example, declination and inclination measured at some point (direct observations or natural remanent magnetization) under the assumption that the geomagnetic field is the field of the central axial dipole. Since the intrusion of a kimberlite pipe is a rather short-term process, which does not allow averaging paleosecular variations for a single object (authors' note)) and, in general, for a cluster of pipes/fields (Verkhnemunskoe diamond deposit) a paleomagnetic pole (PMP is the average virtual geomagnetic pole calculated for some geologic time interval determined by the paleomagnetic method. It is accepted that PMP ≥ 7 VGP) smoothing palaeomagnetic anomalies [1, 3, 13]. To do this, it is necessary to solve problems using the following algorithm:

1. Selection of promising paleomagnetic research sites.
2. Selection of statistically representative collections of oriented samples from kimberlite pipes, taking into account the solution of age-related testing of NRM vectors.
3. Obtaining petrophysical parameters.
4. Conducting magneto-mineralogical analyses.
5. Study of the component chemical composition of minerals of the ferrimagnetic fraction (MFMF).
6. Paleomagnetic studies in order to isolate the In^{ch} component.
7. Analysis of information on the evidence of their primary In^0 nature (primary (synchronous) remanent magnetization In^0 is initial remanent magnetization synchronous to the initial stage of rock formation and fully or partially preserved as part of the natural remanent magnetization by the time the samples are measured).
8. Calculation of PMP and geodynamic interpretation of the obtained material.

Materials and methods

The kimberlite pipes Deimos, Zapolyarnaya, Komsomolskaya-Magnetic, Novinka and the Poiskovaya diamond deposit Verkhnemunskoye (Fig. 1), were selected as objects of paleomagnetic study, which belong to the first ("open") type of diamond mining areas [14]. The studied kimberlite

[1] Pechersky D.M., Sokolov D.D. *Paleomagnetology, petromagnetology and geology. Dictionary-reference book for neighbors in specialty*. Moscow: Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences; 2010. (In Russ.) / Печерский Д.М., Соколов Д.Д. Палеомагнитология, петромагнитология и геология. Словарь-справочник для соседей по специальности. М.: Изд-во ИФЗ РАН, 2010.

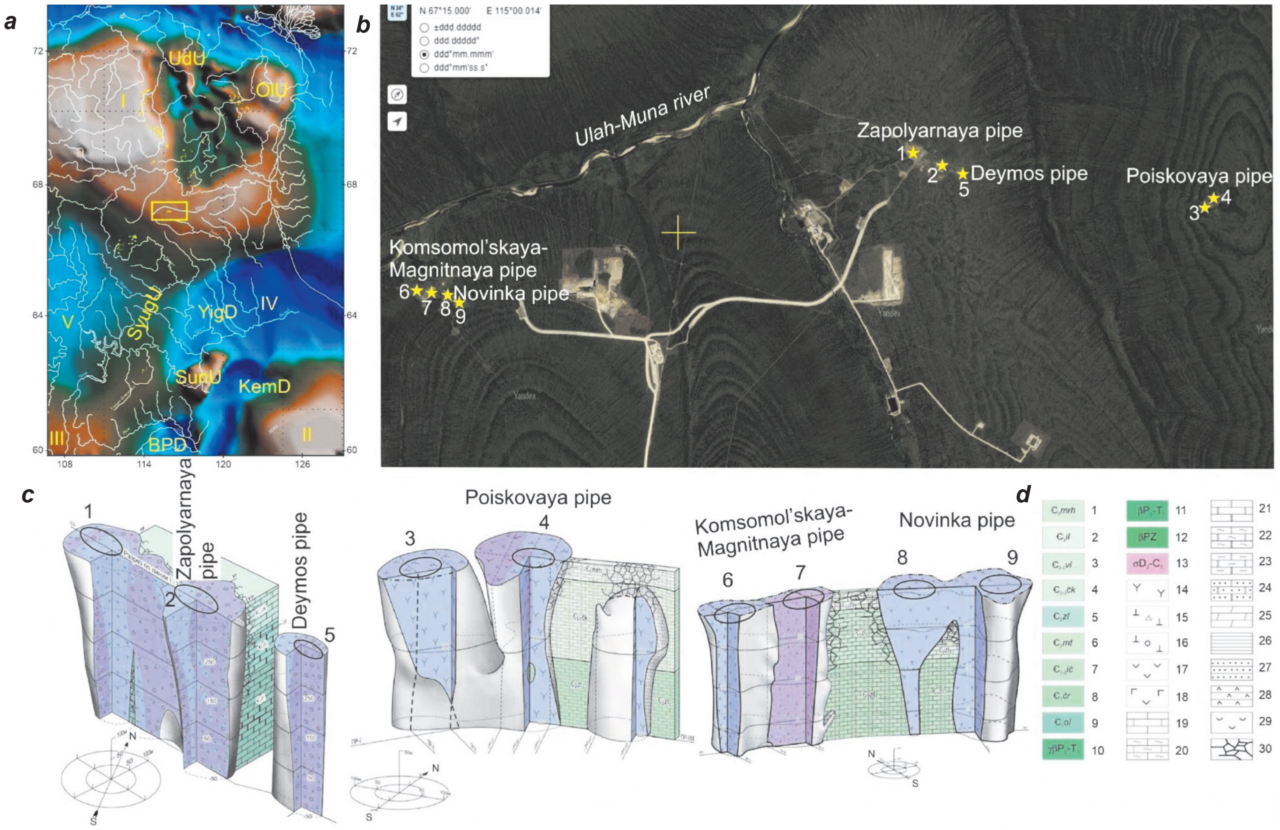


Fig. 1. Position of the area of work (rectangle) on the tectonic scheme of the eastern part of the Siberian Platform (a), the scheme of location of kimberlite bodies of the Verkhnemunskoe field (b), their volume models (c)[2] and symbols (d):
1–9 – Cambrian formations: 1 – Markhinskaya, 2 – Ilginskaya, 3 – Verkholenskaya, 4 – Chukukskaya, 5 – Zelenotsvetnaya, 6 – Metegerskaya, 7 – Icherskaya, 8 – Charskaya, 9 – Olekminskaya; 10, 11 – Permo-Triassic dolerite sills: 10 – upper level formations, 11 – lower level formations; 12 – Paleozoic dolerite sills; 13 – kimberlite bodies; 14 – coherent kimberlite; 15 – volcaniclastic kimberlite; 16 – pyroclastic kimberlite; 17 – dolerites; 18 – dolerite-basalts; 19 – limestones; 20 – clayey limestones; 21 – dolomites; 22 – clayey dolomites; 23 – silty dolomites; 24 – sandy dolomites; 25 – marlstones; 26 – mudstones; 27 – sandstones; 28 – anhydrites; 29 – rock salt; 30 – near-contact brecciation zones in sedimentary strata
Basement structures of the Siberian Platform: first order – anteclises (I – Anabarskaya, II – Aldanskaya, III – Nepsko-Botuobinskaya), syneclises (IV – Vilyuiskaya, V – Tungusskaya); second order – uplifts (SunU – Suntarskaya, OlU – Olenekskaya, UdU – Udzhinskaya, SyugU – Syugdzherskaya), depressions (BPD – Baikal-Patomskaya, KemD – Kempendian, YigD – Ygyattinskaya)
Ovals with numbers are exploration trenches and their numbers

Рис. 1. Положение района работ (прямоугольник) на тектонической схеме восточной части Сибирской платформы (a), схеме расположения кимберлитовых тел Верхне-Мунского месторождения (b), их объемные модели (c)[2] и условные обозначения (d):
1–9 – свиты кембрия: 1 – мархинская, 2 – илгинская, 3 – верхоленская, 4 – чукукская, 5 – зеленоцветная, 6 – метегерская, 7 – ичерская, 8 – чарская, 9 – олекминская; 10–11 – пермо-триасовые долеритовые силлы: 10 – верхнего уровня, 11 – нижнего уровня; 12 – палеозойские долеритовые силлы; 13 – кимберлитовые тела; 14 – когерентный кимберлит; 15 – вулканокластический кимберлит; 16 – пирокластический кимберлит; 17 – долериты; 18 – долерито-базальты; 19 – известняки; 20 – глинистые известняки; 21 – доломиты; 22 – глинистые доломиты; 23 – алевритистые доломиты; 24 – песчанистые доломиты; 25 – мергели; 26 – аргиллиты; 27 – песчаники; 28 – ангидриты; 29 – каменная соль; 30 – приконтактовые зоны брекчирования в осадочной толще
Структуры фундамента Сибирской платформы: первый порядок – антеклизы (I – Анабарская, II – Алданская, III – Непско-Ботуобинская), синеклизы (IV – Вилюйская, V – Тунгусская); второй порядок – поднятия (SunU – Сунтарское, OlU – Оленекское, UdU – Уджинское, SyugU – Сюгджерское), впадины (BPD – Байкало-Патомская, KemD – Кемпендяйская, YigD – Ыгыаттинская)
Овалы с цифрами – разведочные канавы и их номера

[2] Kostrovitsky S.I., Spezicius Z.V., Yakovlev D.A., Von-der-Flaass G.S., Suvorova L.F., Bogush I.N. *Atlas of root diamond deposits of the Yakutsk kimberlite province*. Mirny: ALROSA, 2015, 480 p. (fig. 475, tab. 125). (In Russ.) / Костровицкий С.И., Специус З.В., Яковлев Д.А., Фон-Дер-Флаасс Г.С., Суворова Л.Ф., Богуш И.Н. Атлас коренных месторождений алмазов Якутской кимберлитовой провинции. Мирный: Изд-во АЛРОСА, 2015. 480 с. (рис. 475, табл. 125).

pipes belong to the Verkhnemunskoe field of the Mun-Tungskii diamondiferous province of the YaDP, located on the southeastern slope of the Anabar anteclise (Fig. 1, *a*) [12].

The Verkhnemunskoye field is located on the right bank of the Ulakh-Muna River (Fig. 1, *b*). The host rocks are variegated carbonate, clay-carbonate rocks of the Middle and Upper Cambrian. Igneous rocks are represented by kimberlite pipes and dykes, as well as gabbro-diabase necks and dykes [15, 16]. Trap formations (sills, dykes, etc.) of the Vilyui and Tunguska syneclises have not been established within the VMP. The kimberlites of the studied tubes are characterized by xenoliths of different facies depth levels: crustal and mantle [12, 15, 16]. According

Table 1. Absolute age of kimberlite bodies of the Verkhnemunskoe diamond deposit
Таблица 1. Абсолютный возраст кимберлитовых тел Верхне-Мунского месторождения алмазов

