Article

Petrographical and Geochemical Characteristics of Magmatic Rocks in the Northwestern Siberian Traps Province, Kulyumber River Valley. Part II: Rocks of the Kulyumber Site

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Received: 3 April 2020; Accepted: 3 May 2020; Published: 7 May 2020

Abstract: The origin of the Siberian trap province is under discussion even though numerous models of its formation have been created over the last three decades. This situation is mainly due to lack of modern geochemical data on magmatic rocks around the province. These data are a very important tool to reconstruct of magmatic evolution within the province in time and space and to understand a mechanism of province formation. Geochemical study has only been carried out so far for the Norilsk and Meimecha–Kotuy areas. For the first time, we have studied the geochemical and mineralogical characteristics of magmatic rocks at the Kulyumber river valley located 150 km to south from the Norilsk ore district, in the junction of the Tunguska syncline and Norilsk–Igarka zone. It comprises three sites, i.e., Khalil, Kaya, and Kulyumber. The geochemical data on the magmatic rocks of the Khalil and Kaya sites were published earlier (Part I). This article (Part II) regards geochemical and mineralogical data on igneous rocks at the Kulyumber site. Seventeen intrusive bodies (41 samples) and six samples of sedimentary rocks were studied by X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS). Isotopes analyses (Sr, Nd, Pb) were conducted for 12 samples. These data were compared with data for intrusions of the Norilsk area, the Dzhaltdulsky massif, Kureyka river, and intrusions in Angara river valley published earlier. The whole list of analyses includes 102 items. Three groups of intrusive rocks were recognized: (1) Mafic rocks with elevated K₂O without negative Ta–Nb and Pb-positive anomalies, with (Gd/Yb)_n = 2.0 and εNd = −1.0; attributed to a new Kulyumbinsky complex; (2) subalkaline rocks with elevated SiO₂, TiO₂, P₂O₅, and K₂O with small negative Ta–Nb and positive Pb anomalies and (Gd/Yb)_n = 1.8, εNd = −3.8; Ergalakhsky complex; and (3) mafic rocks with strong Ta–Nb and Pb anomalies and (Gd/Yb)_n = 1.2–1.4, εNd = +0.4–+2.2. The third group is rather nonhomogeneous and includes intrusions of the Norilsk, Kuryesky, Katangsky, Ogonersky, and Daldykansky complexes differing in MgO content and trace element distribution (values of Ta–Nb, Pb, and Sr anomalies). Three groups of intrusive bodies had different magma sources and different condition of crystallization reflecting their origin in rift and platform regimes.

Keywords: Siberian traps; Norilsk-Igarka paleorift; Kulyumber river valley; magmatism; geochemistry

1. Introduction

The origin of the Siberian traps province, the largest continental flood basalt province on Earth (SFBP), is still under discussion, even though it has been studied for many years [1–17]. A huge volume of magmatic rocks and related extra-large PGE-Cu-Ni deposits are the main points of interest for geologists [18–29]. Many different models have been suggested for its formation and the source of mineralization [5,21,30–32]. However, none of these models satisfies the requirements for the quality of modern constraints. The main problem arises from the lack of geological data since the SFBP is vast and comprises many remote and inaccessible areas. Nevertheless, advances in the use of geochemical data can help to improve our understanding of magmatic rocks around the Siberian province and also to reconstruct the history of their formation and evolution. By this moment, precious geochemical data were obtained for two regions of the province, Norilsk and Meimecha–Kotuy [33–44]. These data are mostly from basaltic rocks. Investigation of intrusive rocks comprised mainly the Norilsk ore-bearing intrusions [34,35,45–50], while the intrusions from other parts of the province have almost not been analyzed yet.

The research of igneous rocks around the Siberian province is an ongoing project and the results will be published in a series of articles. The first area that was studied was the Kulyumber river valley (KRV) located 150 km to the south of the Norilsk area [50] (Figure 1). Its tectonic structures and magmatic rocks are very similar to that of the unique Norilsk ore district. The KRV is located between the Tunguska syncline and Norilsk–Igarka paleorift tectonic zone and provide information on magmatic activities within both structures. Additionally, unlike poorly mineralized nearby areas, the KRV includes some disseminated and massive sulfide ore potentials. We studied igneous rocks at three sites within the Kulyumber river valley including two northern sites (Khalil and Kaya) and one southern site, Kulyumber site.

Figure 1. Scheme of the Siberian traps province with position of the Kulyumber river valley (dark rectangle). Norilsk–Igarka PR—paleorift zone.

This article briefly describes the geology of the KRV and petrological and geochemical characteristics of rocks (mostly, intrusive rocks) of the Kulyumber site, whereas, magmatic rocks in the northern part of this area were described earlier [51]. For the first time, the authors gathered a large amount of modern geochemical and mineralogical data on magmatic rocks of the Kulyumber river valley. That allowed us to subdivide intrusive rocks into complexes more correctly than was done before.

2. Brief Geological Characteristics of the Kulyumber River Valley

The study area is located in the Northwestern Siberian platform (Figure 1) where the Tunguska syncline joins with the Norilsk–Igarka paleorift. The tectonic structure of the area is described in [51] on the basis of geophysical data (1:200,000 gravity mapping and aeromagnetic data of 1:100,000 scale). It is characterized by a submeridional band of the gravitational field positive values and low values of the magnetic field stretching along the Yenisey river (100 km wide) and bordering the ancient Siberian craton. It has three sublatitude branches, one of them coincides with the stretch of the Kulyumber river valley.

The local tectonic structures include the Nirungdinsky trough and the Mogen–Khalil anticline (Figure 2). The Lower Ordovician–Lower Carboniferous formations in the area consist of carbonate-terrigenous rocks, whereas the Tunguska Group (C₂–P₂) sediments are composed of sandstones and coal. The Late Permian–Early Triassic magmatic rocks belong to the Siberian flood basalts province. Like the Norilsk area [52], volcanic rocks from the Nirungdinsky trough are divided into several formations, including Syverminsky, Gudchikhinsky, Khakanchansky, Tuklonsky, and Nadezhdinsky, that were comprehensively described in the first part of the article [51]. The two lower formations contain trachybasalts and olivine basalts with TiO₂ content >1.5 wt.% and high Gd/Yb ratio, which evidences presence of garnet in magmas' sources. The upper formations consist of tholeiitic basalts with TiO₂ < 1 wt.% and low Gd/Yb ratio.

Intrusive bodies are mostly enclosed by sedimentary rocks, and are exposed in the western part of the area (Figure 1). During the geological mapping (1:200,000 scale) these rocks were classified into several complexes on the basis of their textures and structure as well as a few X-ray fluorescence (XRF) analyses. They were attributed to the intrusive complexes typical of the Tunguska syncline (Katangsky, Kuzmovsky, [53]), the Norilsk area (Ergalakhsky, Norilsk, Daldykansky, Ogonersky) [52], and the local Kureysky complex. However, this classification does not take into account modern geochemical techniques that allow distinguishing different types of intrusive rocks more precisely.

The intrusions occur as sill-like bodies (with a thickness up to 5–6 to 100 m and a length of up to 10–15 km). Rare dykes cut volcanic rocks. The magma intrusion was mainly controlled by Imangdinsky–Letninsky and Khalilsky faults (Figure 2). Intrusive bodies compositionally vary from olivine gabbro-dolerite to gabbro and leucogabbro. Magnesium-rich rocks (MgO = 9 wt.%) rather occur as separate horizons within differentiated intrusions than forming separate bodies.

Figure 2. Geological map of the Kulyumber river valley (after Norilskgeology Ltd. data with the authors' corrections).

3. Materials and Methods

The authors studied igneous rocks sampled from the outcrops in the Kulyumber river valley including three sites, i.e., the (1) Khalil, (2) Kaya, and (3) Kulyumber (samples labeled X, 3.21–3.22, and Kul, respectively) (Figures 2 and 3 [51]) and from the cores of the boreholes PR-1, PR-4, and PR-11 drilled by Norilskgeology Ltd. and shown in Figure 4. The last area is located immediately to the west from the Kulyumber site. Its eastern boundary coincides with the western boundary of the area shown on Figure 3. We named it the western Kulyumber site. The data on magmatic rocks from two first areas were considered in Part I of the article [51]. Some samples of Devonian and Carboniferous-Permian sedimentary rocks were analyzed as well. In order to compare the magmatic rocks with the rocks of the Norilsk district, we also studied gabbro-dolerites of the Dal'dykansky and

Ogonersky complexes (outcrops). Furthermore, we used geochemical data published by us earlier [51] for the ore-bearing Norilsk 1 intrusion (borehole DM-27), the Dzhaltulsky massif in the Kureyka river valley, and Padunsky sill in the Angara river valley, regarded as reference intrusions for the Norilsk, Kureysky, and Katangsky complexes, respectively.

Figure 3. Geological map and cross-section of the of the Kulyumber site. The number in circle means the intrusion number (after Norilskgeology Ltd. data with the authors' corrections).

Figure 4. Geological map and cross-section of the western Kulyumber site (after Norilskgeology Ltd. data with the authors' corrections).

Major elements in rocks were determined by X-ray fluorescence (XRF) at the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry of Russian Academy of Science (IGEM RAS), Moscow (analyst A.I. Yakushev). Trace elements in whole rocks were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) at the Institute of Microelectronics Technology and High Purity Materials RAS (IMT RAS), Chernogolovka, Russia (analyst V.K. Karandashev). These methods have been described earlier [29,54,55].

The Sr, Nd, and Pb isotope composition of the whole rocks was measured with the aid of a Triton (Thermo) solid-phase multi-collector mass spectrometer in static mode at the A.P. Karpinsky Russian Geological Research Institute VSEGEI Laboratory (Saint Petersburg, Russia). The values used for normalization were $^{88}\text{Sr}/^{86}\text{Sr} = 8.375209$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Preliminary decomposition of silicate samples and separation of elements were performed through a standard method of ion exchange column chromatography. The blank values during the analysis did not exceed 0.1 ng for Sm, Nd, Sr, and 0.05 for Pb, Rb. The isotopic compositions of the standards were JNdi-1: $^{143}\text{Nd}/^{144}\text{Nd} = 0.512105 \pm 0.000004$ and SRM987 $^{87}\text{Sr}/^{86}\text{Sr} = 0.710250 \pm 0.000009$. The error of the corresponding isotope ratio was at 95% significance level in absolute values (2 s, abs) or percentages (2 s, %). The model age in millions of years (TMa) corresponds to the evolution model of the Earth's lead composition (Stacey-Kramers, [56]). DM1 and DM2 model ages (in million years) calculated relative to a one- and two-stage model of the mantle neodymium isotope composition evolution. The $^{87}\text{Sr}/^{86}\text{Sr}^*$, $^{143}\text{Nd}/^{144}\text{Nd}^*$, $\epsilon\text{Nd}(\text{T})$ is the initial isotope composition of corresponding sample at the time of its origin (250 Ma).