No.	Object	Type and variety of rock	Method, [source]	Age, million years	Epoch
1	Dyke Zhyla 2	Kimberlite (?)	Rb-Sr [8]	376	D_3-C_1
2	Pipe 325 years of Yakutia	Zircon from VK	U-Pb [9]	440-443	O_3
		–	U-Pb [21]	345±12	D_3-C_1
		–	U-Pb [23]	355.5±1.5	D_3-C_1
		–	U-Pb [24]	354±9	D_3-C_1
		–	U-Pb [10]	347.1±8.2	D_3-C_1
		–	U-Pb [18]	353.2±4.8	D_3-C_1
		Zircon from VK 17 crystal	Tracks U [19]	362±5	D_3-C_1
		–	Lu-Hf [20]	360	D_3-C_1
3	Vympel pipe	Zircon from VK 5 crystal	Tracks U [8]	367±9	D_3-C_1
4	Zapolyarnaya pipe	VK	K-Ar [8]	360±10	D_3-C_1
		–	K-Ar (1) [9]	360±1	D_3-C_1
		–	Lu-Hf [20]	360	D_3-C_1
		–	U-Pb 2 [9]	361±10	D_3-C_1
		–	U-Pb 3 [9]	366.3±3.2	D_3-C_1
		–	U-Pb 4 [9]	355.6±4.1	D_3-C_1
5	Zimnyaya pipe	VK	K-Ar [8]	354±20	D_3-C_1
		–	U-Pb [10]	353±5	D_3-C_1
6	Intercosmos pipe	Zircon from VK 3 crystal	Tracks U [19]	369±11	D_3-C_1
		VK	K-Ar [8]	458±12	O_3
		–	U-Pb [10]	356.1±3.9	D_3-C_1
		–	U-Pb [18]	356.3±4.1	D_3-C_1
		–	Lu-Hf [20]	360	D_3-C_1
7	Komsomolskaya pipe	VK	K-Ar [9]	375-382	D_3-C_1
8	Magnitnaya pipe	VK	K-Ar [8]	334±4	D_3-C_1
9	Novinka pipe	VK	K-Ar [8]	426±20	S_2-D_1
		VK	Rb-Sr [8]	375	D_3-C_1
		–	U-Pb [17]	355±11	D_3-C_1
		–	Rb-Sr [8]	374±4	D_3-C_1
10	Rassvet pipe	Zircon from VK	Tracks U [9]	414-451	O_3
		–	Tracks U [19]	374±14	D_3-C_1
		–	U-Pb [22]	344	D_3-C_1
11	Poiskovaya pipe	–	U-Pb [17]	357±13	D_3-C_1
		–	U-Pb [10]	361.8±3.2	D_3-C_1
12	Komsomolskaya-Magnitnaya pipe	–	Rb-Sr [25]	402±3	S_2-D_1
		–	Rb-Sr [28]	400	S_2-D_1
		–	K-Ar [8]	334±4	D_3-C_1
		–	K-Ar [8]	382±1	D_3-C_1
		–	K-Ar [29]	375±15	D_3-C_1
		–	Ar-Ar [20]	427±12	O_3
		–	Sm-Nd [30]	360	D_3-C_1

to the analysis of the available absolute dates [7–9, 17–25], it is advisable to assume that the age of kimberlite formation is the time interval from 460 to 340 million years, which coincides with the Silurian-Devonian (429–408 Ma) and Devonian-Carboniferous (376–344 Ma) the stages of kimberlite magmatism (Table 1). The second stage of formation of the Verkhnemunskoye diamond deposit is manifested most reliably.

A comprehensive study of the material composition of kimberlite pipes of the Verkhnemunskoye diamond deposit [15, 26–37] revealed common and individual features of the material composition of kimberlites of this field:

1. Kimberlites of VMP tubes are represented by three varieties:

– coherent kimberlite (CC), a full-crystalline massive kimberlite that contains up to 5 % xenoliths and/or xenocrysts, its formation occurs by direct crystallization or solidification of kimberlite magma;

– volcanoclastic kimberlite (VC), consists of fragments of volcanites (melt fragments) and xenoliths of host rocks (from 5 to 50 % of the volume). VC is formed by indirect crystallization from a melt.

– pyroclastic kimberlite (PC), contains magmaclasts, juvenile pyroclasts or pellet lapilli (rounded fragments consisting of an inner part and an outer rim, autolith kimberlites and xenoliths of host rocks up to 5–40 %.

2. The kimberlites of the studied tubes are of the magnesium-ferruginous petrochemical type by chemical composition (MgO = 30–33 wt. %, FeO (total) = >6 wt. %, TiO_2 = > 1 wt. %), the most common within diamondiferous kimberlite fields.

3. In general, the kimberlites of the pipes of the Verkhnemunskoye deposit are dense rocks, slightly modified by secondary mineralization processes. Compared with kimberlites of other fields, they contain fewer fragments of sedimentary rocks and a greater number of mantle xenoliths of lherzolite and dunite-harzburgite paragenesis.

4. Kimberlites of this field are characterized by a high content of unchanged olivine, monticellite and perovskite and a low content of ilmenite.

5. There is a large number of garnets with powerful kelyphyte rims, or completely replaced by kelyphyte, which indicates the aggressive effect of kimberlite melt on mantle barophilic minerals, including diamonds.

6. The almost complete absence of xenoliths of eclogites and garnets of eclogite composition is characteristic, which indicates the specificity of the lithospheric mantle under the kimberlite pipes of the Verkhnemunskoye deposit.

7. The high-temperature nature and elevated redox conditions at the final stages of crystallization of kimberlite magmas in the tubes of the Verkhnemunskoye deposit apparently determined the corrosion of crystals and the dissolution of some diamonds. On the other hand, the relatively low diamond content of kimberlites in this field is probably due to the specific composition of the lithosphere under this field with the practical absence of an eclogite substrate and the dominant ultrabasic one, which, in turn, caused the absence of eclogite paragenesis diamonds in the diamond populations of these tubes.

Thus, given the favorable geological (platform position, absence of post-ore magmatic objects) and physical/petromagnetic (presence of unchanged indicator minerals of kimberlites of ferrimagnetic fraction) data, as well as reliable geochronological dating (376–344 Ma), we can hope to obtain a reliable paleomagnetic result for kimberlites of the Verkhnemunskoye diamond deposit for clarifications of the APWP of the Siberian platform for the era under consideration.

The methodology of comprehensive studies of kimberlite pipes of the Verkhnemunskoe deposit to obtain PMP included:

1. Selection of oriented samples (lumps of rocks) from exploration trenches (Fig. 1, 2) and sample preparation (making cubes with a rib of 20 mm, microsections, polished sections, powders, etc.).

2. Primary measurements of bulk density σ, magnetic susceptibility æ and NRM vectors.

3. Magneto-mineralogical analyses included the study of anisotropy of magnetic susceptibility æ (AMS), hysteresis constants (HC) and Curie points (Θ) of MFMF.

4. Study of the mineralogical composition of kimberlites.

5. Study of the component composition of NRM vectors and isolation of the characteristic component In^{ch} [38].

6. A system of geological, physical (petro-magnetic) and geophysical (palaeomagnetic) evidence of the nature of In^{ch}: analytical studies of MFMF, field baked contact tests, analytical studies of conglomerates and/or folds, etc. [1]. In case In^0 is preserved in kimberlites (of thermo-sufficient or other origin, see above), the age of the kimberlite pipe is established, in case of secondary nature In^m: the time of manifestation of hypergene or other processes in kimberlites.

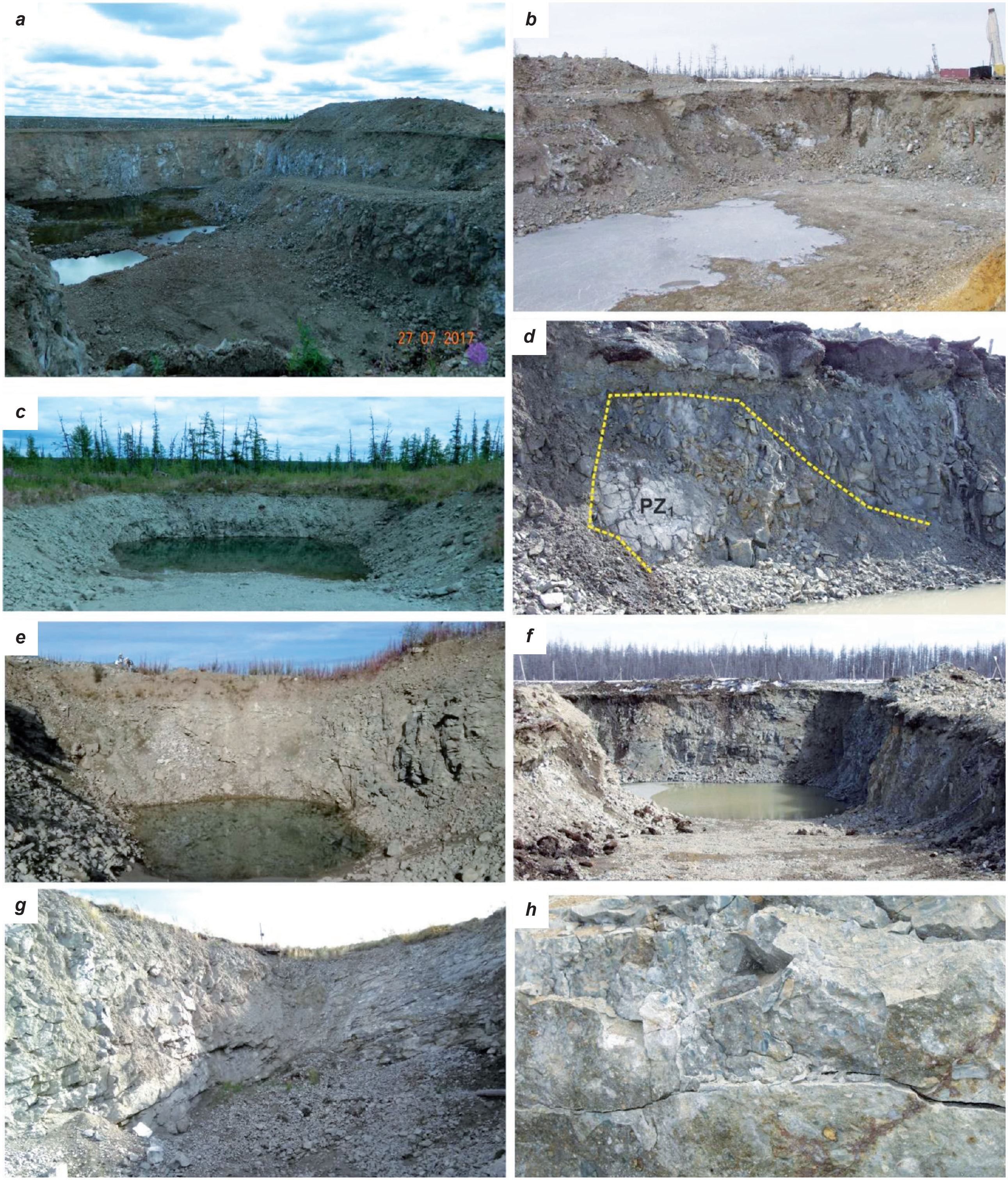


Fig. 2. Selection of oriented samples from the Verkhnemunskoe diamond deposits
(see the georeferencing in Fig. 1):
Kimberlite pipes: a, b, h – Zapolyarnaya (trenches, respectively, 1 (CK) and 2 (VK)); c – Deimos; d, f – Poiskovaya (trenches, respectively, 3 and 4; the boundaries of the host terrigenous-sedimentary rocks of the Early Paleozoic PZ1 are outlined); e – Komsomolskaya-Magnitnaya (trench 7); g – Novinka (trench 9)
Photo by K.M. Konstantinov

Рис. 2. Отбор ориентированных образцов из Верхне-Мунского месторождения алмазов
(привязку см. на рис. 1):
Кимберлитовые трубки: a, b, h – «Заполярная» (канавы, соответственно, 1 (СК) и 2 (VК)); c – «Деймос»; d, f – «Поисковая» (канавы, соответственно, 3 и 4; контурной линией выделены границы выхода вмещающих терригенно-осадочных пород раннего палеозоя PZ1); e – «Комсомольская-Магнитная» (канава 7); g – «Новинка» (канава 9)
Фото К.М. Константинова

7. Calculation of PMP.

8. Interpretation of the paleomagnetic data in the light of solving the set tasks (geochronology, geodynamics, etc.).

The oriented samples were collected according to the generally accepted methodology [1] from nine exploration trenches of the Verkhnemunskoe diamond deposits (Fig. 1, *c*; 2, *a*–*g*). Kimberlites (KK and VC) and deep xenoliths (DX), which are conglobreccia of 0.15–0.25 m diameter of metamorphic basement rocks, were sampled in the geographical coordinate system (GCS). At the Poiskovaya pipe (Fig. 1, *c*; 2, *d*) in the third trench, according to bedding, it was possible to select deformed host terrigenous-carbonate rocks of early Paleozoic era from the exocontact zone to do a baked contact test. To achieve this goal marking in the stratigraphic coordinate system (SCS) was used: azimuth and dip angle were measured. Two or three cubes with a 20 mm rib were sawn from each lump of rock, totaling more than 660 cubes.

The studies were carried out using modern equipment: scanning electron microscope (SEM) TESCAN MIRA 3 LMU equipped with energy dispersive spectrometers (EDS) with microanalysis system AztecLive Advanced Ultim Max 40 and nitrogen-free detector (Oxford Instruments Analytical Ltd, England), magnetic susceptibility meters æ (KLY-3s and MFK1-FA, AGICO, Czech Republic), spin magnetometers for measuring NRM vectors (JR-6, AGICO, Czech Republic), demagnetizing units with alternating magnetic field (AF-Demagnetizer, Molspin LTD, UK) and temperature (MMTD80, Magnetic Measurements LTD, UK), vibration magnetometers and magnetic fraction meters (KFU, Russian Federation), etc.

The complex of conducted studies of kimberlites included:

Mineralogical studies. Using SEM-EDS, images of the investigated surface in back-scattered electrons and chemical composition of minerals in the point were obtained. Working conditions: high vacuum mode at accelerating voltage of 20 kW of distance of 15 mm.

Petrophysical studies*,* characterizing the gravitational and magnetic state of rocks in situ. The studies are based on the research of the bulk density σ, vectors *In*, induced magnetization *Ii* = æ*H* (where *H* is the vector of the Earth's magnetic field in the area of work) and total magnetization *Is* = *Ii* + *In*, which determine the type of anomalous magnetic field over kimberlites. In turn, the magnetization vectors (*In*, *Ii*, or *Is*) are determined in space by three components: magnitude (*In*, *Ii*, and *Is*, respectively), declination (0 < *D* < 360°), and inclination (-90° < *J* < 90°)[3]. The *In*/*Ii* ratio is characterized by the Koenigsberger ratio (*Q*), which is usually 0.3–0.6 for YaDP kimberlites [39–42]. The primary measurements were summarized in the database "RSEARCH" [43].

Magnetic and texture analysis, based on measurements of the anisotropy of magnetic susceptibility æ (AMS) of oriented samples. According to the AMS tensors (long K_1, middle K_2 and short K_3 axes of the ellipsoid), the parameters were calculated according to the following formulas [44]:

– specified degree of anisotropy

$$P_J = \exp\sqrt{\{2[(\eta_1-\eta_m)^2+(\eta_2-\eta_m)^2+(\eta_3-\eta_m)^2]\}},$$

where $\eta_1 = lnK_1$; $\eta_2 = 1nK_2$; $\eta_3 = 1nK_3$; $\eta_m = (\eta_1 + \eta_2 + \eta_3)/3$;

– lineation $P_1 = L = \frac{K_1}{K_2}$;

– plane $P_3 = F = \frac{K_2}{K_3}$;

– grain shape $T = \left[\frac{2\ln(K_2/K_3)}{\ln(K_1/K_3)}\right] - 1$.

Flattened bodies have values 0 < *T* ≤ 1, while negative values -1 ≤ *T* < 0 are characteristic of elongated bodies. Neutral grains, which shape resembles so-called plane deformed ellipsoids, have values T→0. The long K_1 and middle K_2 axes of the AMS ellipsoid form the plane of magnetic bedding, along which the matter motion is carried out: relatively increased velocity (more than 0.01 m/s) will be observed along the K_2 axis, and decreased velocity will be observed along the K_1 axis.

In addition, according to the kimberlite pipe model [45], the type of AMS is not constant and varies vertically (from the bottom to the top): dyke, chaotic, and sedimentary [46, 47]. Thus, the AMS data can be used to judge the level of erosional shearing of the kimberlite pipe. The AMS measurements were summarized in the "RSEARCH" database [43].

Magneto-structural analysis was performed to determine the hysteresis constants (HC) of ferrimagnetic minerals of kimberlites: the values of specific magnetic moment of saturation (Ms),

[3] Logachev A.A., Zakharov V.P. *Magnetic prospecting*. Leningrad: Nedra; 1979, 351 p. (In Russ.) / Логачев А.А., Захаров В.П. Магниторазведка: учебник для вузов. Л.: Недра, 1979. 351 с.

coercivity (H_C) from the induced magnetization curve and determination of the values of specific magnetic moment of residual saturation (Mrs) and its destructive field (Bcr) [48, 49]. To improve the accuracy of the obtained values of hysteresis constants, corrections for the background of paramagnetic minerals were applied into the graphs.

Thermomagnetic analysis allows to determine the component chemical composition of ferrimagnetics by Curie points (Θ) on the dependency graphs æ = *f*(*T*) based on the Hopkinson effect(the Hopkinson effect is a sharp increase in the magnetic susceptibility of magnetic materials in weak magnetic fields near their Curie point, due to a sharp decrease near this temperature in the magnetic anisotropy of the materia). Two heating cycles were applied to study the MFMF. The methodology of stepwise demagnetizations by temperature was based on the data of thermomagnetic analysis.

Paleomagnetic studies of the component composition of NRM vectors [1]. Laboratory experiments on demagnetization by an alternating magnetic field and temperature were performed on samples of kimberlites (CK and VK), deep xenoliths (DX), and host terrigenous carbonate rocks of the Early Paleozoic from the exocontact zone (PZ_1). The characteristic In^{ch} components of kimberlites were taken along straight lines passing through at least three points and the center of the Zijderveld vector diagram [38]. In complicated cases, a joint analysis of single directions and remagnetization circles was used [50]. The resultant statistics included data on one sample from each lump of rock that underwent stepwise demagnetization by temperature or alternating magnetic field.

In conducting petromagnetic and paleomagnetic studies, we took into account domestic and foreign methodological developments on the graphical and analytical realization of solutions of petromagnetic and paleomagnetic problems using the computer programs Statistica-6 [51], Opal-3 [52], Enkin-96 [53], Anisoft-42 [54], and PetroStat [43] and others.

Results

1. The studied kimberlites of the Verkhnemunskoe deposit are essentially carbonate-serpentine rock with relics of unaltered olivine. The chemical composition of MFMF varies within a fairly wide range and corresponds to magnetite, magnesioferrite, titanomagnetite, ilmenite, and chromospinelide[2] (Fig. 3).

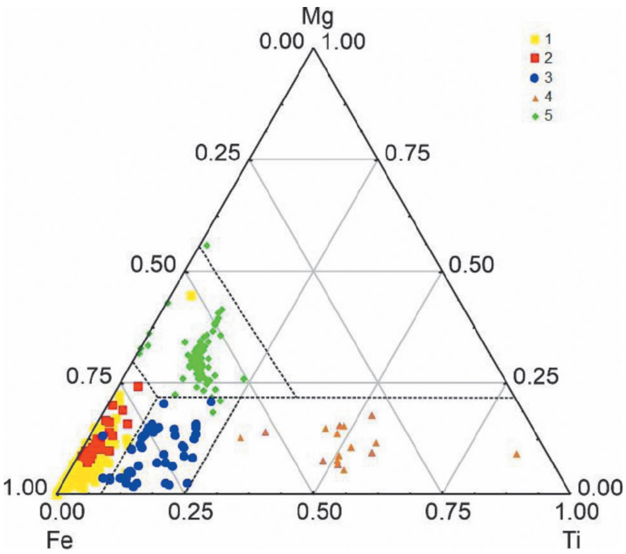
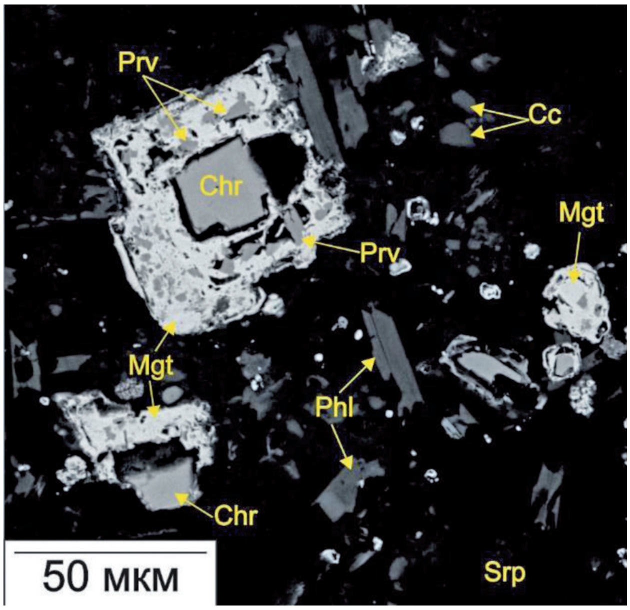


Fig. 3. Chemical composition of minerals of ferritagnetic fractions of kimberlites from the Verkhnemunskoe deposit:
1 – magnetite; 2 – magnesioferrite; 3 – titanomagnetite; 4 – ilmenite; 5 – chromospinelide
Рис. 3. Химический состав минералов ферритагнитной фракиии кимберлитов Верхне-Мунского месторождения:
1 – магнетит; 2 – магнезиоферрит; 3 – титанолмагнетит; 4 – ильменит; 5 – хромшпинелид

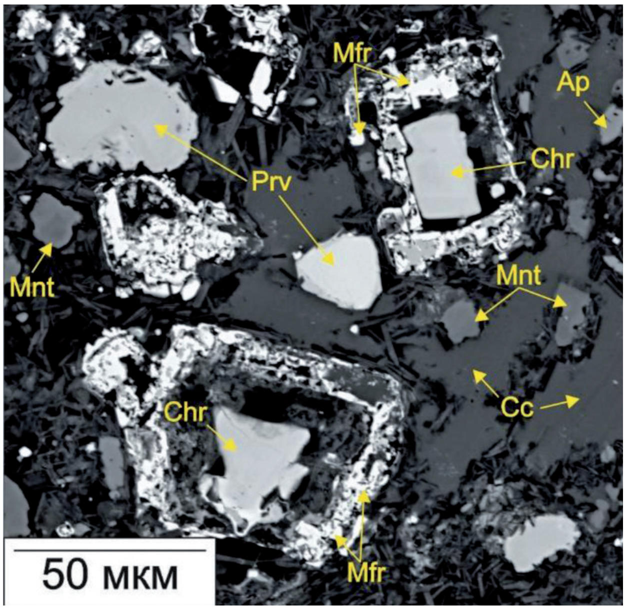
In general, in the majority of the studied kimberlite samples, the following minerals (up to 100 microns in size) were constantly diagnosed: zonal spinelides (where the core is chromspinelide, the rim contains magnetite and/or magnesioferrite), perovskite, phlogopite, apatite, serpentine, calcite, ±dolomite, ±chlorite. However, for example, in the samples of the Komsomolskaya-Magnetic tube, in addition to the mentioned minerals, monticellite and jerfisherite (K-Cl containing iron-nickel sulfide) were noted. In addition, ilmenite was found in some samples of kimberlites of Zapolyarnaya, Deimos and Search tubes, which forms an outer rim along the perovskite of the ground mass.

It was found that the distribution of oxide mineralization in the majority of kimberlites is uniform, and the main primary ferrimagnetic minerals-carriers of magnetization (MCM) are magnesioferrite ($MgFe_2O_4$) and magnetite ($FeFe_2O_4$), which: 1) form outer rims around the zonal chrome spinelides of the ground mass; 2) form an randomly scattered fine impregnations in the mesostasis of kimberlites (Fig. 4).

Magnesioferrite is mainly distributed only in the Komsomolskaya-Magnitnaya tube, and is also found in some samples of kimberlites of the Novinka tube. Magnesioferrite has the following



a



b

Fig. 4. Backscattered electron image:
a – Zapolyarnaya pipe: Chromspinelide (Chr) is surrounded by a magnetite rim (Mgt), with crystalline inclusions of perovskite (Prv); Phl – phlogopite, Cc – calcite; mesostasis is filled with serpentine (Srp)
b – Komsomolskaya-Magnitnaya pipe: Chromspinelide (Chr) is surrounded by an outer rim of magnesioferrite (Mfr); Prv – perovskite, Mnt – monticellite, Ap – apatite, Cc – calcite
Рис. 4. Изображение в обратно рассеянных электронах:
а – трубка «Заполярная: хромшпинелид (Chr) окружен каймой магнетита (Mgt), с кристаллическими включениями перовскита (Prv); Phl – флогопит, Cc – кальцит; мезостазис заполнен серпентином (Srp);
b – трубка «Комсомольская-Магнитная»: хромшпинелид (Chr) окружен внешней каймой магнезиоферрита (Mfr);
Prv – перовскит, Mnt – монтичеллит, Ap – апатит, Cc – кальцит

composition variations by % wt: Specific gravity FeO = 69.23–75.26; MgO = 10.5–14; Al_2O_3 = 1.66–4.16; TiO_2 = 1–4.32; MnO = 0.56–0.92; Cr_2O_3 = 0.25–1.02.