Composition of rock-forming minerals was determined with the electron microprobe CAMECA SX 100 at the Vernadsky Institute of Geochemistry and Analytical Chemistry of Russian Academy of Science (Moscow, Russia) Analyses (analyst N.N. Kononkova) and Geol 8200 at IGM RAS (Moscow, Russia) (analyst V. Taskaev). The device was equipped with 5 wave spectrometers. Shooting conditions: Accelerating voltage was 20 kV, a probe current was 20 nA, the diameter of the probe was 1 mk, exposure time was 10 sec. Natural minerals were used as standards (element-analytical line): Sanidine ($\text{Si}_{\text{K}\alpha}$, $\text{Al}_{\text{K}\alpha}$, $\text{K}_{\text{K}\alpha}$), sc olivine ($\text{Fe}_{\text{K}\alpha}$, $\text{Ni}_{\text{K}\alpha}$, $\text{Mg}_{\text{K}\alpha}$), spessartin ($\text{Mn}_{\text{K}\alpha}$), anorthite ($\text{Ca}_{\text{K}\alpha}$), albite ($\text{Na}_{\text{K}\alpha}$), chromite ($\text{Cr}_{\text{K}\alpha}$), F-phlogopite ($\text{F}_{\text{K}\alpha}$), ilmenite ($\text{Ti}_{\text{K}\alpha}$), and Cl-apatite ($\text{Cl}_{\text{K}\alpha}$). Element concentrations were calculated by the ZAF correction method.

4. Results

Here we describe the sedimentary and magmatic rocks of the third site, named the Kulyumber site (Figures 2 and 3) including its western part (Figure 4). Some intrusive bodies were studied in the cores of the boreholes drilled in the western part of this area, shown in Figure 4.

4.1. Sedimentary Rocks

The sedimentary rocks' outcrop is in the western part of the Kulyumber site (Figures 3 and 4), where they form the western part of the Nirungdinsky trough. The Devonian sediments in the Kulyumber river valley dip to east at 10–12 degrees. The thickness of these deposits was 50 m. They consist of brown-red crimson, coarse-grained marls, and dark grey limestones, combined in the Nakokhozsky formation [57]. The chemical compositions of four representative samples (Kul-8–Kul-11, Table 1) had different SiO_2/CaO (wt.%) ratio varying from 0.04 to 2.01, which reflects admixture of terrigenous component in carbonate rocks. The high SiO_2 and MgO contents are typical of marls (Table 1, Nos. 1 and 2) while low SiO_2 and absence of MgO in rocks correspond to limestones. The contact of the Devonian deposits with overlain rocks was intruded by gabbro sills but it is described as subconformed [57]. The Tunguska Group of rocks ($\text{C}_2\text{--P}_2$) comprises terrigenous rocks with coal horizons belonging to the Burguklinsky formation in this area. It is widespread in the Kulyumber river valley and consists of dark-grey, layered argillite, siltstone, and sandstone. We studied these rocks in the Khalil river valley (Table 1, Nos. 5 and 6). Quartz dominates in these rocks while carbonate and clay minerals occur as well.

Table 1. Composition of sedimentary rocks in the Kulyumber river valley.

No	1	2	3	4	5	6
Sample, N	Kul-8	Kul-9	Kul-10	Kul-11	X-39-1	X-47-2
Site	3	3	3	3	1	1
Age	D ₃	D ₃	D ₃	D ₃	C ₂ -P ₂	C ₂ -P ₂
Rock	marls	marls	limestone	limestone	argillite	siltstone
SiO ₂	37.37	31.59	9.73	2.36	73.15	60.82
TiO ₂	0.57	0.47	0.2	0.06	0.42	0.6
Al ₂ O ₃	8.83	6.69	2.24	0.6	9.92	15.42
Fe ₂ O ₃	4.51	3.42	1.01	0.71	2.47	5.1
MnO	0.09	0.12	0.05	0.03	0.09	0.08
MgO	9.50	6.45	0.60	0.68	0.79	2.18
CaO	18.09	26.03	48.75	53.84	4.07	2.98
Na ₂ O	0.08	0.09	0.19	0.08	1.11	5.3
K ₂ O	2.60	1.29	0.72	0.17	3.03	1.18
P ₂ O ₅	0.14	0.11	0.07	0.03	0.11	0.23
Cr ₂ O ₃	2.07	1.21	0.20	0.04	0.00	0.00
LOI	18.0	22.6	35.8	40.9	4.7	5.5
S	0.07	1.07	0.51	0.45		
Total	101.9	101.1	100.1	100.0	99.9	99.4
Li	42.8	49.5	11.2	7.24	16.6	16.2
Rb	56.2	37.5	17.7	6.6	112.0	37.5
Sr	257	134	103	236	63	177
Y	20.1	14.7	8.00	1.71	17.0	23.2
Cs	0.97	1.35	0.30	0.14	1.44	2.10
Ba	305	88	541	20	343	171
La	27.7	15.0	9.06	3.20	28.0	29.3
Ce	53.7	30.9	18.3	5.7	53.8	60.3
Pr	6.17	3.75	2.16	0.63	5.97	6.65
Nd	22.78	14.36	8.07	2.24	20.64	26.40
Sm	4.63	3.00	1.67	0.41	4.12	5.00
Eu	1.08	0.83	0.44	0.08	0.85	1.14
Gd	3.47	2.60	1.36	0.31	2.50	4.58
Tb	0.64	0.45	0.24	0.05	0.47	0.70
Dy	3.56	2.63	1.41	0.30	2.83	4.32
Ho	0.77	0.54	0.29	0.06	0.60	0.85
Er	2.22	1.56	0.80	0.18	1.71	2.57
Tm	0.30	0.22	0.11	0.02	0.24	0.35
Yb	2.02	1.45	0.70	0.16	1.48	2.46
Lu	0.28	0.21	0.10	0.02	0.24	0.36
Pb	2.88	3.91	4.18	4.39	4.67	3.13
Th	4.93	3.90	1.11	0.14	6.21	8.75
U	2.28	2.30	0.61	0.41	1.43	3.01
Sc	8.76	7.32	3.00	0.95	31.6	13.2
Ti	2778	2144	747	239	2815	3597
V	75	56	19	7	58	100
Cr	51.7	45.4	13.6	7.24	31.2	68.5
Co	9.14	8.34	3.46	0.89	7.06	6.44
Ni	25.5	25.9	7.69	5.04	11.8	53.6
Cu	1.42	4.23	11.3	3.81	29.9	119
Zn	30.6	16.4	bdl	bdl	11.71	62.1
Zr	123	74.1	30.0	8.71	105	156
Nb	15.3	6.44	2.62	0.30	14.4	11.3
Hf	2.34	1.67	0.51	0.19	3.03	4.06
Ta	0.92	0.40	0.20	0.02	1.09	0.73

Note: Here and in Table 3, oxides are given in wt.%, elements in ppm. Analyses number sites: 1–4 are Kulyumber and 5 and 6 are Khalil; bdl—below detected limit; LOI—loss of ignition.

Figure 5 demonstrates the abundance of trace and rare Earth elements in the Devonian and Tunguska Group rocks. All rock samples show similar distribution patterns, though their elemental contents may differ by about two orders of magnitude. They are characterized by the Ta-Nb-negative and U- and Pb-positive anomalies; these features are typical of crust rocks. All rocks were depleted in Ti. The (La/Sm)_n ratio ranged from 3.2 to 5.1 and is higher than this ratio in intrusive rocks. The (Gd/Yb)_n ratio varied in narrow range from 1.4 to 1.6. The highest elements' concentrations occurred in marls and siltstones, while carbonate rocks were depleted in them. Composition of sedimentary rocks is important for the estimation of assimilation of surrounding rocks by magma during emplacement.

Figure 5. Trace-elements' spider diagrams for sedimentary rocks of the Kulyumber river valley, normalized to primitive mantle after [58].

4.2. Volcanic Rocks

Volcanic rocks form the eastern part of the area, and they occur in the center of the Nirungdinsky trough (Figure 2). They are represented by the basalts and tuffs that were correlated with volcanic rocks of the Norilsk area. Five formations were recognized within the studied area: Syverminsky, Gudchikhinsky, Khakanchansky, Tuklonsky, and Nadezhdinsky. We studied in detail the structure and composition of the lower part of the lava sequence in the Khalil site and compared it with the lower part of the volcanic section in the Norilsk area (Lake Lama). These data were published earlier [51] and volcanic rocks were not described in this article.

4.3. Intrusive Rocks

4.3.1. General Characteristics of Intrusive Rocks

As mentioned above, the study area is located at the border of two different tectonic zones (Figure 1), and this led to the formation of intrusive bodies with characteristics resembling both environments. Thus, the classification of these rocks is not straightforward. The geological map (Figures 2–4) shows that this area comprises seven different complexes including: Ergalakhsky, Norilsk, Daldykansky, Ogonersky (typical of the Norilsk area), Kuzmovsky, Kureysky, and Katangsky (typical of the Tunguska syncline) [50,57]. The intrusive bodies constituting these complexes show similar morphology, texture, and composition. It is very difficult to recognize them without special study, on the basis of only major components in rocks. Along with the major components, we analyzed trace elements in all samples (Table 2) as well as radiogenic isotopes in some of them.

The intrusions account around 15% of the surface (Figures 2 and 3). They are represented by sills or sill-like bodies located subconsequently in sedimentary rocks (O, S, D, C₂-P₂), i.e., they extend in submeridional direction at 15–20 km and fall to the east at 10–12° to the center of the Nirungdinsky trough. Several intrusive bodies are dykes cutting volcanic rocks (site 1). The thickness of intrusions varies from 5–10 m to 150 m. Initially on the surface all intrusive bodies were subdivided into

three complexes: The Ergalakhsky of elevated alkalinity and Katangsky and Kureysky of normal alkalinity. Fine-grained gabbro-dolerites were attributed to the Katangsky complex while medium- and coarse-grained and weakly stratified rocks (up to leucogabbro) were referred to the Kureysky complex. The rocks of the first complex dominate in the Kulyumber area. The temporal relationships between intrusions of different complexes are unknown because there are no geological boundaries between them because they are separated by sedimentary rocks. Their correlation with lavas was carried out on the bases of their chemical compositions: The Ergalakhsky complex is correlated with Ivakinsky formation due to elevated Ti, alkalis, and (La/Sm)_n contents in their rocks. Katangsky and Kureysky complexes are similar to the lavas of the main stage of platform magmatism (Morongovsky–Samoedsky formations). The paleomagnetic data give similar results [59,60]. The most convincing results were obtained for the Ergalakhsky complex, which is characterized by reverse magnetization like the Ivakinsky formation.

Table 2. List of studied intrusive complexes.

Complex	Intrusion No, Borehole	Rocks	Sample
Ergalakhsky	Intrusion 7	Trachydolerites	Kul-15
Katangsky	Intrusion 1	Olivine gabbro-dolerites	Kul-2/1, (Kul-1, Kul-3–Kul-5, Kul-7, Kul-38) *
	Intrusion 2	Olivine gabbro-dolerites	Kul-19, Kul-21, Kul-22
	Intrusion 6	Gabbro-dolerites	Kul-14 *
	Intrusion 8	Olivine gabbro-dolerites	Kul-25, Kul-28, Kul-31, Kul-32 Kul-34
	Intrusion 9	Olivine gabbro-dolerites	Kul-44 *
Kureysky	Intrusion 4	Olivine gabbro-dolerites, gabbro-dolerites, Ti-Mag gabbro	K-1, K-2, K-16 *
	Intrusion 3	Olivine gabbro-dolerites,	Kul-40
Kulyumbinsky	Intrusion 5	Gabbro-dolerites	Kul-12a, Kul-12 *
Supposed Daldykansky	PR-4, PR-11	Gabbro-dolerites, olivine-bearing gabbro-dolerites	PR-4/75.5, PR-4/80, PR-11/486, PR-11/489.5, PR-11/492.6
Supposed Kuzmovsky	PR-4	Gabbro-dolerites	PR-4/437, PR-4/440, PR-4/447.5
Supposed Ogonersky	PR-6	Gabbro-dolerites	PR-6/339
Norilsk	PR-1	Olivine gabbro-dolerites, gabbro-dolerites, leucogabbro	PR-1/214.6, PR-1/216, PR-1/216.3, PR-1/224, PR-1/234, PR-1/256, PR-1/262, PR-1/262.1, PR-1/266

Note. *—after [60].