Magnetite is mainly developed in samples of kimberlites of the Zapolyarnaya, Deimos, and Poiskovaya tubes, as well as in the Novinka tube, where there is no magnesioferrite. The following variations of compositions are observed in the magnetite of the studied samples by % wt: FeO = 61.42–90.60; MgO = 0.76–10.3; Al_2O_3 = 0.3–5.61; TiO_2 = 0.27–15.9; MnO = 0.21–1.54; V_2O_3 = 0.18–0.50; Cr_2O_3 = 0.13–1.43; NiO up to 0.38. Crystalline inclusions of perovskite, about 5 µm in size, are observed in the magnetite rim forming the outer rims around the chrome spinel.

In addition to the primary MCM, magnetites were found in kimberlites, probably of xenogenic and secondary genesis.

In particular cases, individual grains larger than 150–200 µm to 500 µm were diagnosed in all studied kimberlite samples: 1) magnetite (FeO = 87.24–93.64; TiO_2 up to 1.52; Al_2O_3 up to 0.64; MgO up to 0.63; MnO up to 0.54; all by % wt.); 2) magnetite (FeO = 60.71–75.04; TiO_2 = 2.01–16.81; MgO = 3.25–7.18; V_2O_3 = 0.75–1.18; Al_2O_3 = 0.45–0.98; MnO = 0.4–1.28; Cr_2O_3 = 0.25–0.41, all by % wt.) in concretion with ilmenite. Probably, such large grains are xenocrystals that are fragments of disintegrated xenoliths.

Magnetite is constantly observed in kimberlites of the studied samples in at least three more forms of manifestation: 1) manifestations of the stringer-porphyry mineralization type, which form extended veins and flaws, as well as aggregates of radial or radial fibrous structure; 2) continuous, homogeneous clusters of magnetite, as well as clusters of skeletal structure, are observed. In addition, magnetite is always found in kimberlites of VMP, in serpentine pseudomorphoses after olivine, forming ore margins/clusters inside altered grains.

The magnetites of these manifestations have variations in compositions by % wt: FeO = 86.34–93.39; MgO = 0.78–3.25; MnO up to 1.1; and probably have a secondary genesis. Hematite and maghemite are constantly observed in association with magnetite, which form fine-grained mineralized zones, as well as crystalline inclusions of goethite in magnetite.

2. Kimberlites from the pipes of the Verkhnemunskoye deposit are characterized by complex distributions of magnetic parameters

(Fig. 5; Table 2), obeying the lognormal law typical for such geological formations [55, 56]. For example, the average geometric values of æ for kimberlites varies from 25 to 100,000·10-5 ISU, *In* from 1 to 100·10-3 A/m, the Q ratio from 0.01 to 100 (!). The average geometric values of the Q ratio are noticeably increased (from 0.3 to 2.4) compared with the previously studied Middle Paleozoic kimberlites of the YDP [39–46]. Perhaps this fact indicates the presence of highly magnetic xenoliths in the cementitious matrix, the peculiarities of kimberlite formation processes, the manifestation of physical and chemical changes in kimberlites caused by hypergenic processes, etc. The directions of the vectors *In* do not form compact clusters and are scattered throughout the sphere: the density is less than 3, and the confidence ovals α95>13°. The exception is the Novinka tube, which is characterized by predominance of kimberlites with a high Q = 1.40 index and a close clustering of vectors *In*: Dsr = 328°, Jsr = -61°, *k* = 21.4° and *α*95 = 3.8°.

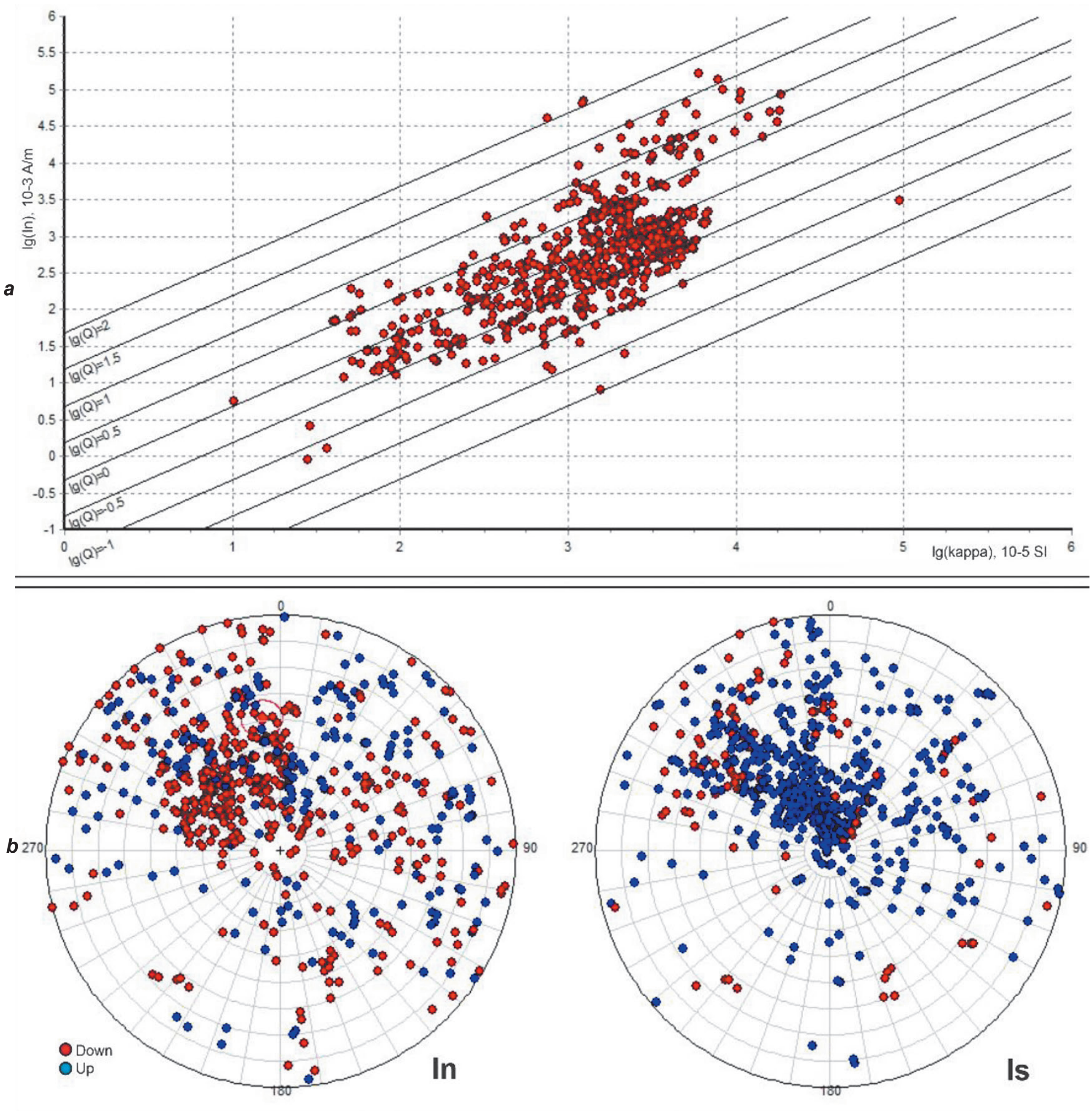


Fig. 5. Distributions of scalar (a) and vector (b) values of magnetic parameters of samples from the Verkhnemunskoe deposit
Рис. 5. Распределения скалярных (a) и векторных (b) значений магнитных параметров образцов Верхне-Мунского месторождения

Table 2. In situ magnetic parameters of kimberlite rocks of the Verkhnemunskoe deposit
Таблица 2. Магнитные параметры горных пород Верхне-Мунского месторождения в «естественном залегании»

No.	Pipe, rock type	*N*	*σ* (*), kg/м³	*n*	æ (**), 10^{-5} SI	NRM				*Q* (**)	*Ii***, 10^{-3} A/m	SM			
						In (**), 10^{-3} A/m	*D*, °	*J*, °	k/α_{95}, °			*Is***, 10^{-3} A/m	*D*, °	*J*, °	k/α_{95}, °
1	Deimos, CK	9	2534 (10.5)	106	622 (1.13)	107 (1.13)	20	-56	2/13.6	0.34 (1.07)	301 (1.13)	256 (1.14)	356	67	7.4/5.4
2	Zapolyarnaya, CK	6	2480 (13.8)	196	1771 (1.06)	704 (1.11)	105	-65	1.3/32.9	0.82 (1.09)	858 (1.06)	1085 (1.09)	350	65	2.2/16.1
3	Zapolyarnaya, VK	5	2377 (31.7)	52	800 (1.16)	343 (1.20)	52	-1	1.7/24.1	0.89 (1.12)	387 (1.16)	552 (1.20)	45	63	4.2/11.1
5	Zapolyarnaya, DX	–	–	36	190 (1.27)	170 (1.20)	345	85	1.2/47.7	1.87 (1.13)	90 (1.27)	210 (1.20)	350	75	1.9/24.5
6	Poiskovaya, CK	6	2377 (15.5)	120	841 (1.16)	948 (1.24)	10	35	1.8/14.7	2.33 (1.13)	407 (1.16)	1334 (1.21)	8	59	3/9.2
7	Poiskovaya, PZ_1 (exocontact)	–	–	11	82 (1.40)	10 (1.50)	344	4	1.8/50	0.25 (1.56)	40 (1.40)	44 (1.42)	330	65	4.6/24
8	Novinka, CK	20	2520 (11.4)	67	2498 (1.07)	1693 (1.06)	328	-61	21.4/3.8	1.40 (1.08)	1210 (1.07)	1398 (1.06)	329	-8	3.1/11.9
9	Komsomolskaya-Magnitnaya, CK	12	2592 (18.5)	48	3468 (1.05)	878 (1.07)	312	-29	3.2/14	0.52 (1.11)	1680 (1.05)	1709 (1.06)	318	55	4.9/10.4
10	Komsomolskaya-Magnitnaya, VK	7	2468 (28.2)	26	3437 (1.06)	1020 (1.37)	12	-26	1.4/45.4	0.61 (1.31)	1665 (1.06)	2250 (1.23)	25	61	2.1/26.9
–	–	65	–	662	–	–	–	–	–	–	–	–	–	–	–

Note. *N*/*n* – number of pieces/cubes participating in the statistics; NRM (*In*), IM (*Ii*) and SM (*Is*) – natural remanent, induced and total magnetizations; *D* – declination, *J* – inclination, *k* – heap, α_{95} – 95 % probability confidence oval of the NRM or SM vectors; */** – standard error of the arithmetic mean/geometric mean; CK – coherent kimberlite, VK – volcaniclastic kimberlite, DX – deep xenoliths of metamorphic basement rocks, PZ_1 – host terrigenous carbonate rocks of the Early Paleozoic.

Elevated, compared to their epigenetically sterile (unaltered by the processes of kimberlite intrusion) age analogs [62], geometric mean values æ = 80·10^{-5} SI, *In* = 10·10^{-3} A/m and factor Q = 0.26 (Table 2) were determined for the host terrigenous carbonate rocks of the Early Paleozoic PZ_1 (Fig. 2, *d*). They may have experienced some heating from the host kimberlite magma, which is confirmed by the presence of *In* directions with high negative inclination coinciding with the *In* directions of the kimberlites.

The deep xenoliths (DX) of the basement rocks are characterized by geometric mean scalar parameters: æ = 190-10^{-5} SI, *In* = 170-10^{-3} A/m and factor Q = 1.87. The directions of *In* vectors of the studied xenoliths are distributed over the whole sphere.