The rocks of the Ergalakhsky, Kureysky, Norilsk, and Katangsky complexes were recognized in outcrops while the Supposed Ogonersky, Daldykansky, Kuzmovsky, Kruglogorsky, and Norilsk subcomplex of the Norilsk complex were diagnosed in the boreholes (Figure 4, Table 2). To understand the difference between rocks of these complexes, we studied mineral and chemical compositions of rocks from the Kulyumber site and from the reference complexes (Daldykansky, Ogonersky, and Norilsk) in the Norilsk area and Katangsky and Kureysky in the Tunguska syncline. Within the Kulyumber site (Figure 3) only one intrusive body had sub-alkaline composition and belongs to the Ergalakhsky complex (Kul-15). Three intrusive bodies were attributed to the Kureysky complex, including the large Intrusion 4 (Figure 3, samples Kul-16, K-1, K-2), one intrusion in the central part of site (sample Kul-12), and one in its right side (sample Kul-40). According to our geochemical data, these intrusive bodies belong to different complexes (see below).

Intrusions of the Katangsky complex dominate in the area. We studied five sills in the Kulyumber site across their thickness (points Kul-2–7, 13, 14) as well as along their length (Kul-25–35, 41–44).

The intrusion penetrated by the borehole PR-1 at depths of 213–279 m was attributed to the Norilsk complexes (Kruglogorsky subcomplex) on the bases of the leucogabbro horizons in it and the discovery of disseminated sulfides in its lower zone (271–275 m), although it is not completely correlated with the ore-bearing intrusions of the Norilsk area. It was named the Gabbrovy intrusion. Some intrusions penetrated by boreholes PR-4 and PR-11 (Figure 4) were presumably recognized as sills of the Daldykansky (PR-4/80, PR-11/480), Ogonersky (PR-6/339), and Kuzmovsky (PR-4/430 m). We named them Supposed Daldykansky, Supposed Ogonersky, and Supposed Kuzmovsky before getting analytical data.

4.3.2. Petrographical and Mineralogical Characteristics of Intrusive Rocks

The Ergalakhsky complex. Trachydolerite of this complex was described in the first part of this article. It consists (vol.%) of plagioclase (An_{40–55}, 50–60%), clinopyroxene (Wo_{41–42}, En_{36–39}, and Fs_{19–22}, 35–40%, Ti-augite), orthopyroxene (0–3%), and olivine (Fo_{50–55}, 1–3%).

Kureysky complex. The largest intrusion of the Kureysky intrusive complex is the Intrusion 4 in Figure 3. It is formed by coarse-grained and middle-grained olivine gabbro-dolerites and gabbro-dolerites. The main rock-forming minerals are olivine, clinopyroxene, plagioclase; moreover, rare minerals are represented by biotite, magnetite, and apatite. Composition of olivine (representative analyses of rock-forming minerals are given in Table 3, full data are in Table S1) varied significantly from Fo₄₉ to Fo₇₅, and the largest grains have a zoned structure where border zones are enriched in Fe (Figure 6a,b). The CaO content reached 0.32 wt.%, and the NiO contents were low (0.05–0.17 wt.%). This composition strongly distinguishes from the olivine compositions of the ore-bearing intrusions of the Norilsk area, in particular, from the Norilsk 1 intrusion (Table 3 and Table S1) and other intrusions [24,25,61–63]. Clinopyroxene has a more stable composition. Its Mg number ranged between 64–74. Chromium is practically absent (at the level of the electron microprobe analysis (EPMA) sensitivity) and TiO₂ content reached 1 wt.%. Maximum concentrations were (wt.%) Al₂O₃—2.25 and Na₂O—0.40. The composition of plagioclase varied from An₅₆ to An₇₀. Magnetite contained 12–14 wt.% TiO₂. The mineral composition of the Khalil intrusion (the Khalil site), attributed to the Kureysky complex, which was also studied in the samples X-19 and was close to that of Intrusion 4 in the Kulyumber site.

Table 3. Representative compositions of rock-forming minerals, wt.%.

No.	No. Point	No. Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	NiO	Total
1	1	K-2	35.64	0.01	0.03	32.39	0.46	30.45	0.25	bdl	0.17	99.43
2	2	K-2	35.63	0.08	1.55	26.93	0.41	34.85	0.32	0.75	0.14	101.1
3	3	K-2	36.95	0.03	0.74	25.65	0.37	35.10	0.29	0.05	0.13	99.31
4	4	K-2	37.27	bdl	0.03	26.49	0.38	35.60	0.20	0.04	0.14	100.2
5	11	K-2	35.76	bdl	bdl	37.76	0.53	26.08	0.20	bdl	0.10	100.4
6	15	K-2	35.32	0.02	0.01	36.78	0.51	26.70	0.26	bdl	0.07	99.67
7	26	K-2	49.49	0.02	31.44	0.44	0.03	0.14	14.58	3.28	bdl	99.53
8	31	K-2	47.24	0.04	31.58	1.38	bdl	0.59	14.93	2.55	bdl	98.42
9	34	K-2	52.57	0.12	0.78	19.12	0.45	12.72	9.91	0.16	bdl	95.86
10	35	K-2	50.01	0.14	0.48	37.91	0.64	10.82	1.01	0.07	0.02	101.1
11	38	K-2	51.23	1.02	2.25	13.33	0.36	14.15	17.17	0.40	bdl	99.94
12	59	Kul-16	33.46	0.02	0.04	43.59	0.64	21.68	0.15	0.04	0.12	99.77
13	60	Kul-16	33.89	0.03	0.05	43.07	0.61	21.32	0.21	0.05	0.11	99.34
14	61	Kul-16	32.73	0.02	0.04	47.81	0.78	17.36	0.17	0.04	0.12	99.09
15	73	Kul-16	37.18	bdl	0.05	30.77	0.56	33.14	0.27	0.03	0.12	102.2
16	74	Kul-16	50.07	0.03	29.24	0.66	0.02	0.16	14.36	3.63	0.03	98.35
17	75	Kul-16	50.53	0.02	29.1	0.65	0.02	0.17	13.96	3.91	0.04	98.54
18	103	Kul-5	50.88	bdl	30.27	0.76	bdl	0.08	13.27	3.81	bdl	99.13

Table 3. Cont.

No.	No. Point	No. Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	NiO	Total
19	104	Kul-5	53.98	bdl	28.16	0.77	bdl	0.08	10.83	5.18	bdl	99.15
20	105	Kul-5	67.64	bdl	19.72	0.31	bdl	bdl	0.6	11.28	bdl	99.68
21	109	Kul-5	37.94	bdl	0.12	23.86	0.39	37.33	0.32	bdl	0.19	100.1
22	110	Kul-5	37.71	bdl	0.1	24.24	0.38	36.66	0.32	bdl	0.17	99.59
23	111	Kul-5	37.12	bdl	bdl	25.95	0.38	35.31	0.26	bdl	0.1	99.12
24	112	Kul-5	37.84	bdl	bdl	24.18	0.39	36.97	0.28	bdl	0.12	99.79
25	117	Kul-5	35.84	bdl	0.09	31.93	0.53	29.79	0.3	bdl	bdl	98.48
26	118	Kul-5	36.02	bdl	0.08	33.57	0.55	29.11	0.3	bdl	bdl	99.64
27	119	Kul-5	36.22	bdl	0.14	34.63	0.63	28.7	0.22	bdl	bdl	100.5
28	120	Kul-5	36.35	bdl	0.09	32.04	0.66	30.35	0.26	bdl	bdl	99.75
29	121	Kul-5	49.64	1.58	2.9	14.12	0.34	12.61	18.49	0.46	bdl	100.1
30	122	Kul-5	50.77	1.06	2.83	12.45	0.34	15.33	16.85	0.27	bdl	99.9
31	123	Kul-5	52.49	0.9	0.7	10.86	0.35	14.58	19.11	0.82	bdl	99.81
32	124	Kul-5	50.35	1.13	2.71	12.32	0.25	13.94	18.5	0.28	bdl	99.48
33	133	Kul-7	49.88	1.01	1.49	19.19	0.49	12.81	14.34	0.18	bdl	99.39
34	135	Kul-7	51.05	0.66	2.76	9.86	0.25	15.05	19.77	0.33	bdl	99.73
35	138	Kul-7	51.07	bdl	30.27	0.76	bdl	0.08	13.27	3.81	bdl	99.32
36	141	Kul-38	52.7	0.06	30.28	0.74	bdl	0.11	14.09	3.83	bdl	101.9
37	145	Kul-38	50.38	1.22	3.38	12.57	0.31	13.68	18.36	0.33	0.06	100.6
38	150	Kul-12	52.31	0.57	1.17	8.56	0.25	17.21	19.37	0.2	bdl	100.0
39	151	Kul-12	52.27	0.61	1.61	8.47	0.24	17.12	19.8	0.22	bdl	100.4
40	152	Kul-12	52.41	0.63	1.64	8.51	0.14	17.21	19.37	0.23	bdl	100.5
41	157	Kul-12	55.78	0.06	27.3	0.73	0.01	0.08	9.31	6.36	bdl	100.0
42	158	Kul-12	55.37	0.02	27.42	0.72	0.01	0.11	9.61	6.32	bdl	100.1
43	159	Kul-12	0.10	45.23	0.16	48.33	2.35	0.1	0.22	0.00	bdl	96.83
44	164	Kul-14	38.04	bdl	0.1	24.03	0.38	38.86	bdl	0.05	0.18	101.6
45	165	Kul-14	48.18	0.05	32.62	0.47	bdl	0.17	15.06	2.82	0.03	99.47
46	166	Kul-14	52.58	0.05	30.26	0.67	0.01	0.16	12.03	4.44	0.03	100.4
47	187	PR-1/234	36.02	bdl	0.08	33.59	0.55	30.11	0.3	0.00	0.01	99.64
48	188	PR-1/234	50.51	0.83	1.38	19.32	0.48	14.97	12.19	0.27	0.05	100.1
49	189	PR-1/234	49.95	0.01	30.26	0.37	0.08	0.17	15.96	2.87	0.07	99.83
50	191	OKG13/43	36.61	0.03	0.01	31.46	0.44	31.75	0.07	bdl	0.01	100.5
51	193	OKG-13/43	36.53	0.03	bdl	31.68	0.44	31.6	0.08	bdl	bdl	100.5
52	194	OKG-13/43	36.73	0.03	0.01	31.32	0.44	31.87	0.05	bdl	0.001	100.5
53	195	OKG-13/43	35.62	0.04	bdl	37.69	0.47	26.57	0.18	bdl	0.002	100.6
54	196	OKG-13/43	36.36	0.03	bdl	32.02	0.45	31.12	0.07	bdl	bdl	100.1
55	199	OKΓ-13/69.2	51.63	0.716	2.11	8.68	0.226	15.14	20.73	0.23	0.066	99.52
56	201	OKΓ-13/69.2	51.82	0.469	1.75	8.23	0.203	16.37	19.67	0.17	0.086	98.79
57	218	91	38.22	0.025	0.005	26.04	0.358	36.81	0.067	bdl	0.108	101.7
58	219	91	37.65	0.020	0.004	26.09	0.361	36.82	0.048	bdl	0.108	101.2
59	236	DM-27/20.6	51.47	0.47	1.35	9.54	0.5	14.58	19.8	0.33	bdl	98.04
60	239	DM-27/20.6	52.14	0.51	2.62	6.32	0.22	16.11	20.33	0.25	n/a	98.50
61	241	DM-27/20.6	52.64	bdl	28.91	0.83	0.05	bdl	13.39	3.85	n/a	99.67
62	242	DM-27/20.6	46.77	bdl	28.61	0.58	bdl	bdl	12.22	3.43	n/a	97.61
63	243	DM-27/20.6	51.67	bdl	30.27	0.67	bdl	bdl	13.59	3.63	n/a	99.83
64	245	DM-27/33	51.41	0.74	1.61	10.29	0.03	13.91	20.79	0.43	n/a	99.21
65	250	DM-27/100	51.79	0.48	2.29	6.31	0.16	16.56	20.94	0.21	0.2	98.94
66	253	DM-27/100	51.99	0.09	1.95	7.76	0.34	16.24	21.92	0.22	0.1	100.6
67	256	G-22/64	48.31	0.055	32.22	0.912	0.016	0.010	16.39	1.70	0.001	99.68
68	264	G-22/64	49.10	0.03	31.69	0.787	0.000	0.046	15.03	2.29	0.001	99.07
69	271	G-22/64	38.47	n/a	0.020	19.84	0.310	40.57	0.16	n/a	0.23	99.67
70	272	G-22/64	38.68	n/a	0.017	19.38	0.301	41.00	0.14	n/a	0.24	99.83
71	273	G-22/64	38.95	n/a	0.016	19.49	0.303	41.14	0.15	n/a	0.24	100.4
72	289	G-22/107	38.26	n/a	0.021	24.16	0.394	37.42	0.149	n/a	0.20	100.8
73	330	G-22/108	36.60	n/a	0.013	30.44	0.474	31.71	0.106	n/a	0.10	99.52
74	331	G-22/108	36.29	n/a	0.020	29.91	0.466	31.46	0.112	n/a	0.10	98.59