The petrophysical characteristics obtained for kimberlite pipes of the Verkhnemunskoe deposit (Table 2) allow to solve a direct geophysical problem of calculating gravimagnetic anomalies on the basis of a posteriori PhGM. The ModelVisionPro-17.5 program (Encom Technology, Australia) was used for physical and geological modeling to study the nature of the gravimagnetic effect. It allows building 3D PhGM and comparing their simulated characteristics with field observation data. The program automates the process of direct modelling, which allows to verify the decision on the suitability of a particular deterministic PhGM, as well as to predict some properties of objects. Scalar and vector data on the physical properties of rocks were used to build the petrophysical model.

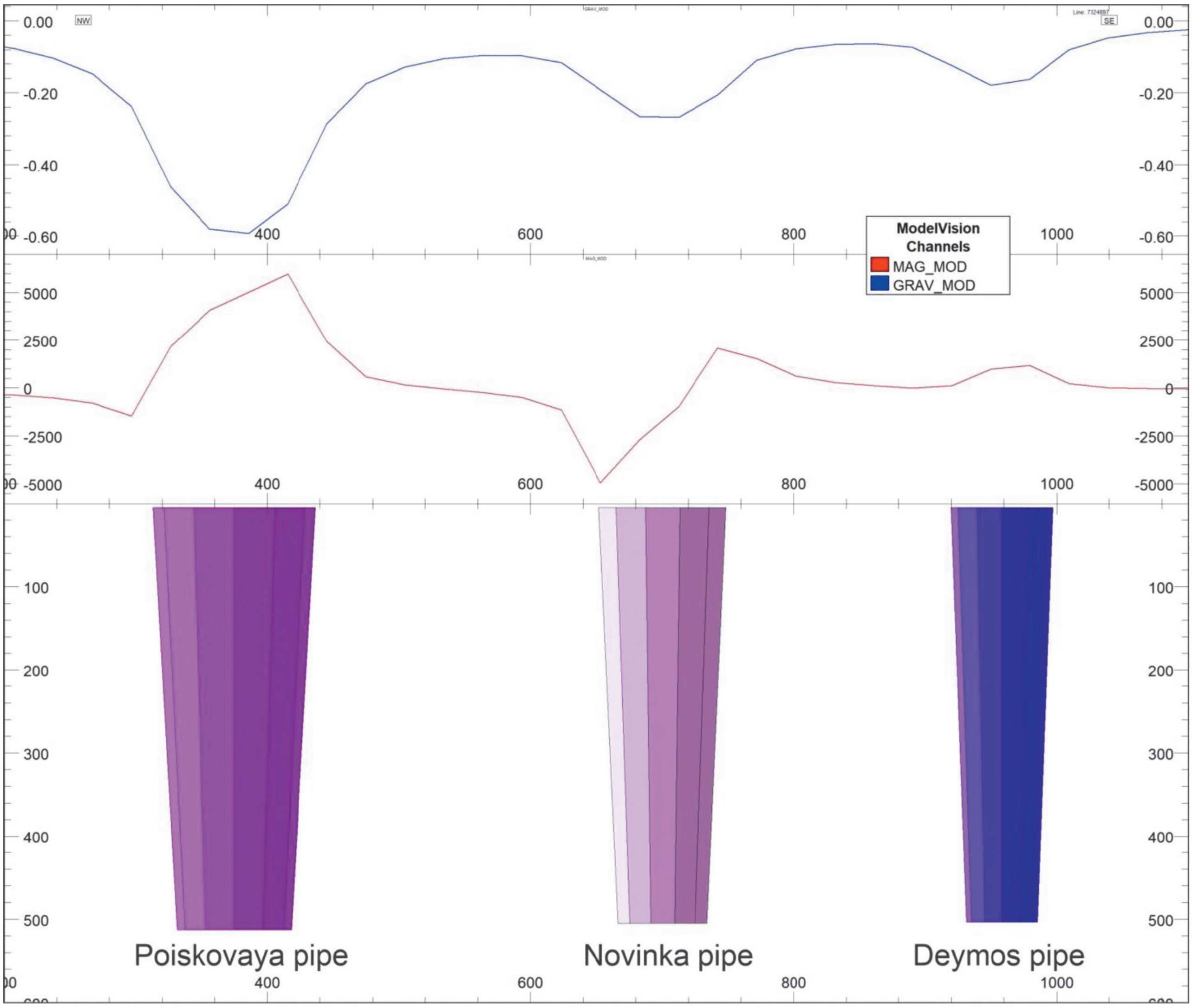


Fig. 6. Physical and geological models of kimberlite pipes of the Verkhnemunskoe deposit (direct problem)
The values of petrophysical properties from Table 2 were used to calculate the gravimagnetic effect
Рис. 6. Физико-геологические модели кимберлитовых трубок Верхне-Мунского месторождения (прямая задача)
Для расчета гравимагнитного эффекта использованы значения петрофизических свойств из табл. 2

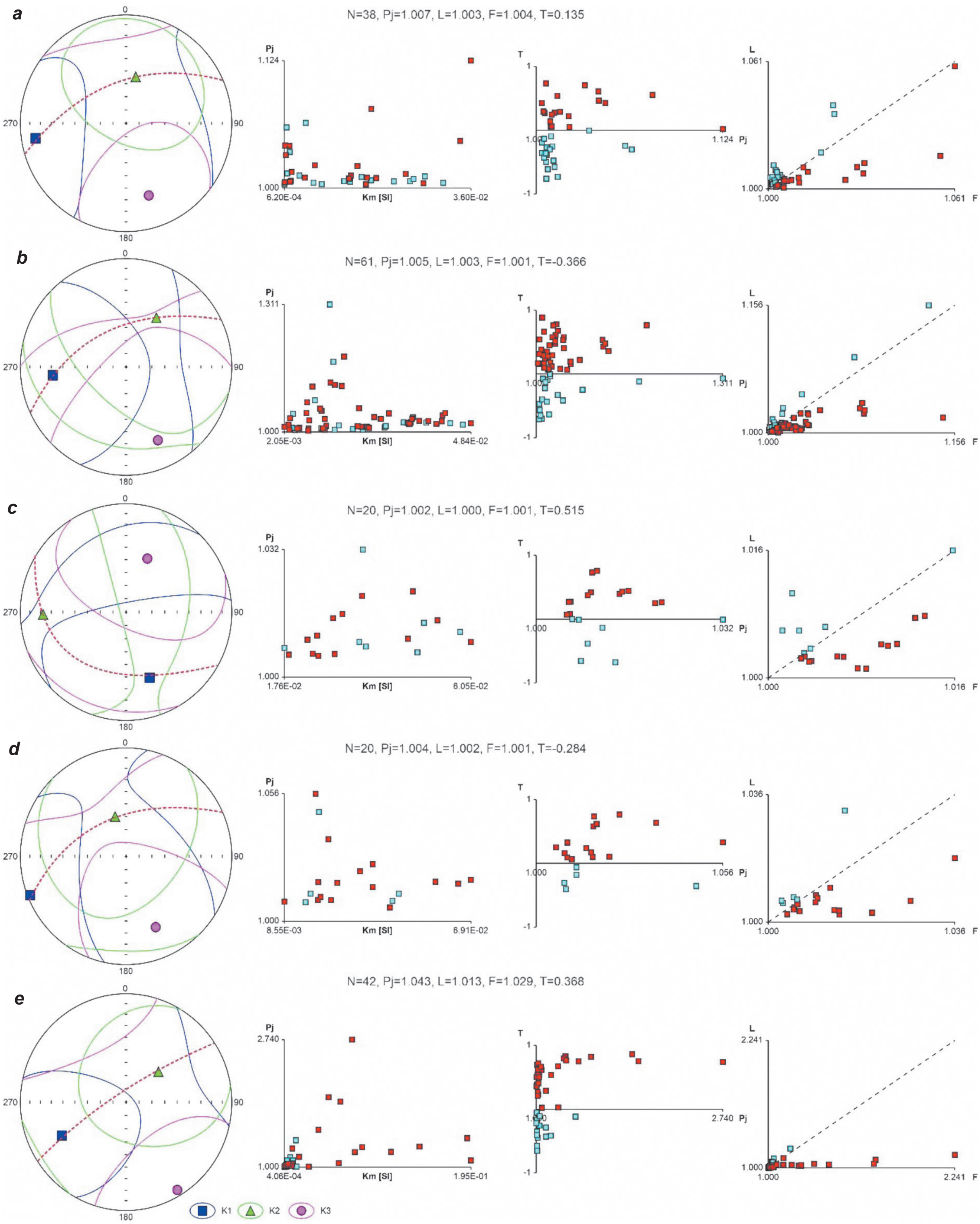


Fig. 7. Magneto-texture studies of kimberlites from the Verkhnemunskoe field pipes
Pipes: a – Deimos, b – Zapolyarnaya, c – Komsomolskaya-Magnitnaya, d – Novinka, e – Poiskovaya
Red/blue figurative dots on the graphs correspond to samples with 0 < T < 1 / -1 < T <0
See the text for other explanations

Рис. 7. Магнито-текстурные исследования кимберлитов трубок Верхне-Мунского месторождения
Трубки: a – «Деймос», b – «Заполярная», c – «Комсомольская-Магнитная», d – «Новинка», e – «Поисковая»
Красные/голубые фигуративные точки на графиках соответствуют образцам с 0 < T < 1 / -1 < T < 0
Другие пояснения приведены в тексте

The host terrigenous-carbonate rocks of the Early Palaeozoic belong to practically non-magnetic formations with an average density of 2670 kg/m³. Despite the fact that the VMF belongs to the 1 diamond geotype, not all kimberlite pipes have "pipe" type anomalies (Fig. 6). For example, the Novinka pipe is characterized by an alternating magnetic anomaly, which is explained by the presence of a gently negative vector of the total magnetization of I kimberlites: D_{cp} = 328°, J_{cp} = -8°, k = 3.1° and α_{95} = 11.9°. In this regard, the maximum of the magnetic anomaly is shifted away from the epicentre of the pipe in contrast to the gravitational minimum. Therefore, it is necessary to correct the position of the drilling exploration well when completing the magnetic anomaly.

3. AMS data (Fig. 7) for kimberlites showed:

– for most of the studied Deimos, Zapolyarnaya, Komsomolskaya-Magnitnaya and Novinka pipes, the P_J values do not exceed 1 %. The values of planar F and linear L anisotropy are comparable. The exception is the Poiskovaya pipe with P_J slightly more than 4 % and F = 1.029 >> L = 1.013, most likely due to the presence of strongly magnetic samples in it. On average, the "grains" resemble neutral ellipsoids (spheres) with shape parameters T close to the zero line (from -0.4 to 0.5). The correlation coefficients P_J and æ are insignificant: r < 0.4. It is possible that the significant confidence intervals of the mean directions of the AMS ellipsoid axes (K_1, K_2 и K_3) are determined not only by different hydrodynamic conditions of formation of kimberlite bodies, but also by the magnetic texture of individual small xenoliths or their agglomerates preserved in the sample matrix.

– the noticeable magnetic stratification of kimberlites corresponds to a transitional (from top to bottom) type from the diatreme facies to the dyke facies of the pipes [42, 46, 47]. The magnetic stratification plane has a northeastern strike with a dip from 60 (Deimos, Zapolyarnaya and Novinka pipes) to 80° (Poiskovaya pipe) and does not depend on the northwestern (Fig. 1, *c*) strike of the studied bodies. This indicates a significant level of erosional shearing of the studied pipes (the crater facies is completely denuded, the diatreme facies is partially denuded) and their reversal in plan relative to the true strike of the supply channels (dykes). The stereograms show that the kimberlite magma movement was carried out with a relatively high speed (more than 0.01 m/s) [44]. The Komsomolskaya-Magnitnaya pipe falls out of this pattern, its AMS, to a greater extent, corresponds to the diatreme facies.

4. The scatter of hysteresis parameters of kimberlites from the studied pipes is maximum

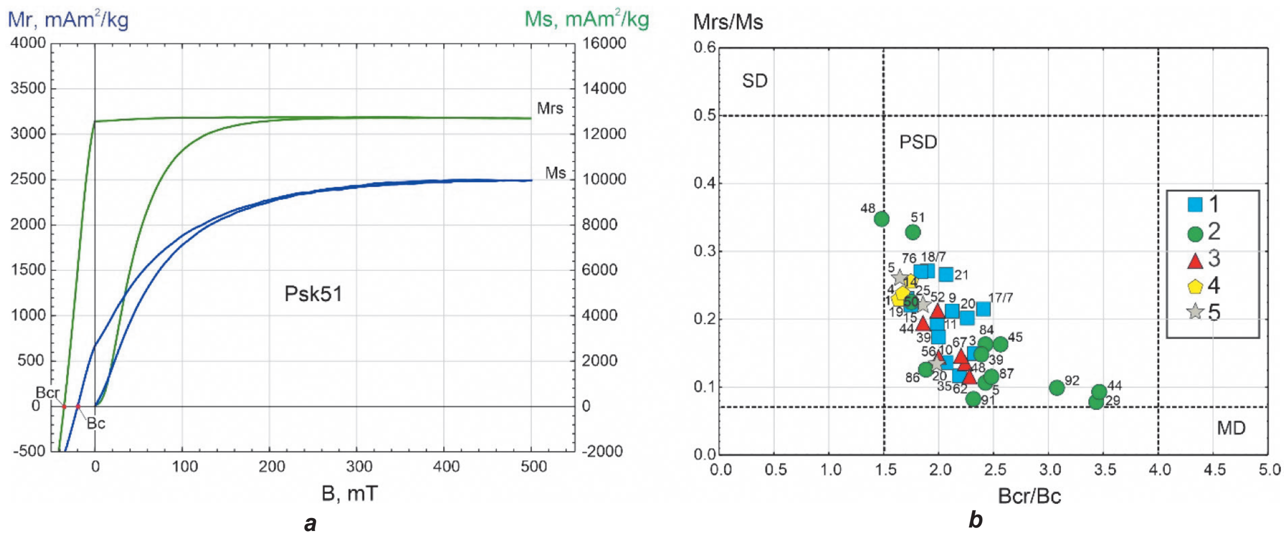


Fig. 8. Studies of the domain structure of magnetization carrier minerals of kimberlites of the Verkhnemunskoe deposit:
a – magnetic hysteresis; b – Day`s diagram (pipes: 1 – Zapolyarnaya, 2 – Poiskovaya, 3 – Deimos, 4 – Novinka, 5 – Komsomolskaya-Magnetic)
SD, PSD and MD – distribution areas of single-, pseudo- and multidomain particles
Numbers show the numbers of studied samples

Рис. 8. Исследования доменной структуры минералов-носителей намагниченности кимберлитов Верхне-Мунского месторождения:
a – магнитный гистерезис; b – диаграмма Дея (трубки: 1 – «Заполярная», 2 – «Поисковая», 3 – «Деймос», 4 – «Новинка», 5 – «Комсомольская-Магнитная»)
SD, PSD и MD – области распределения одно-, псевдо- и многодоменных частиц
Цифрами показаны номера изученных образцов

for saturation magnetisation and, to a lesser extent, for coercive forces (Fig. 8, *a*). According to the Day criterion [48, 49], the minerals of the ferrimagnetic fraction of the kimberlite pipes of the Verkhnemunskoe deposit have a pseudo-single-domain state (Fig. 8, *b*), which may be a favourable condition for setting paleomagnetic studies to establish the NRM vectors of primary nature in kimberlites (pseudo-single-domain grains are magnetic grains occupying an intermediate state in the domain structure between single-domain and multi-domain grains, i.e. grains consisting of a small number of domains. Such magnetic grains behave similarly to single-domain grains in many magnetic properties, especially in magnetic stiffness. The remanent magnetization of the ensemble of pseudo-single-domain grains, like single-domain grains, has high magnetic and paleomagnetic stability).

5. The analysis of TMA curves of magnetic susceptibility showed that the ferrimagnetic fraction of the studied kimberlite pipes (Fig. 9) agrees with the conclusions of the conducted analytical studies (Figs. 3, 4). The spectrum of Curie points of the studied kimberlites of the first heating lies in the range of 400–560 °C, which correlates with the above-mentioned MFMF and some admixture of isomorphic minerals. The similarity of a number of thermomagnetograms to the heating-cooling processes relates to the thermo-sufficient nature of the kimberlite magnetization [58]. According to the magneto-mineralogical features of MFMF, the studied kimberlite pipes of VMP have a single magmatic source (chamber), which is characteristic of a kimberlite cluster. At the same time, by this feature, they differ markedly from the previously studied pipes of other kimberlite fields of YaDP [39–46, 58, 59].

6. Paleomagnetic studies have shown that up to temperature of 200 °C or by an alternating magnetic field of up to 10 mT, the viscous component of the NRM In^v vector (viscous remnant magnetization In^v – part of magnetization formed under isothermal action of a constant geomagnetic field in time) of the studied kimberlites is usually removed (Fig. 10). In rare cases in the temperature range from 200 to 480 °C the existence of secondary (metachronous) In^m components is possible. The characteristic In^{ch} component of kimberlites is recorded in the temperature range from 200 °C to 600 °C and alternating magnetic fields from 10 to 100 mT. The deblocking temperatures of In^{ch} do not exceed 600 °C, which agrees well with the TMA results (Fig. 9). For each sample of In^{ch} vectors of kimberlite pipes of the Verkhnemunskoe field the average directions of In^{ch} and VGP vectors were calculated (Table 3; Fig. 11).

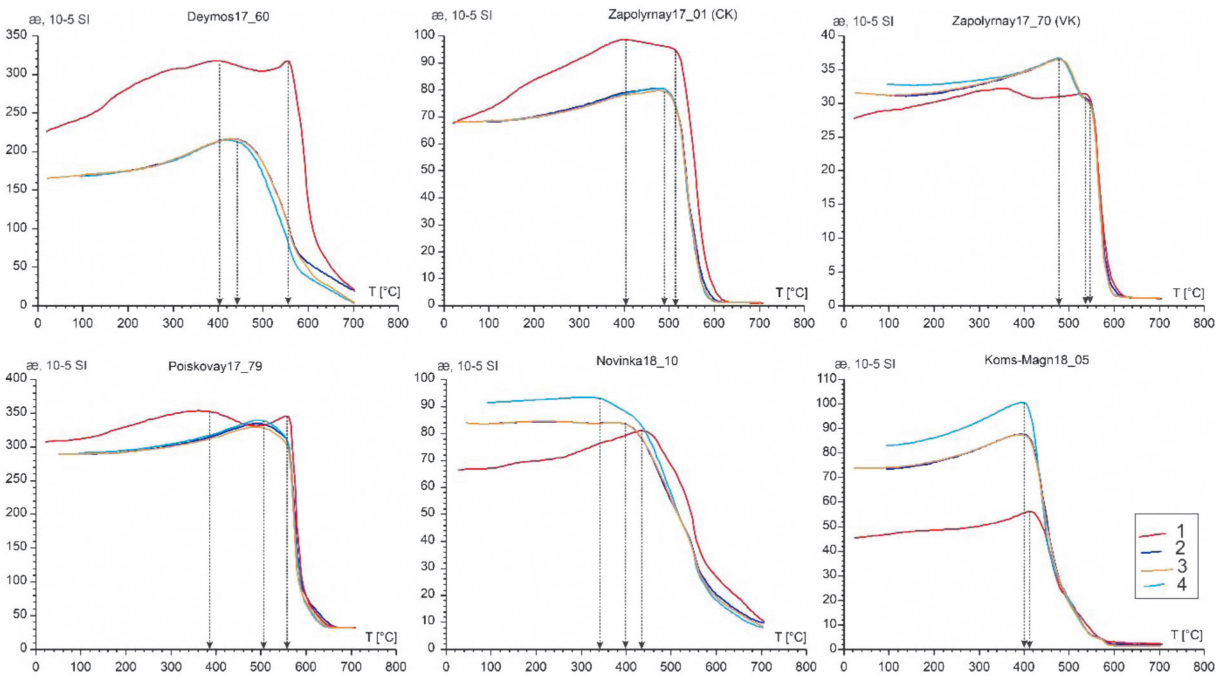


Fig. 9. Thermomagnetograms æ = f(T) of kimberlites from the Verkhnemunskoe deposit
Process: 1 – heating 1; 2 – cooling 1; 3 – heating 2; 4 – cooling 2
Рис. 9. Термомагнитограммы æ = f(T) кимберлитов Верхне-Мунского месторождения
Процесс: 1 – нагрев 1; 2 – охлаждение 1; 3 – нагрев 2; 4 – охлаждение 2

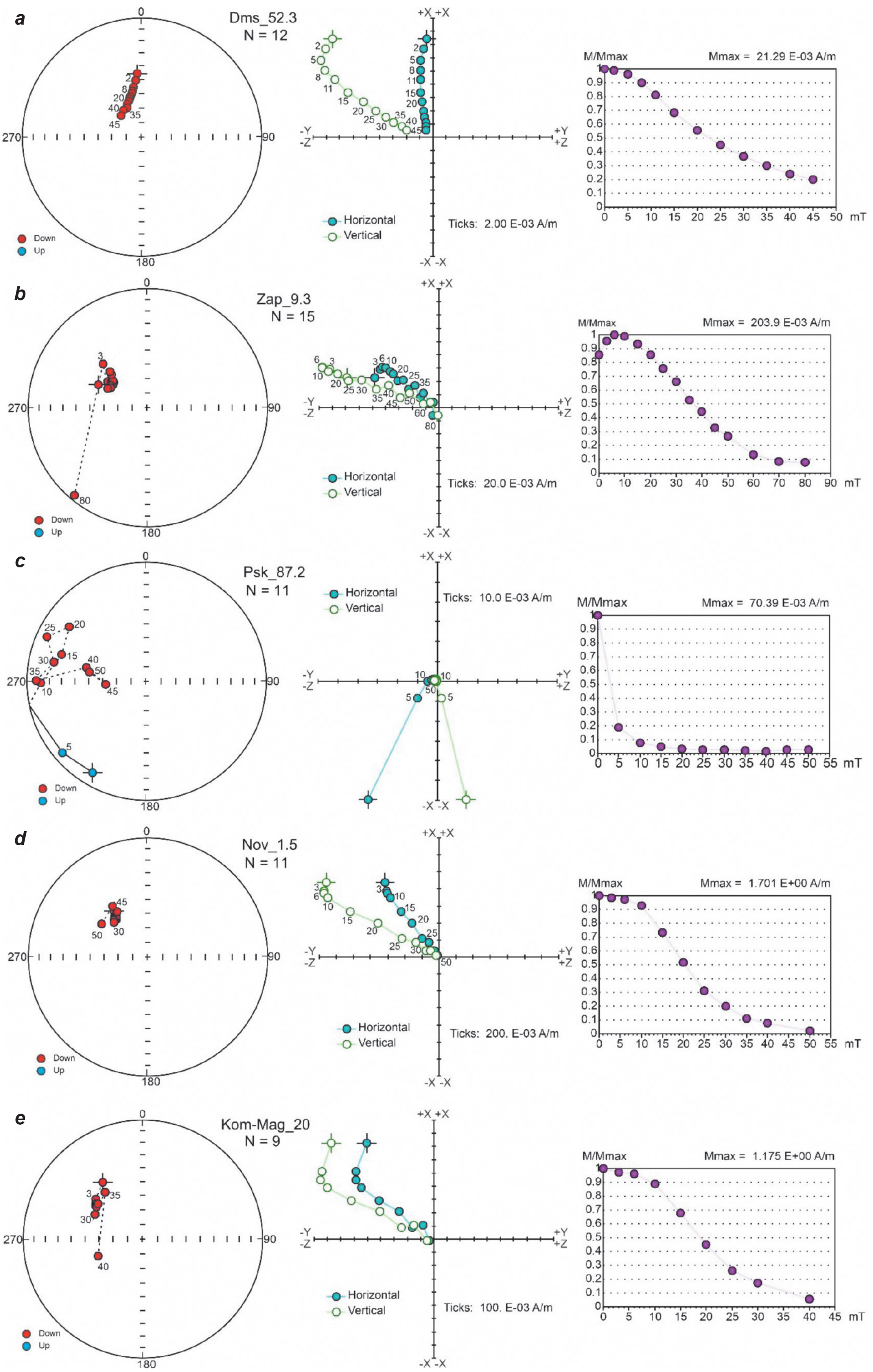


Fig. 10. Laboratory experiments on demagnetization of kimberlites from the Verkhnemunskoye field