Note. No. point = number in Table S1 and in Figure 6. Intrusion, complex: 1–17, Intrusion 4, Kureysky complex; 18–35, Intrusion 1, Katangsky complex; 36, 37—Katangsky complex, 38–43—Kulyumbinsky complex; 44–46—Katangsky complex; 47–49, Gabbrovy intrusion; 50–58, Dzhaltulsky massif, Kureysky complex; 59–74, Norilsk 1, Norilsk complex; n/a, element was not analyzed; bdl, below detection limit. Minerals, numbers: olivine: 1–6, 12–15, 21–28, 44–47, 50–54, 57, 58, 69–74; pyroxene: 9–11, 29–34, 37–40, 43, 47, 55, 56, 59, 60, 64–66; plagioclase: 7, 8, 16–20, 35, 36, 41, 42, 45, 46, 49, 61–63, 67, 68; titanomagnetite: 43. Analyses Nos. 37–40 contain 0.29, 0.32, 0.20, and 0.24 wt.% Cr₂O₃, respectively.

Figure 6. Cont.

Figure 6. BSE images of the intrusive rocks (a,b) Kureysky complex, Intrusion 4, sample K-2 (c,d); (e–l) Katangsky complex; (e–j) sample Kul-5; (k–l) sample Kul-7. Minerals: Ol, olivine; Px, pyroxene; Cpx, clinopyroxene; Pl, plagioclase; S, sulfide. Point numbers correspond to numbers in Table 2.

We studied some samples from the other intrusions of this complex (Kul-40, Kul-12, Figure 4). The sample Kul-12, taken from the intrusion previously attributed to the Kureysky complex in the geological map [57] and allocated by us in a separate complex [60], consisted of plagioclase and clinopyroxene, forming the poikilophytic structure. The pyroxene has a higher Mg number (77–78) than minerals from the intrusions described before. Plagioclase was altered to sericite and An_{35} dominated in rocks.

The reference object of the Kureysky complex was the Dzhaltulsky massif, located several kilometers to the south from the Kulyumber area, in the Kureyka river valley. We studied three samples from the vertical section of this massif taken from the borehole OKG-13 at depth 43.7, 69.2, and 180.2 m. One sample was taken from the surface (No. 91). Olivine changed in a wide range from Fo 55.7 to 81.6 from the upper part of the massif to its bottom. It was characterized by very low concentrations of calcium and nickel (0.07–0.17 wt.% CaO and 0.03–0.06 wt.% NiO). Pyroxene composition was more stable. Its magnesium number varied from Mg# = 65 to Mg# = 81. It comprised a high Al_2O_3 content (up to 3 wt.%) and sample 91 was characterized by elevated Cr_2O_3 , up to 0.12 wt.%.

Intrusions of the *Katangsky complex* are usually composed of fine- to medium-grained homogeneous gabbro-dolerites and olivine-bearing gabbro-dolerites. They have usually a dolerite, poikilophytic structure (Figure 6c–f,k,l), where laths of plagioclase (0.1–0.3 microns) are enclosed in large grains of pyroxene (1–1.5 mm) (samples Kul-5, 7). The composition of olivine in olivine gabbro-dolerites (Kul-5, Figure 6g–j) was close to olivine composition from the Kureysky complex but differed in lower variability (Fo_{60–73}) and higher NiO contents (up to 0.19 for Fo₇₃, it was close to olivine from the Norilsk 1 intrusion). The Mg# number of clinopyroxene varied from 53 to 73, and orthopyroxene from 58 to 69. The compositions of rock-forming minerals in the other samples from the Katangsky complex (samples Kul-7, Kul-14, and Kul-38) were close to the compositions for Kul-5 (Table S1).

Supposed *Norilsk complex* (Kruglogorsky subcomplex). The massif, named Gabbrovy intrusion, located in the Silurian rocks (to the west from the Kulyumber site, Figure 4) was traced by several boreholes. We studied it in the core of the borehole, PR-1 penetrated at the depths from 213 to 275 m. This intrusive body was weakly differentiated. The main volume of intrusion consisted of olivine gabbro-dolerites with leucogabbro occurring in the upper part and the thickness of 2.5 m. This intrusion was attributed to the Norilsk complex, Kruglogorsky subcomplex, on the basis of the leucogabbro occurrence [45].

The taxitic rocks with sulfide mineralization (up to 3 wt.%, 3 m thick) were distinguished in the lower part of the intrusion. Sulfide minerals (pyrrhotite, chalcopyrite) reached up to 3 mm and they were found in the underlying sedimentary rocks as well. There were no high-magnesium rocks in this section (picrite gabbro-dolerites, troctolites) typical of the ore-bearing intrusions of the Norilsk region. The main rock-forming minerals were represented by olivine (3–20 vol.%), plagioclase (45–50%), clinopyroxene (15–35%), and orthopyroxene (0–2%). Minor minerals were titanomagnetite, ilmenite, and apatite.

Olivine was found in all varieties of rocks and its composition changed in the range of Fo₃₂–Fo₆₆. Its amount grows towards the lower part of the intrusion from the top (up to 20–25 wt.%). Its morphology also varied. In the lower part it was represented by idiomorphic crystals, while at the top it formed interstitial grains. Clinopyroxene (augite, Mg# 66–68) had a zonal structure where the central parts were enriched in chromium (up to 0.5 wt.% Cr₂O₃) and border zones contained up to 1.1 wt.% TiO₂. Magnetite was similar in composition to magnetite from the Katangsky gabbro-dolerites (it contained up to 12 wt.% TiO₂).

4.3.3. Chemical Composition of Intrusive Rocks

Major components. Most of the analysis (Figure 7a, Table 4) fell in the field of basalts of normal alkalinity basalts, a number of them were located in trachybasalt and basaltic trachyandesite fields, and only several points occurred in the field of picritic basalts (Dzhaltulsky massif and Norilsk 1 intrusion). A similar distribution was observed in the SiO₂–MgO diagram (Figure 7b), where only some rocks had high Mg compositions (23–28 wt.% MgO) that did not belong to the Kulyumber area. Therefore, we limited further consideration of the compositions of the rocks from the Kuyumber area with MgO contents of 2–12 wt.% (Figure 8). This restriction allowed us to consider the obtained data in more detail.

Table 4. Composition of intrusive rocks.

No.	1	2	3	4	5	6	7	8	9	10
Sample	Kul-15	K-1	K-2	Kul-18	Kul-40	Kul-2/1	Kul-25	Kul-19	Kul-22	Kul-28
SiO ₂	50.96	48.06	47.02	46.62	48.46	51.88	47.24	47.58	47.61	47.59
TiO ₂	2.51	1.34	1.29	1.52	1.42	1.43	1.91	1.46	1.56	1.31
Al ₂ O ₃	13.8	18.51	15.67	14.22	14.98	13.5	14.51	14.71	14.57	14.75
Fe ₂ O ₃	13.52	10.62	13.86	13.37	13.45	13.5	13.69	12.77	13.07	11.56
MnO	0.21	0.18	0.20	0.21	0.20	0.19	0.18	0.21	0.18	0.16
MgO	3.36	5.13	8.3	6.69	6.97	5.69	6.79	7.58	7.01	7.23
CaO	6.96	9.27	9.99	7.04	10.34	8.02	10.07	8.07	9.81	10.99
Na ₂ O	3.61	2.96	2.23	5.02	2.56	3.47	3.03	3.96	3.26	3.45
K ₂ O	2.48	0.85	0.41	0.53	0.5	1.38	0.38	0.78	0.56	0.52
P ₂ O ₅	0.78	0.15	0.14	0.18	0.15	0.15	0.17	0.17	0.2	0.18
LOI	1.74	3.05	0.52	4.43	0.9	1.25	1.94	2.55	2.06	2.18
S	0.04	n/a	n/a	0.05	n/a	n/a	0.08	0.23	0.09	n/a
Rb	81.0	24.3	10.5	n/a	13.3	19.3	14.8	20.9	13.9	10.8
Sr	515	642	187	n/a	199	423	331	315	244	243

Table 4. Cont.

No.	1	2	3	4	5	6	7	8	9	10
Sample	Kul-15	K-1	K-2	Kul-18	Kul-40	Kul-2/1	Kul-25	Kul-19	Kul-22	Kul-28
Y	52.7	24.7	25.0	n/a	25.5	29.5	35.1	27.8	29.0	25.7
Cs	1.78	0.29	0.36	n/a	0.60	0.29	0.09	0.20	0.69	0.07
Ba	807	139	119	n/a	112	172	148	122	144	110
La	57.4	7.8	6.9	n/a	7.0	9.4	10.3	8.5	9.0	7.5
Ce	131	18.7	16.8	n/a	16.8	23.5	25.17	19.7	21.4	18.4
Pr	15.4	2.46	2.30	n/a	2.41	3.13	3.64	2.71	2.91	2.58
Nd	61.4	11.8	11.4	n/a	11.3	15.0	17.0	13.3	14.1	12.3
Sm	12.93	3.28	3.18	n/a	3.48	4.00	4.93	3.83	4.03	3.57
Eu	3.54	1.12	1.14	n/a	1.19	1.34	1.62	1.25	1.31	1.16
Gd	12.29	3.84	3.71	n/a	3.83	5.04	5.37	4.80	5.04	3.86
Tb	1.81	0.65	0.64	n/a	0.69	0.82	0.99	0.83	0.85	0.71
Dy	10.18	4.22	4.14	n/a	4.69	5.49	6.41	5.03	5.26	4.71
Ho	1.96	0.85	0.87	n/a	1.00	1.12	1.35	1.05	1.06	1.05
Er	5.37	2.47	2.47	n/a	2.80	3.34	3.70	3.17	3.24	2.78
Tm	0.70	0.35	0.34	n/a	0.41	0.45	0.54	0.43	0.44	0.40
Yb	4.77	2.41	2.50	n/a	2.65	3.03	3.54	3.02	3.13	2.49
Lu	0.68	0.34	0.35	n/a	0.40	0.46	0.51	0.43	0.45	0.37
Pb	2.41	0.92	3.62	n/a	2.11	1.32	0.88	0.65	0.83	0.93
Th	5.62	1.12	0.98	n/a	0.79	1.47	1.41	1.22	1.33	0.98
U	1.51	0.42	0.38	n/a	0.33	0.59	0.56	0.45	0.65	0.39
Sc	25.8	0.4	0.4	n/a	36.8	37.8	50.0	36.7	37.2	36.6
V	146	n/a	n/a	n/a	279	319	329	288	306	244
Cr	33	105	98	n/a	168	165	249	151	153	181
Co	25	38	65	n/a	47	45	54	46	47	41
Ni	13	120	244	n/a	136	79	148	128	125	111
Cu	15	426	481	n/a	225	119	104	65	61	76
Zn	32	25	87	n/a	118	76	20	72	50	93
Zr	411	88	88	n/a	88	118	118	107	104	82
Nb	32.61	4.64	4.29	n/a	3.44	6.78	5.92	5.33	5.54	4.15
Hf	8.95	2.10	2.30	n/a	1.72	3.01	2.77	2.82	2.86	1.90
Ta	1.78	0.26	0.28	n/a	0.21	0.32	0.38	0.32	0.33	0.24
No.	11	12	13	14	15	16	17	18	19	20
Sample	Kul-31	Kul-34	Kul-32	Kul-24	Kul12/1a	1/214.6	1/216.0	1/216.3	1/224	1/234
SiO ₂	47.06	47.35	47.60	47.54	49.37	47.88	43.05	46.95	50.04	47.75
TiO ₂	1.53	1.51	1.56	1.39	1.35	0.92	0.64	1.07	2.22	1.12
Al ₂ O ₃	14.37	14.54	14.59	14.66	16.52	16.72	17.84	15.74	12.11	16.30
Fe ₂ O ₃	13.61	13.87	13.86	12.11	8.53	7.12	11.24	11.71	16.10	12.29
MnO	0.17	0.22	0.19	0.18	0.12	0.12	0.15	0.17	0.24	0.18
MgO	7.23	7.31	7.01	7.26	7.60	6.80	10.81	7.46	4.44	8.30
CaO	10.08	9.26	10.16	10.36	8.27	14.58	9.41	12.18	8.51	10.14
Na ₂ O	3.29	2.99	2.68	3.32	3.18	1.64	1.76	2.13	3.74	2.51
K ₂ O	0.44	0.64	0.47	0.54	1.73	2.03	0.79	0.75	1.13	0.44
P ₂ O ₅	0.18	0.18	0.19	0.16	0.16	0.09	0.08	0.10	0.42	0.15
LOI	1.87	2.05	1.61	2.34	2.89	2.05	4.19	1.73	0.89	0.61
S	0.18	0.10	0.04	0.11	n/a	<0.05	<0.05	<0.05	n/a	n/a
Rb	11.4	13.4	12.7	15.1	53.7	38.9	18.6	16.7	28.4	11.5
Sr	244	238	231	219	662	525	477	270	234	208
Y	27.0	27.7	27.6	28	15.4	18.1	12.1	18.7	61.3	23.4
Cs	0.20	0.20	0.39	0.6	4.20	1.67	3.09	1.55	n/a	n/a
Ba	103	142	140	159	298	179	68	63	249	123
La	8.4	8.6	8.93	8.50	9.03	4.30	3.30	4.24	21.39	7.65
Ce	19.9	20.0	20.9	21.3	20.8	10.2	7.8	10.0	50.9	18.0

Table 4. Cont.

No.	11	12	13	14	15	16	17	18	19	20
Sample	Kul-31	Kul-34	Kul-32	Kul-24	Kul12/1a	1/214.6	1/216.0	1/216.3	1/224	1/234
Pr	2.70	2.71	2.93	2.90	2.66	1.45	1.08	1.39	6.79	2.45
Nd	13.1	13.4	13.54	13.1	12.3	7.5	5.3	7.1	31.1	11.1
Sm	3.77	3.88	3.82	3.94	3.02	2.19	1.43	2.13	9.08	3.51
Eu	1.14	1.29	1.27	1.30	1.09	0.79	0.58	0.78	2.35	1.06
Gd	4.74	4.86	4.20	4.17	3.36	2.96	1.93	2.86	9.85	3.59
Tb	0.79	0.82	0.77	0.78	0.52	0.48	0.32	0.48	1.68	0.63
Dy	5.02	5.01	5.07	5.03	3.18	3.24	2.14	3.31	10.9	4.15
Ho	1.03	1.04	1.08	1.10	0.59	0.65	0.43	0.68	2.26	0.89
Er	3.10	3.14	2.98	3.00	1.56	1.88	1.27	2.00	6.43	2.44
Tm	0.41	0.43	0.44	0.43	0.22	0.27	0.19	0.29	0.94	0.36
Yb	2.94	2.94	2.85	2.76	1.48	1.80	1.26	1.86	6.07	2.40
Lu	0.42	0.43	0.42	0.43	0.22	0.27	0.18	0.28	0.92	0.35
Pb	0.74	1.10	1.73	3.82	0.54	1.17	0.71	0.74	5.17	2.33
Th	1.20	1.17	1.08	1.10	0.98	0.63	0.54	0.63	3.21	1.08
U	0.55	0.50	0.57	0.43	0.23	0.26	0.22	0.26	1.37	0.44
Sc	38.0	38.7	37.1	37.0	25.4	52.9	17.2	48.0	39.8	27.9
V	313	315	295	301	220	311	139	304	327	223
Cr	156	161	157	126	317	253	82	408	36	131
Co	50	52	48.8	47.8	21.6	29.8	64.5	42.4	38.5	53.4
Ni	125	127	123	128	118	88	393	119	57	170
Cu	165	153	179	248	81	78	31	68	284	131
Zn	62	84	133	194	28	41	59	49	110	<110
Zr	99	101	71	110	115	55	40	60	208	74
Nb	5.10	5.10	4.63	4.00	6.92	2.68	2.80	2.71	10.74	3.86
Hf	2.68	2.75	2.26	2.3	2.17	1.53	1.08	1.49	5.16	1.85
Ta	0.30	0.32	0.29	0.21	0.38	0.19	0.19	0.18	0.67	0.27
No.	21	22	23	24	25	26	27	28	29	30
Sample	1/256	1/262	1/262.1	1/266	4/75.5	4/80	11/486	11/489.5	11/492.6	6-339
SiO ₂	48.07	46.36	47.14	47.61	46.53	46.72	47.86	48.45	46.55	47.64
TiO ₂	1.22	1.32	1.31	1.29	1.65	1.57	1.38	2.02	1.33	1.31
Al ₂ O ₃	16.19	14.81	15.08	16.41	15.03	14.78	15.13	13.56	15.62	14.98
Fe ₂ O ₃	12.42	13.52	13.31	12.06	13.81	13.95	12.51	13.55	12.61	13.25
MnO	0.18	0.19	0.19	0.17	0.19	0.20	0.18	0.22	0.18	0.21
MgO	8.21	9.21	9.05	7.90	7.09	7.15	7.37	5.54	7.76	7.63
CaO	10.28	10.26	9.83	10.54	10.32	10.13	11.16	11.28	10.05	11.34
Na ₂ O	2.43	2.44	2.45	2.46	2.54	2.51	2.50	2.82	2.38	2.42
K ₂ O	0.44	0.48	0.49	0.48	0.47	0.43	0.42	0.76	0.44	0.48
P ₂ O ₅	0.16	0.17	0.17	0.15	0.16	0.15	0.14	0.21	0.15	0.15
LOI	0.29	1.1	0.84	0.77	2.14	2.36	1.27	1.23	2.87	0.37
S	n/a	n/a	n/a	n/a	<0.05	<0.05	<0.05	0.34	<0.05	n/a
Rb	11.8	n/a	13.8	12.7	11.1	11.6	9.8	20.0	11.6	12.1
Sr	204	n/a	208	224	196	199	196	427	204	255
Y	24.4	n/a	25.4	25.0	28.1	29.7	23.3	35.8	23.5	24.0
Cs	n/a	n/a	n/a	n/a	0.31	0.34	0.39	1.40	0.39	0.41
Ba	125	n/a	132	132	112	117	116	169	124	114
La	7.66	n/a	8.26	8.13	7.23	7.68	6.17	10.74	6.69	6.83
Ce	18.3	n/a	19.6	19.4	17.7	18.6	14.8	25.5	15.8	16.0
Pr	2.48	n/a	2.70	2.63	2.47	2.60	2.03	3.42	2.15	2.18
Nd	11.7	n/a	12.4	11.9	12.3	13.0	10.1	16.5	10.7	10.5
Sm	3.60	n/a	3.85	3.68	3.53	3.75	2.89	4.57	2.99	2.98
Eu	1.12	n/a	1.13	1.12	1.25	1.38	1.08	1.52	1.10	1.08
Gd	3.79	n/a	4.05	3.87	4.56	4.80	3.69	5.75	3.66	3.81
Tb	0.68	n/a	0.71	0.68	0.75	0.80	0.61	0.93	0.62	0.63

Table 4. Cont.

No.	21	22	23	24	25	26	27	28	29	30
Sample	1/256	1/262	1/262.1	1/266	4/75.5	4/80	11/486	11/489.5	11/492.6	6-339
Dy	4.41	n/a	4.58	4.47	4.99	5.27	4.09	6.28	4.11	4.28
Ho	0.92	n/a	0.95	0.94	1.00	1.08	0.81	1.26	0.81	0.84
Er	2.61	n/a	2.60	2.70	2.93	3.15	2.41	3.76	2.43	2.51
Tm	0.38	n/a	0.40	0.41	0.42	0.45	0.34	0.53	0.34	0.35
Yb	2.47	n/a	2.51	2.51	2.77	2.93	2.31	3.57	2.29	2.36
Lu	0.37	n/a	0.37	0.38	0.41	0.44	0.34	0.52	0.34	0.35
Pb	2.26	n/a	3.36	2.71	2.00	2.09	1.94	2.31	2.00	3.62
Th	1.10	n/a	1.13	1.29	1.06	1.09	0.89	1.66	0.94	1.02
U	0.47	n/a	0.45	0.70	0.36	0.38	0.34	0.61	0.36	0.44
Sc	30.1	n/a	27.6	28.3	31.7	36.5	36.8	38.1	29.6	33.5
V	241	n/a	239	255	287	311	317	350	266	280
Cr	149	n/a	145	108	150	291	300	86	191	245
Co	51.6	n/a	57.2	49.2	52.0	57.3	46.5	37.4	52	49
Ni	184	n/a	259	206	136	228	124	62	178	142
Cu	157	n/a	170	154	189	197	147	241	158	138
Zn	<IIIO	n/a	62	<IIIO	105	108	94	75	99	91
Zr	80	n/a	82	82	108	109	84	135	87	90
Nb	4.42	n/a	4.37	4.46	2.70	2.71	1.98	3.36	2.08	2.19
Hf	2.04	n/a	1.83	2.19	0.34	0.34	0.25	0.41	0.28	0.27
Ta	0.28	n/a	0.29	0.24	0.20	0.20	0.19	0.17	0.14	0.17