Pipes: a – Deimos; b – Zapolyarnaya; c – Poiskovaya; d – Novinka; e – Komsomolskaya-Magnetnaya

Рис. 10. Лабораторные эксперименты по размагничиванию кимберлитов Верхне-Мунского месторождения

Трубки: a – «Деймос»; b – «Заполярная»; c – «Поисковая»; d – «Новинка»; e – «Комсомольская-Магнитная»

Table 3. Paleomagnetic directions of kimberlites of the Verkhnemunskoe deposit calculated from the characteristic component In^{ch}
Таблица 3. Палеомагнитные направления кимберлитов Верхне-Мунского месторождения, рассчитанные по характеристической компоненте In^{ch}

No	Object	*N*/*n*	D_{cp}, °	*Jcp*, °	*k*, unit	α_{95}, °	*Φ*, °	*Λ*, °	*dp*/*dm*, °	*fm*, °
1	Deimos, VK	1/12	315.6	-63.9	51.9	6.1	27.8	148.6	7.7/9.7	46
2	Zapolyarnaya, CK, NW	1/24	305.7	-64.9	28.3	5.7	31.3	155.5	7.4/9.2	47
3	Zapolyarnaya, CK, SE	1/10	320.4	-61.6	39.9	7.9	24.1	145.8	9.4/12.2	43
4	Zapolyarnaya, VK, SE	1/9	336.5	-62.6	24.8	10.7	22.7	133.1	13.1/16.7	44
5	Zapolyarnaya	3/43	316	-64.2	26.6	4.3	28.1	148.2	5.5/6.9	46
6	Poiskovaya, C	1/25	332.1	-65.8	31.7	5.2	27.3	135.6	6.9/8.5	48
7	Poiskovaya, PZ_1 exocontact	gcs 1/5	323	-57	21.1	17.1	18.5	145.2	18.1/24.9	38
		scs	8	-72	2.4	57.2	–	–	–	–
8	Komsomolkaya-Magnitnaya, NW	1/7	331.3	-55.1	10	20.1	15.2	138.9	20.3/28.6	36
9	Komsomolkaya-Magnitnaya, SE	1/13	359.1	-73.4	6.2	18.1	36.5	115.6	29.1/32.4	59
10	Komsomolkaya-Magnitnaya	2/20	344.2	-67.3	6.7	13.6	28	126.4	18.8/22.6	50
11	Novinka, NW	1/12	310.8	-70.2	22.6	9.3	37	148.6	13.8/16	54
12	Novinka, SE	1/12	315.3	-62.4	26	8.7	26.1	149.5	10.6/13.6	44
13	Novinka	2/24	313.4	-66.3	23.8	6.2	31.2	149.1	8.4/10.2	49
14	Summary definition		324.1	-64.8	99.6	4.9	26.5	142.2	6.2/7.8	46
15	Zapolyarnaya, DX	1/13	323.9	78.3	1.2	98.4	–	–	–	–
16	Terragenic-carbonate rocks of the Upper Lena $Є_3$*vl*, Morkoka $Є_3$*mrk* and Oldonda $Є_3$-O_1*ol* formations*		338.9	14.6	35.7	6.7	-35	136	3.5/6.9	-8
17	Aikhal, Sytykanskaya, Yubileinaya, traps of the Markha and Vilyui rivers**	11/–	–	–	–	–	11.1	149.7	8.9	31

Note. NW/SE/C – ore pillars, respectively, northwest/southeast/central; *N*/*n* – number of sites/samples participating in the statistics; gcs/scs – geographic/"stratigraphic" coordinate system; paleomagnetic pole: latitude – *Φ*, longitude – *Λ*, confidence intervals – *dp*/*dm* and paleolatitude – *fm*; Paleomagnetic data on: * – [59, 60]; ** – [41]. See Table 2 for other explanations.

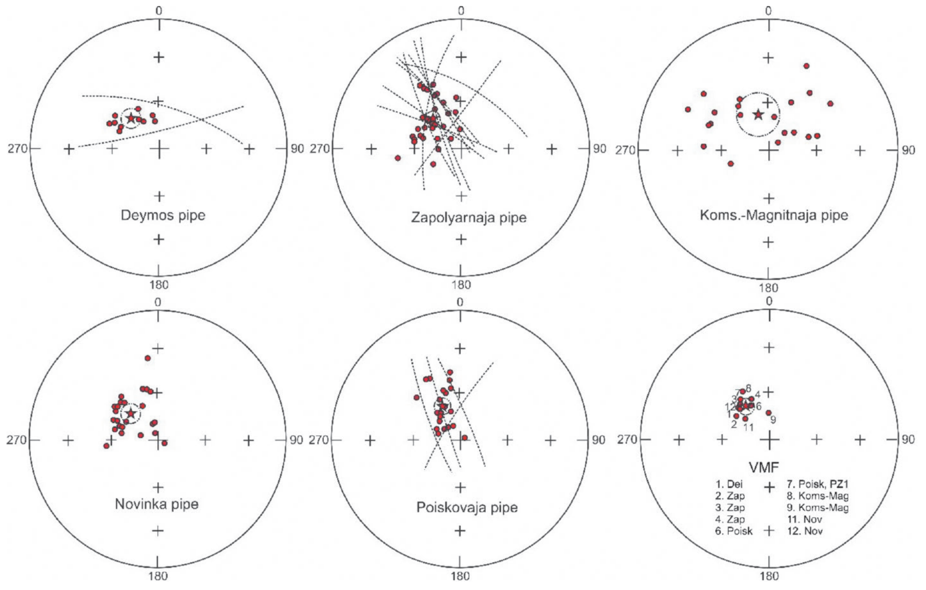


Fig. 11. Results of component paleomagnetic analysis of the natural remanent magnetisation vectors of kimberlites from the Verkhnemunskoe field:
Numbers correspond to the numbers of Table 3
VMF – Verkhnemunskoe field (summary definition)
Рис. 11. Результаты компонентного палеомагнитного анализа векторов естественной остаточной намагниченности кимберлитов Верхне-Мунского месторождения:
Цифры соответствуют номерам табл. 3
VMF – Верхне-Мунское поле (сводное определение)

The component composition of *In* DX vectors is also quite simple (Fig. 12, *a, b*). Only In^{ch} (Zap08m2ks) is present in most of the samples. In other samples the viscous component is removed by an alternating magnetic field of up to 10 mTl (Zap01m2ks) and can account for about 70 % of the original *In* value (Zap06m2ks). The In^{ch} DX vectors are scattered over the whole sphere (Fig. 12, *d*).

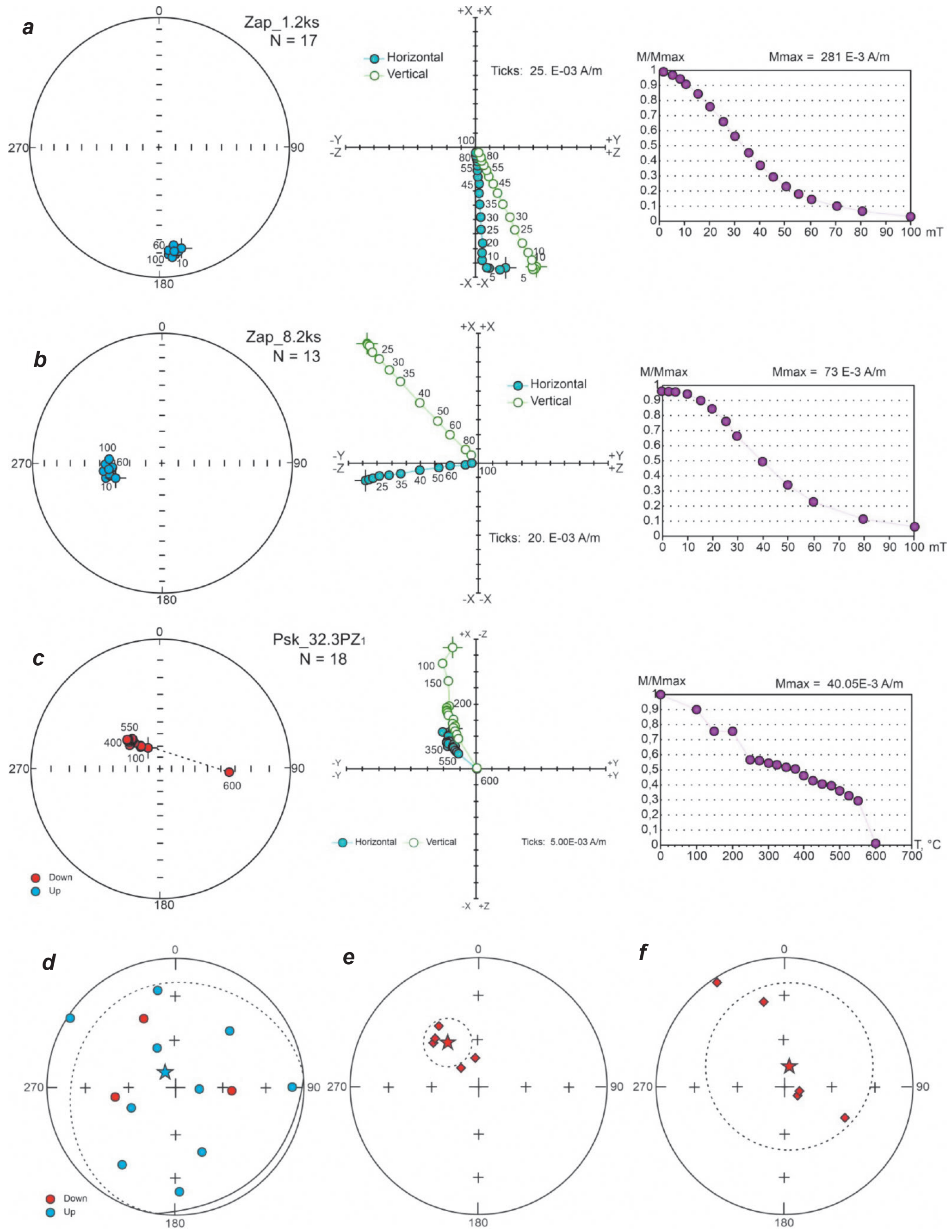


Fig. 12. Laboratory experiments of demagnetization and the results of component paleomagnetic analysis of natural remanent magnetisation vectors of xenoliths and host rocks of the Verkhnemunskoye field:
a, b – deep xenoliths of the Zapolyarnaya pipe; c – host rocks from the exocontact with kimberlites of the Poiskovaya pipe; d – vectors of characteristic natural remanent magnetisation of deep xenoliths; e/f – vectors of characteristic natural remanent magnetisation of host rocks from the exocontact in the geographic/"stratigraphict" (reduced to the horizontal plane) coordinate system

Рис. 12. Лабораторные эксперименты по размагничиванию и результаты компонентного палеомагнитного анализа векторов естественной остаточной намагниченности ксенолитов и вмещающих пород Верхне-Мунского месторождения:
a, b – глубинные ксенолиты трубки «Заполярная»; c – вмещающие породы из экзоконтакта с кимберлитами трубки «Поисковая»; d – векторы характеристической естественной остаточной намагниченности глубинных ксенолитов; e/f – векторы характеристической естественной остаточной намагниченности вмещающих пород из экзоконтакта в географической/«стратиграфической» (приведенные к горизонтальной плоскости) системе координат

The NRM vectors of the host terrigenous-carbonate rocks of the Early Paleozoic from the exocontact zone PZ_1 also turned out to be hard magnetic and retained their directions up to complete destruction by the temperature of 600 °C (Fig. 12, *c*). In the geographic coordinate system (gcs), their average direction (Fig. 12, *e*; Table 3) corresponds quite well with the characteristic NRM of the studied kimberlites (Fig. 10, 11; Table 3). Their grouping decreases markedly (k_{gcs} = 21.1 > k_{scs} = 2.4), the confidence oval increases with 95 % probability (α_{95gcs} = 17.1° < α_{95scs} = 57.2°) when they are converted to the stratigraphict coordinate system (tectonic correction for emplacement elements) (Fig. 12, *f*; Table 3). In addition, the average NRM vector with respect to rock layering does not agree in inclination with the previously studied age analogs of the Verkholenskaya, Morokokinskaya, and Oldondinskaya formations of the Early Paleozoic [41, 57, 59, 60]. Therefore, the nature of the vectors of the characteristic NRM of the host rocks of the exocontact is metachronous (overlying) and, most likely, formed due to their "baked contact test" by kimberlites in the process of pipe formation (contact test [1]).