No.	31	32	33	34	35	36	37	38	39	40	41
Sample	4/437	4/440	4/443.5	DL-2	DL-1	DL-3	Val-2	Val-1	Og-1	Og-2	Og-3
SiO ₂	47.32	47.87	48.23	49.47	49.60	49.20	50.41	50.03	49.23	48.93	48.58
TiO ₂	1.49	1.42	1.24	1.71	1.61	1.73	1.64	1.92	1.32	1.43	1.16
Al ₂ O ₃	14.40	15.83	15.41	15.77	15.55	15.06	14.74	14.30	15.74	15.81	17.15
Fe ₂ O ₃	13.22	12.37	12.54	12.89	12.79	13.66	13.22	13.49	12.16	12.89	11.78
MnO	0.20	0.18	0.18	0.26	0.22	0.27	0.25	0.24	0.22	0.21	0.19
MgO	6.98	6.39	7.23	5.93	6.20	5.94	6.09	5.79	6.54	6.70	7.77
CaO	10.79	10.64	11.01	10.29	10.15	10.30	10.30	10.80	11.23	10.53	10.07
Na ₂ O	2.55	2.70	2.56	2.96	2.91	2.92	2.71	2.66	2.59	2.62	2.70
K ₂ O	0.48	0.55	0.44	0.57	0.59	0.54	0.65	0.63	0.46	0.47	0.40
P ₂ O ₅	0.16	0.16	0.14	0.17	0.19	0.23	0.21	0.15	0.16	0.17	0.10
LOI	2.36	1.83	0.95	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
S	<0.05	<0.05	<0.05	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Rb	10.7	13.4	10.8	14.5	15.4	13.2	18.6	18.5	13.2	13.8	11.0
Sr	175	194	192	223	227	204	230	216	240	238	225
Y	23.8	27.3	23.9	31.5	32.1	33.4	31.6	32.0	29.6	26.4	18.2
Cs	0.39	0.37	0.42	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Ba	120	140	118	168	146	153	161	144	123	144	117
La	6.72	8.04	6.68	10.9	10.1	10.8	10.7	10.2	8.89	8.43	5.79
Ce	16.1	19.2	15.8	23.15	22.0	24.0	22.1	22.9	20.4	19.7	13.4
Pr	2.26	2.61	2.18	3.19	3.14	3.34	3.09	3.18	2.77	2.63	1.76
Nd	10.8	12.7	10.7	15.9	15.7	16.4	15.5	15.6	13.5	13.1	8.47
Sm	3.14	3.55	3.08	4.4	4.49	4.70	4.38	4.58	3.89	3.55	2.40
Eu	1.16	1.24	1.14	1.62	1.66	1.67	1.56	1.58	1.50	1.42	1.13
Gd	4.03	4.44	3.86	4.91	4.96	5.22	4.78	4.90	4.52	4.06	2.83
Tb	0.66	0.71	0.63	0.86	0.89	0.93	0.85	0.89	0.78	0.72	0.49
Dy	4.29	4.84	4.29	6.17	6.39	6.17	6.25	6.02	5.58	4.92	3.31
Ho	0.87	0.94	0.85	1.28	1.29	1.38	1.25	1.27	1.18	1.02	0.70
Er	2.61	2.78	2.53	3.22	3.23	3.46	3.14	3.20	3.02	2.71	1.86
Tm	0.35	0.39	0.36	0.42	0.44	0.50	0.46	0.45	0.42	0.39	0.26
Yb	2.40	2.63	2.38	3.09	3.23	3.48	3.33	3.34	2.99	2.76	1.87

Table 4. Cont.

No.	31	32	33	34	35	36	37	38	39	40	41
Sample	4/437	4/440	4/443.5	DL-2	DL-1	DL-3	Val-2	Val-1	Og-1	Og-2	Og-3
Lu	0.36	0.39	0.35	0.48	0.44	0.50	0.47	0.47	0.44	0.39	0.27
Pb	2.22	2.64	1.86	0.73	1.51	3.11	3.26	1.49	0.73	0.97	0.56
Th	0.88	1.14	0.93	1.27	0.96	1.49	1.46	1.38	1.17	1.10	0.73
U	0.32	0.43	0.36	0.45	0.34	0.52	0.45	0.49	0.38	0.36	0.23
Sc	38.6	32.5	35.0	34.1	37.3	38.7	43.0	44.1	40.0	34.4	27.3
V	312	261	271	273	304	342	327	364	298	303	244
Cr	204	145	242	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Co	49	46	48	46	48	47	49	49	50	54	59
Ni	119	105	122	100	111	100	80	66	115	126	174
Cu	141	150	154	226	210	308	212	222	217	182	146
Zn	96	94	101	71	100	154	129	92	76	84	49
Zr	80	85	77	133	101	121	123	126	91	95	65
Nb	1.97	2.19	1.96	6.84	6.55	7.37	6.31	6.84	4.79	4.81	4.36
Hf	0.29	0.32	0.27	3.47	2.39	3.52	3.01	2.99	2.34	2.47	1.70
Ta	0.13	0.13	0.13	0.44	0.41	0.45	0.49	0.39	0.28	0.31	0.27

Note: Oxides are given in wt.%, elements are in ppm. Nos. (N), borehole/depth (m): 16–24 PR, 25–26 PR-4, 27–29 PR-11, 30 PR-6, 31–33 PR-4; n/a, element was not analyzed; Intrusive complexes, No: Katangsky-1, 6–14; Kureysky, 2–5; Kulyumbinsky, 15; Norilsk, Kruglogorsky subcomplex, 16–24; Supposed Dal'dykansky, 25–29; Supposed Ogonersky, 30; Supposed Kuzmovsky, 31–33; Dal'dykansky, 34–38; Ogonersky, 39–41.

Figure 7. Diagrams SiO₂ vs. Na₂O + K₂O (a) after [64] and MgO vs. SiO₂ (b) for intrusive rocks.

Figure 8. Diagrams MgO vs. TiO₂ (a), Fe₂O₃ (b), Al₂O₃ (c), CaO (d), Na₂O (e), K₂O (f), P₂O₅ (g), and MnO (h) for intrusive rocks.

Analysis of behavior of the major elements in the rocks (Figure 8) indicated the presence of two groups of rocks which differed in silica and alkali contents: The Ergalakhsky complex was characterized by the highest concentrations of titanium, potassium, and phosphorus and low silica and calcium in comparison with the other rocks, the points of composition which were plotted close together. According to the TiO_2 concentrations, rock compositions from different intrusions formed a single negative trend (Figure 8a) of the titanium depending on the MgO concentrations, which may be due to the fractional crystallization of a single magma. A similar behavior was observed for F_2O_3 , although the composition points had a much larger spread (Figure 8b). In both cases, the Norilsk 1 massif had the lower content of these elements, which distinguishes it from other rocks, including the Gabbrovy intrusion, referred to as the Kruglogorsky subcomplex of the Norilsk complex (Figure 9). Thus, the weighted mean TiO_2 content in the Gabbrovy intrusion was 1.35 wt.% (Table 4), while its average mean content in the Norilsk 1 intrusion was 0.87 wt.%, i.e., <1 wt.% that is typical of the ore-bearing massifs in the Norilsk area [18,65,66]. According to these oxides, this massif could be attributed to the Katangsky complex.

Figure 9. Main types of trace elements' spider diagrams for intrusive rocks of the Kulyumber river valley. Complexes: (a) Kulyumbinsky, (b) Ergalakhsky, (c) Katangsky.

A slightly lower content of MnO is also typical of the Norilsk 1. The CaO and Al₂O₃ demonstrated opposite trends, i.e., they directly correlated with MgO contents (Figure 8c,d). Points of the Na₂O concentrations formed two trendlines; one of them was typical of the Norilsk and Kureysky complexes and the second line characterized distribution of this oxide in other rocks (Figure 8e). The highest K₂O and P₂O₅ contents (Figure 8f,g) were typical of the Ergalakhsky and Kulyumbinsky complexes that distinguish them from the other rocks.

For studying for Kuyumber river it is important valley to compare two complexes that were most widespread: Katangsky and Kureysky. The last named complex was attributed to the Dzhaltulsky massif. We used samples from this massif. The data showed (Figure 8) that there was no difference between the Kureysky intrusive bodies and Katangsky intrusions while the Dzhaltulsky massif differed in low TiO₂, high Mg, high Al, and low alkalis. The Supposed Kuzmovsky complex was similar to the Katangsky intrusions.

Trace elements. The distribution of trace elements in rocks from different intrusive complexes is shown in a series of spider diagrams (Figure 9), as well as in binary diagrams that reflect the main features of the spectrum topology (Figure 10). There were 3 types of spectra that were fundamentally different from each other: (1) Without Ta-Nb and Pb anomalies characterized by a strong slope of the right part of the spectrum (Gd/Yb)_n = 2.1, samples Kul-12, Kul-12/1 (Figure 9a). We attributed this intrusion to a new Kulyumbinsky complex. (2) with minor Ta-Nb and Sr-negative anomalies, weak positive Pb anomaly, and steep slope of the right part of the spectrum, (Gd/Yb)_n = 1.9–2.1, (La/Sm)_n = 2.5–2.8, typical of the subalkaline rocks of the Ergalakhsky complex (Figure 9b). (3) With a distinct negative Ta-Nb and positive strong Pb anomalies and with a weak slope of the right part of the spectrum (Gd/Yb)_n = 1.3, typical of most rocks of the Kulyumbinsky and other areas. It included rocks of the Katangsky, Kureysky, Norilsk, Daldykansky, and Oogonersky complexes, and Norilsk 1 and Gabbrovy intrusions. Figure 9c shows patterns for the Katangsky complex. The lowest concentrations of trace elements in this type were typical of the rocks of the Dzhaltulsky massif and picritic gabbro-dolerites from the Norilsk 1 massif, due to the large amount of olivine in the rocks.

Thus, the third group included many intrusions of similar composition in terms of major components but differed in trace elements. These differences reflect the value of anomalies (Ta-Nb, Pb, Sr, and Ti) and inclination of patterns on the X axis. Figure 10 demonstrates the difference between the spectra of the rocks from different complexes belonging to the third group. First of all, it was important to compare the rocks of the Norilsk complex from the Norilsk area and the rocks preliminary data attributed to this complex rocks of the Gabbrovy intrusion (Figure 10a,b). Both intrusions had similar spider diagrams and a big difference in trace elements' contents between high-Mg and low-Mg varieties, with total trace element contents changing 2–3 times.

One spectrum in the Gabbrovy intrusion (sample PR-1/224, MgO = 4.44 wt.%) is dramatically enriched in trace elements, i.e. their contents are 3 times higher than the contents in Mg-rich rocks (sample PR- 1/962, MgO = 9.21 wt.%) and it was characterized by negative Sr anomaly, which was absent in other patterns. The rocks of similar composition from the Norilsk 1 intrusion had no similar enrichment in trace elements (for example, DM-27/46, MgO = 4.51 wt.%) and had positive Sr anomaly. We suggest the occurrence of xenolith of any rocks or late sill inside the Gabbrovy intrusion because the behavior of major trace elements did not support the theory of the origin of this sample as a result of fractionation crystallization. The Dzhaltulsky massif (Figure 10e), despite its similarities with the Norilsk 1 and Gabbrovy intrusions, had some differences, i.e., smaller Ta-Nb anomaly and Th and U contents, and strong positive Pb anomaly (despite the absence of sulfides in these samples).

The rocks from the other intrusive complexes of the third group from the Kuyumber river valley, Norilsk area, and Tunguska syncline were characterized by different spider diagrams that we demonstrate in Figure 10 for clarity because they have visible differences. The most widespread complexes were Katangsky and Kureysky in the studied area. The first complex comprised sills of gabbro-dolerites and olivine gabbro-dolerites boarding the lavas area of the Siberian trap province.

These intrusions had thickness varying from one to to 400–500 m. We studied intrusion from this complex outside the Kulyumber river valley, i.e., Padunsky sill in the Angara river valley [29], as well.

Figure 10. Cont.

Figure 10. Cont.

Figure 10. Trace elements' spider diagrams for intrusive rocks of the Siberian platform. Data are in Table 3 and [51]. Complexes: (a) Norilsk, (b) Supposed Norilsk, (c) Katangsky, (d) Kureysky, (e) Supposed Daldykansky, (f) Daldykansky, (g) Supposed Kuzmovsky (h) Ogonersky, (i) Katangsky.

The geochemical features of these intrusions (Figure 10i) were close to the features of the Katangsky (Figure 10c) and Kureysky (Figure 10d) complexes in the Kulyumber site. The rocks of the Daldykansky and Ogonersky complexes located in the Norilsk region differed significantly from those described above (Figure 10f,j). Thus, the rocks preliminarily attributed to these complexes within the Kulyumber area clearly do not belong to them (Figure 10g,h).

A more thorough analysis of the spider diagrams used the ratio of a number of elements that reflected the topology of the spectra (Figure 11). These main relationships included $(La/Sm)_n$, $(La/Yb)_n$, and $(Gd/Yb)_n$, reflecting the overall slope of the spectrum, as well as its individual parts, including the behavior of rare Earth elements in rocks. The U/Nb ratio (or Th/Nb) characterizes the value of Ta-Nb anomalies. The diagram $(La/Sm)_n$ – $(Gd/Yb)_n$ (Figure 11a) shows that all intrusions are subdivided into three groups, as noted above. The first two groups included the Ergalakhsky and Kulyumbinsky complexes that were characterized by similar high $(Gd/Yb)_n$ ratio (1.9–2.1) and elevated $(La/Sm)_n$ value, which was higher for rocks of the Ergalakhsky complex in comparison with this ratio in the Kulyumbinsky complex (2.6–2.9 and 1.9–2.0, respectively). The third group was represented by several intrusive complexes with similar parameters. But these intrusions showed certain differences among themselves in the $(U/Nb)_n$ ratio (Figure 11b,c), and a significant difference from the rocks of the first and second groups (Kulyumbinsky and Ergalakhsky complexes), characterized by minimal values of this ratio.

Figure 11. Diagrams $(La/Sm)_n$ vs. $(Gd/Yb)_n$ (a) and $(U/Nb)_n$ vs. $(La/Yb)_n$ (b,c) for intrusive rocks. The symbols on all three diagrams are the same as on (a).

The rocks of the third group formed a wide range of compositions, varying in $(U/Nb)_n$ ratio. A more detailed examination of these rocks (Figure 11c) indicated that there were intrusions with high, low, and intermediate $(U/Nb)_n$ ratios, reflecting the most pronounced Ta-Nb anomaly, the minimum pronounced, and ordinary apparent. The highest $(U/Nb)_n$ ratio was typical of the Supposed Kuzmovsky and Supposed Daldykansky complexes penetrated by PR-4 and PR-11 boreholes. One sample from the Gabbrovy intrusion (PR-1/224) has a high $(U/Nb)_n$ ratio, as well, and occurred in the same field which supports its xenogenous origin in comparison with the other samples from this intrusion. The lowest $(U/Nb)_n$ ratio characterized the Daldykansky and Ogonersky complexes (Norilsk area), Norilsk-type intrusion in the Khalil site, and Dzaltulsky massif. The rock compositions of the Norilsk 1 intrusion, Gabbrovy intrusion, and Katangsky and Kureysky complexes formed a single field, where points of the Khalil intrusion occurred at the edge of this field.

4.3.4. Isotope Composition of Intrusive Rocks

To characterize the initial isotope composition for the main intrusive complexes of the Kuluymber river valley, we analyzed Sr, Nd, and Pb isotope systems of representative samples from the Ergalakhsky, Kulyumbinsky, Kureysky (Khalil intrusion), Supposed Norilsk-type (the Khalil site), and Gabbrovy intrusion. The obtained results for 11 whole-rock samples of mafic intrusions and one of argillite from host Tunguska Group are presented in Table 5 and in Figures 12 and 13. The variations in element contents were prominent for Rb and Sr: From 0.8 up to 50 and from 170 up to 660 ppm, correspondingly, and were pretty restricted for Sm and Nd: From 2.4 up to 3.6, and from 8.4 up to 12.8 ppm, respectively, excluding subalkaline rocks of the Ergalakhsky complex and sulfide-metasomatized rocks of the Katangsky complex, which are enriched in REE by 2–4 times in comparison with other samples.

Figure 12. Initial isotope signatures for dolerites and basalts from intrusive complexes of the Kuluymber river valley in comparison with rock composition of the same complexes from Norilsk-type locality.

Figure 13. Pb-Pb isotope diagram for measured Pb isotope data for whole-rock samples of intrusive complexes of the Kuluymber river valley. Green triangle, subalkaline dolerite from Ergalakhsky complex; red squares, Kulyumbinsky complex; blue diamonds, Supposed Norilsk-type Gabbrovy intrusion; blue rectangles, Kureysky complex; magenta circle, argillite of the Tunguska Group; dashed line corresponds to isochron with the age 251 Ma on Kureysky complex samples, including sulfide mineralized sample X-15-2.

Table 5. Isotope composition of the intrusive whole rocks from the Kulyumber river valley.

No.	Sample	Rb, ppm	Sr, ppm	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr ± 2σ	Sr _i	εSr		
1	X-40	55.1	388	0.41110	0.707496 ± 6	0.706034	25.9		
2	Kul-12	52.1	643	0.23448	0.707582 ± 6	0.706745	36.0		
3	Kul-12/1	52.6	647	0.23536	0.707613 ± 4	0.706773	36.4		
4	K-1	23.1	618	0.10819	0.707404 ± 14	0.707019	39.9		
5	K-2	10.0	201	0.14361	0.705375 ± 7	0.704864	9.30		
6	X-6	0.84	175	0.01388	0.705743 ± 6	0.705694	21.1		
7	PR-1/262	13.1	208	0.18165	0.705868 ± 11	0.705222	14.4		
8	PR-1/234	11.0	200	0.15897	0.705453 ± 8	0.704887	9.62		
9	PR-1/266	11.7	223	0.15232	0.705748 ± 7	0.705206	14.2		
10	X-32	8.36	218	0.11071	0.705669 ± 5	0.705275	15.1		
11	X-15-2	15.6	666	0.06796	0.708479 ± 6	0.708237	57.2		
12	X-47-2	38.6	178	0.62973	0.711116 ± 12	0.708876	66.3		
No.	Sm, ppm	Nd, ppm	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd ± 2σ	Nd _i	ε Nd	²⁰⁶ Pb/ ²⁰⁴ Pb ± 2σ	²⁰⁷ Pb/ ²⁰⁴ Pb ± 2σ	²⁰⁸ Pb/ ²⁰⁴ Pb ± 2σ
1	11.6	55.4	0.12612	0.512325 ± 2	0.512118	−3.84	17.9002 ± 5	15.4741 ± 7	37.9470 ± 23
2	3.14	12.7	0.14942	0.512508 ± 3	0.512263	−1.02	19.0257 ± 102	15.5595 ± 68	39.2923 ± 181
3	3.18	12.8	0.15011	0.512512 ± 7	0.512265	−0.97	19.0320 ± 17	15.5387 ± 15	39.2027 ± 42
4	3.33	12.1	0.16623	0.512656 ± 5	0.512384	1.32	19.4365 ± 12	15.6122 ± 10	39.0764 ± 27
5	3.32	11.8	0.16968	0.512614 ± 6	0.512337	0.40	18.2287 ± 7	15.6180 ± 7	38.0641 ± 19
6	3.40	11.6	0.17796	0.512727 ± 2	0.512435	2.34	19.2871 ± 8	15.6147 ± 7	39.1369 ± 21
7	3.64	13.1	0.16820	0.512680 ± 2	0.512405	1.73	18.6576 ± 9	15.5558 ± 8	38.1920 ± 20
8	3.25	11.6	0.16889	0.512704 ± 2	0.512428	2.19	18.7802 ± 20	15.5679 ± 17	38.3141 ± 43
9	3.25	11.6	0.16970	0.512702 ± 2	0.512424	2.12	18.8960 ± 7	15.5662 ± 6	38.2286 ± 16
10	2.41	8.37	0.17377	0.512652 ± 5	0.512367	1.01	18.3089 ± 8	15.5636 ± 8	38.1935 ± 24
11	6.48	30.3	0.12915	0.512388 ± 6	0.512176	−2.70	23.5360 ± 9	15.8283 ± 7	40.7615 ± 18
12	5.37	27.8	0.11677	0.512345 ± 3	0.512153	−3.16	20.7381 ± 6	15.7081 ± 5	40.4289 ± 19

Note. Nos. 1–11 correspond to the analysis of samples from intrusive complexes: 1, Eraglakhsy; 2, 3, Kulyumbinsky; 4–6, Kureysky; 7–10, Norilsk; 7–9, Kruglogorsky subcomplex; 10, Norilsk-type intrusion; 11, metasomatized gabbro-dolerite; 12, argillite from the Tunguska Group. Nd_i, Sr_i, εNd, and Sr_i—the initial isotopic compositions of the studied samples (in absolute or relative values-ε) were calculated for the age of 250 Ma and sample 12 for 295 Ma. Color means different rock groups.

Despite these variations, the initial isotopic signatures of the samples studied were characterized by high consistency inside the intrusive complexes and, at the same time, they differed significantly between these complexes. Thus, the rocks of Ergalakhsky complex had an initial strontium ratio value (Sri) at 0.7060 and lowest epsilon neodymium value, -3.8 , while the rocks of the Kulyumbinsky complex were characterized by Sri 0.7067 and epsilon neodymium at -1.0 , and the Gabbrovy intrusion had the lowest Sri values, from 0.7049 up to 0.7052, and the highest epsilon neodymium, from $+1.0$ up to $+2.2$ (Figure 12). While the metasomatized sulfide-containing basalt of the Katangsky complex had initial isotopic parameters that were almost identical to the sedimentary rocks of the Tunguska Group, namely, Sri 0.7082 for basalt (X-15-2) versus 0.7088 for argillite (X-47-2) and ϵNd -2.7 for basalt and -3.2 for argillite. The studied samples of the Kureysky complex had the most variable isotopic characteristics, so the initial isotopic composition of strontium varied from the lowest value among the studied samples, 0.7048, to one of the highest, -0.7070 . In this case, the isotopic composition of neodymium varied within 2 units of epsilon, from $+0.4$ to $+2.3$. Perhaps these variations, which are atypical for other complexes, are explained by a combination of separate intrusions genetically belonging to other intrusive complexes (e.g., Intrusion 4 and Khalil intrusions).