Discussion

Despite the fact that kimberlite pipes of the Verkhnemunskoe deposit were affected by hypergenic and other processes, they retained the directions of the primary NRM vectors characterizing the time of intrusion (Fig. 11). The main arguments that allow to identify the characteristic NRM as syngenetic (synchronous) to the solidification of kimberlite magma are:

1. The presence of a wide range of MFMF as the main MCM, the main ones being magnetite and magnesioferrite, characterized by pseudo-single-domain structure and thermo-sufficient nature.

2. No dependence between the directions of the interpreted components of the characteristic NRM of kimberlites and the directions of the principal axes of the AMS ellipsoid (Figs. 7 and 11).

3. A significant difference in the direction of kimberlites from the known younger directions of the Siberian Platform including the "trap" direction which is present in a number of kimberlite pipes as a remagnetization direction of Permo-Triassic age [41–46].

4. Positive result of the xenolith test for the Zapolyarnaya pipe (Fig. 12, *d*): chaotic distribution of vectors on the sphere interpreted as a possibility of preservation of ancient (pre-deformation) magnetization (paleomagnetic stability) which indicates the absence of complete remagnetization processes in the studied kimberlite pipes.

5. Positive contact test (Fig. 12, *e, f*). Presence of host rock samples from the exocontact in the geographic coordinate system of NRM directions (Fig. 12, *e*) similar to the characteristic NRM of kimberlites (Fig. 10).

6. Coherence with single-age (D_3-C_1) VGP of kimberlite pipes of the YaDP (Fig. 13, *a*; Table 3) [41–46].

Positive tests of xenoliths and baking do not contradict the mechanism of formation and development of kimberlite bodies of YDP [13, 15, 66] and indirectly confirm the above conclusions about the existence of NRM of primary nature in the samples of the studied pipes.

According to the obtained groupings of the primary NRM vectors of the studied kimberlite pipes and host rocks from the exocontact the VGP were calculated which were combined into the average paleomagnetic pole: Φ = 26.5°N, Λ = 142.2°E, dp/dm = 6.2/7.8 (Table 3; Fig. 13, *a*). According to [13] it has a sufficiently high reliability criterion (Q = 6) which is determined by the following factors:

1. The correspondence to the absolute (geologic) Late Devonian-Early Carboniferous age (epochs) of YaDP kimberlites is 360±10 Ma.

2. High statistical values – $N \geq 7$, $k > 10$ and $\alpha_{95} < 16$.

3. Identity of the directions of the characteristic NRM of kimberlites obtained from stepwise experiments on demagnetization by alternating magnetic field and temperature.

4. Positive field tests of xenoliths (conglomerates) and baking (contact).

5. Structural and tectonic connection of the VMF with the Siberian Platform.

6. Difference from young paleomagnetic poles of the Siberian Platform.

Comparing the calculated PMP with the APWP of the Siberian Platform [5] according to the method [58] the paleomagnetic age of the studied kimberlite pipes is estimated to be 356±6 Ma (Fig. 13, *a, c*). This date agrees quite well with geological and isotopic data [7–9, 17–37]. Thus, the paleomagnetic data on VMF kimberlite pipes as well as other geological methods confirm the existence of the Late Devonian-Early Carboniferous epoch of kimberlite formation on the Siberian Platform. At this time the Siberian

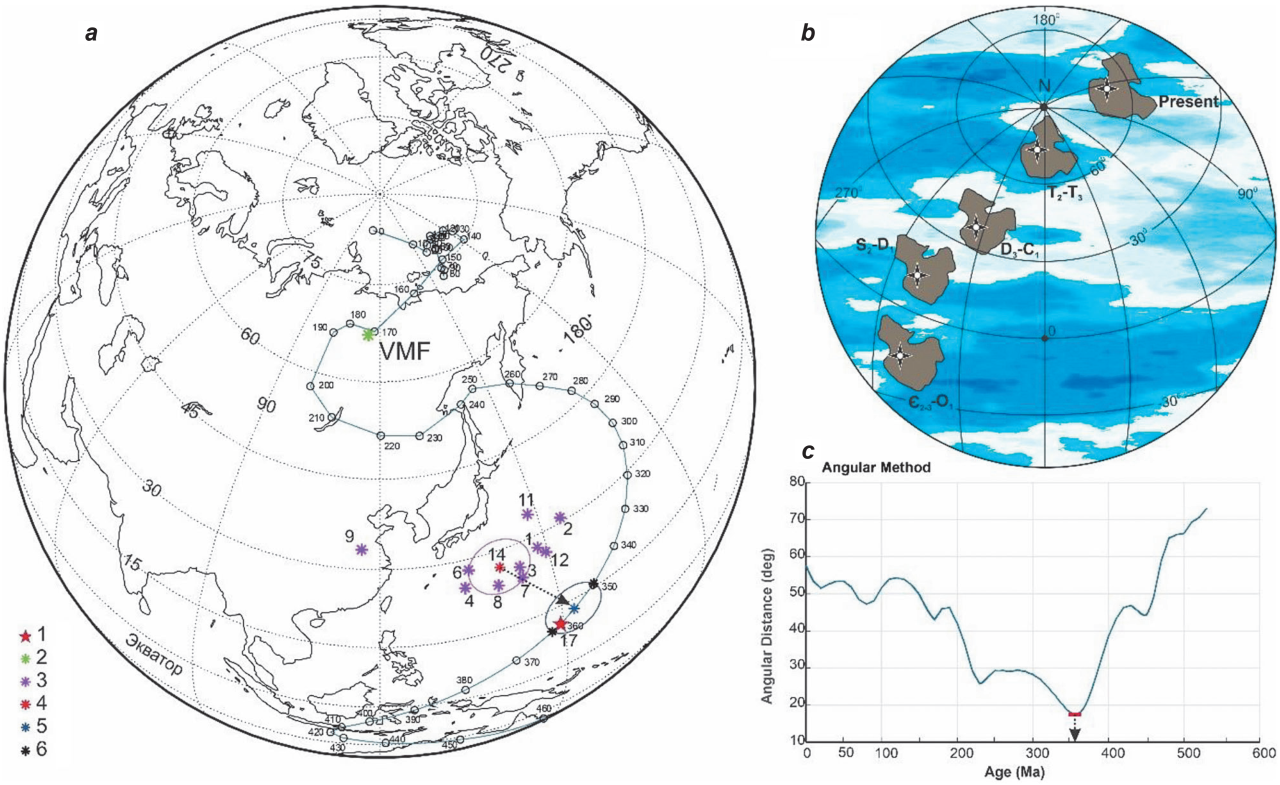


Fig. 13. Dynamic and geochronologic interpretation of paleomagnetic data obtained from kimberlites of the Verkhnemunskoe field:
__a__ – comparison of kimberlites virtual geomagnetic poles (numbers correspond to Table 3) with apparent polar wander paths of the Siberian Platform [5] according to the method [62]: 1 – paleomagnetic pole PZ2 [41], 2 – Verkhnemunskoe field, 3 – virtual geomagnetic poles (numbers correspond to Table 3), 4 – paleomagnetic pole of kimberlites (No. 14 in Table 3), 5 – paleomagnetic date; 6 – error in determining the paleomagnetic age; b – paleomagnetic reconstructions of the Siberian Platform in the Paleozoic – Early Mesozoic; c – paleomagnetic dating of kimberlites (graph of dependence of the deviation of the palaeomagnetic pole coordinates and the baseline palaeomagnetic trajectory)

Рис. 13. Динамическая и геохронологическая интерпретация палеомагнитных данных, полученных по кимберлитам Верхне-Мунского месторождения:
a – сопоставление виртуальных геомагнитных полюсов кимберлитов (номера соответствуют табл. 3) с траекторией кажущейся миграции полюса Сибирской платформы [5] по методике, описанной в источнике [62]: 1 – палеомагнитный полюс PZ2 [41], 2 – Верхне-Мунское поле, 3 – виртуальные геомагнитные полюсы (номера соответствуют табл. 3), 4 – палеомагнитный полюс кимберлитов (№ 14 в табл. 3), 5 – палеомагнитная дата, 6 – погрешность определения палеомагнитного возраста; b – палеомагнитные реконструкции Сибирской платформы в палеозое – раннем мезозое; c – палеомагнитное датирование кимберлитов (график зависимости отклонения координат палеомагнитного полюса и базовой палеомагнитной траектории)

Platform was located in the northern hemisphere at latitudes from 30 to 50° and was facing north with its southern flank (Fig. 13, *b*).

Conclusions

For the first time petro- and paleomagnetic data were obtained for kimberlite pipes of the Verkhnemunskoe deposit which significantly supplemented knowledge of the paleomagnetism of kimberlites of the YaDP [39–46, 59, 63]. This is mainly necessary for:

1. Construction of a priori PhGM to develop a correct methodology for searching for kimberlite pipes using geophysical methods. It should be noted that the amplitude, nature and size of magnetic anomalies (see Fig. 6) allow effective detection of kimberlite pipes by means of detailed magnetic survey which is most expedient to be carried out in the variant with the use of unmanned aerial vehicle (UAV) on the largest scale taking into account the current level of magnetic exploration – 1:500–1:2000 [64, 65]. Unfortunately, at the moment we do not have similar in performance UAV-gravimagnetic survey technologies that provide the necessary sensitivity but it is hoped that in the near future it will be possible to conduct complex UAV-gravimagnetic surveys which will allow us to solve the problem of search with maximum reliability.

2. PMP calculations to clarify the Late Devonian-Early Carboniferous (360±10 Ma) APWP interval of the Siberian Platform.

3. Constructions of dynamic PhGM in order to test hypotheses of kimberlite intrusion on the Siberian Platform.

Due to the specifics of the formation kimberlites are complex objects of paleomagnetic studies and for this reason many methodological techniques for them may be ineffective for solving geological problems. Therefore, as recommendations for improving the quality of paleomagnetic studies of kimberlites it is necessary firstly to conduct a correct selection of oriented samples not only from the bedrock body itself but also from the host (from the contact and at a considerable distance) overlying rocks and xenoliths. It is desirable to select edge and center pieces if they have large dimensions. Secondly, the evidence of the nature of the obtained NRM vectors should be based on a complex of studies including petrography, mineralogy (including magnetic), geochemistry, magnetic susceptibility anisotropy, componental paleomagnetic analysis, etc. Statistical methods of proving the nature of NRM are of particular importance: tests of xenoliths (conglomerates), baking (contact) and folds (host rocks). Thirdly, we should not forget that the magnetization of a kimberlite pipe can be associated with a paleomagnetic anomaly (excursion). Therefore, at least 7 pipes or kimberlite emplacement phases of one cluster/field are required to calculate the PMP. If such methodological requirements are met, the paleomagnetic data in combination with geological paleontological and isotopic studies will make it possible to definitely resolve the age of kimberlites which is a prerequisite for the prediction of primary diamond deposits in YaDP.

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I.S. Sharygin did sampling, was responsible for geological study, petrography, geochemistry.

D.M. Kuzina performed magneto-mineralogical studies.

S.V. Potapov carried out analytical studies.

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