It should be noted that the initial isotopic characteristics of intrusive complexes from the Kulyumber river valley were close to those obtained previously for the complexes of the same name sampled in other areas of the Norilsk region. Thus, the subalkaline trachydolerites of the Ergalakhsky complex from the northern and southern parts of the Norilsk district had neodymium composition nearly the same: ϵNd within -3.8 and -4.2 [67–69] and only the initial strontium isotopic composition, 0.7064–0.7075, was slightly higher than the value we measured in sample X-40.

Mafic rocks of the Kruglogorsky subcomplex of the Norilsk intrusive complex were characterized by weakly positive values of neodymium epsilon, from $+1.5$ to $+2.2$, and strongly varying strontium isotopic compositions, from 0.7062 to 0.7084 [67], while the Supposed Kruglogorsky subcomplex of the Norilsk complex in the Kulyumber river valley (Gabbrovy intrusion) had a comparable isotopic neodymium composition (from $+1.0$ to $+2.2$) and significantly less radiogenic compositions of strontium, 0.7048–0.7052, which apparently is associated with steadily low rubidium content in these rocks. Thus, at first glance, the initial isotopic characteristics of the Gabbrovy intrusion rocks did not contradict the assumption that they belong to the Norilsk complex (Kruglogorsky subcomplex).

Alternatively, a separate local mantle source could exist for the Kulyumbinsky intrusive complex, which differed in composition both from the sources of the Norilsk type and from the Ergalakhsky subalkaline type of intrusion. The fact that it was rather a separate mantle source is also suggested by the specificity of the lead isotopic composition (Figure 13). The rocks of the Kulyumbinsky complex occupied an intermediate position between the Kureysky and Ergalakhsky rocks on the isotopic diagram $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{207}\text{Pb}/^{204}\text{Pb}$, but presented data were limited only by two samples of rocks of the Kulyumbinsky complex, which were almost identical in composition, and we do not know the real scatter of isotopic data for this complex. Nevertheless, there is no doubt over the influence of the host rocks during the formation of sulfide-containing metasomatite upon gabbrodolerite (sample X-15-2). For example, in the Pb–Pb isotope space, it was possible to construct an isochron line on the samples of the Kureysky complex through a sulfide-containing dolerite of sample X-15-2, corresponding to an age of 250 Ma, and the argillite data point also fell on this line (Figure 13).

5. Discussion

5.1. Tectonic Structure

In 1936 V. Sobolev [1] performed the first detailed petrographic description of igneous rocks of the Siberian traps province. This publication defined the main directions of intraplate magmatism study for many years. These lines of research included: (1) Study of regional petrochemical provinces within the Siberian platform, (2) determination of the composition of the initial magmas, (3) analysis of magma intra-chamber differentiations, and (4) ore deposits' formation modeling.

The analysis of the different petrographic provinces is given in many works of V. Zolotukhin with co-authors [3,5,7]. The following structural zones were identified: Prieniseysky, Putorana, Tunguska syncline, Predtaymyrsky, and South Taimyr on the basis of the State Geological Survey (1:200,000 scale) and the analytical data were obtained by the authors on the composition of magmatic rocks within the Siberian platform. Magmatism within these zones is controlled by (1) Early Mesozoic swell-like uplifts that underwent inversion in the Late Mesozoic and is associated with ancient (Riphean) rifts (Khantaysko–Rybninsky, Kureysko–Letninsky, Pyasinsky), (2) ancient linear structures that did not undergo inversion (Predtaymyrsky), (3) ancient aulacogens regenerated in the pre-Mesozoic period (Vilyuysky, Udzhinsky), and (4) early Mesozoic troughs (within the Tunguska syncline) that did not undergo inversion.

The Prieniseysky zone is the most important tectonic structure which is characterized by a diverse composition of magmatic rocks and high concentration of Cu-Ni deposits. It includes [70] Khantaika–Rybinskoe and Kureysky–Letninsky zones. The latter is a part of a large submeridional tectonic structure in the border zone of the Siberian craton comprising three sublatitude branches, one of which is located within the Kulyumber river valley.

This structure was identified on the basis of the gravimetric mapping of 1:200,000 scale and airmagnetic data of 1:100,000 scale [51] and named as the Norilsk–Igarka paleorift earlier [2,71].

5.2. Magmatic Rocks

Subdivision of Intrusive Rocks

The study of igneous rocks of the Kulyumber river valley and adjacent territories was carried out in the early 1960s in the course of geological mapping. On the basis of the internal structure of intrusive bodies and the distribution of the main components, the Ergalakhsky complex of high alkalinity and four complexes of moderate alkalinity were identified. The latter include (1) Katangsky complex, comprising undifferentiated or weakly differentiated small- to medium-grained intrusions stable in composition (gabbro-dolerites with 6–7 wt.% MgO) and widespread in the frame of the lava field of the Siberian trap province; (2) Kureysky complex, combining differentiated large intrusive bodies of elevated MgO (8–9 wt.%) with troktolite lenses in olivine gabbro-dolerites; (3) Kuzmovsky complex, integrating weakly differentiated gabbro-dolerite intrusions with ferrogabbro and granophyres in the upper part of intrusive bodies; and (4) Norilsk complex, which includes highly differentiated intrusions with average MgO—10–12 wt.%.

Our geochemical data indicated the presence of four different groups of igneous rocks within the Kulyumber river valley, which includes effusive and intrusive facies:

(1) Mafic and ultramafic volcanic rocks of high and moderate magnesium (MgO = 7–12 wt.%) with elevated TiO₂ (1.2–1.4 wt.%) characterized by the absence (or very weakly presence) of Ta-Nb-negative and Pb-positive anomalies and the following geochemical parameters: (La/Sm)_n = 1.45, (Gd/Yb)_n = 1.89, ⁸⁷Sr/⁸⁶Sr = 0.70544, εNd = +3.9. These rocks had a mantle origin [42] with garnet in their source and belong to the Gudchikhinsky formation.

(2) Mafic intrusive rocks of moderate magnesium (MgO = 7.7 wt.%) with TiO₂ = 1.36 wt.% without Ta-Nb and Pb anomalies with (La/Sm)_n = 2.00, (Gd/Yb)_n = 2.00, ⁸⁶Sr/⁸⁷Sr = 0.70675, and preliminarily attributed to the Gudchikhinsky formation [60] but differing in reduced values of εNd = −1.0 (in comparison with +4 for the Gudchikhinsky rocks). On the basis of these data, we identified a new intrusive complex named Kulyumbinsky (Figure 3).

(3) Subalkaline volcanic rocks of low magnesium (MgO = 3.5–5.1 wt.%) with high TiO₂ (1.5–1.8 wt.%) of the Syverminsky formation and intrusive rocks (MgO = 3.2; TiO₂ = 2.4 wt.%) of the Ergalakhsky complex with a small Ta-Nb anomaly. Volcanic and intrusive rocks are characterized by (La/Sm)_n = 2.3–3.5 and 2.5–2.8, and (Gd/Yb)_n = 1.5–1.8 and 1.9–2.0, ⁸⁷Sr/⁸⁶Sr = 0.70754–0.70824 and 0.706034, εNd = −3.1 and −3, respectively. They are from crustal source enriched in garnet.

(4) Mafic intrusive rocks of moderate and increased magnesium ($\text{MgO} = 6\text{--}9 \text{ wt.}\%$) with strong negative Ta-Nb and positive Pb anomalies. Wide range of ratios are typical of these rocks ($(\text{La}/\text{Sm})_n = 1.3\text{--}1.4$, $(\text{Gd}/\text{Yb})_n = 1.2\text{--}1.5$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.70489\text{--}0.70702$, $\epsilon_{\text{Nd}} = 0.4\text{--}2.2$). This group includes different rocks, attributed to the Katangsky, Kuzmovsky, and Norilsk complexes. Their geochemical features are given in Table 6.

The special relationships between studied intrusions of these complexes are unclear due to an absence of geological boundaries between them caused by their separated positions. The legend to the State Geological map [53] confirms the earlier formation of the Katangsky complex in comparison with the Kureysky because several dykes preliminarily attributed to the last complex cut the Dzhaltulsky massif and basalts of the Mokulaevsky formation. Paleomagnetic data [60] show evidence that intrusions in the Kulyumber site (mainly Katangsky complex) are coeval with the basalts of the Mokulaevsky–Kharaelakhsky formations. This conclusion correlates with geochemical data showing TiO_2 increasing in basalts during the evolution of platform magmatism in western Siberia (from Tuklonsky to Samoedsky formation [72]). Similar TiO_2 behavior occurred in the intrusive rocks: The earliest intrusions belong to the Norilsk complex ($\text{TiO}_2 < 1 \text{ wt.}\%$), which cuts the Lower Nadezhdinsky formation and include the Dzhaltulsky massif ($0.8 \text{ wt.}\% \text{ TiO}_2$). The latest intrusions are the Katangsky and Kureysky complexes, very close ($1.4\text{--}1.5 \text{ wt.}\% \text{ TiO}_2$) to the Kharaelakhsky formation, which cuts the Mokulaevsky formation.

The complexity of the last group required separate consideration of studied rocks. First, the rocks of the Supposed Daldykansky and Supposed Kuzmovsky complexes penetrated by boreholes PR-4 and PR-11 were similar in composition and did not actually correspond to the reference Daldykansky and Kuzmovsky complexes in the Norilsk area (Figure 10e–g): They were characterized by low titanium and pronounced Ta-Nb-negative anomaly. They correspond to the rocks of the Katangsky complex.

Many studied intrusive bodies belonged to the Katangsky complex. They had very similar fabric and composition and there was no doubt in regards to their attribution. Several intrusive bodies within the Khalil and Kulyumber areas were described as massifs of the Kureysky complex (Khalil intrusion, Intrusion 4 in the Kulyumber site, sample Kul-40) on the basis of coarse-grained texture and elevated MgO content (Table 5). Nevertheless, two main intrusions, Khalil and Intrusion 4, were not identical. They have some differences in ϵ_{Nd} (2.34 and 1.3). Intrusion 4 in the Kulyumber site was very similar to the Gabbrovy intrusion (borehole PR-1) in major and trace elements as well isotope composition.

The Gabbrovy intrusion is of a particular interest in the Kulyumber river valley due to its sulfide mineralization. It is considered as a promising object for the prospecting of Cu-Ni-rich ore. It was attributed to the Kruglogorsky subcomplex of the Norilsk complex on the basis of the occurrence of leucogabbro horizon in its upper zone (Figure 13). Sill-like bodies of this subcomplex occur in the main ore junctions of the Norilsk region, the Norilsk and Talnakh, along with ore-bearing intrusions. This combination raises the question of the genetic relationship between the Norilsk and Kruglogorsky subcomplexes. This question was first formulated by Likhachev in 1965 [73]. Leucocratic rocks were also present not only in the Kruglogorsky sills but in ore-bearing intrusions as well. These rocks were represented by two varieties: Coarse-grained panidiomorphic rocks, often with massive or porphyritic texture, and rocks with ataxitic structure [73–76]. In both cases, the rocks were enriched in plagioclase, the amount and morphology of which varied. The first variety consisted of short-prismatic plagioclase crystals (70–90 vol.%) and represented anorthosites (with $\text{An}_{65\text{--}90}$). The second variety is comprised of more dark-color minerals (pyroxene and olivine, 20–40 vol.%) that are irregularly distributed in rocks and form segregations in 2–10 cm. They were named taxitic gabbro-dolerites. Usually these rocks are described together as leucogabbro. Meanwhile, they had different positions within intrusive bodies and different origins.

Table 6. Comparison of different intrusions from different complexes.

No.	Complex	Site, Intrusion	Sample (n)	MgO	TiO ₂	Na ₂ O + K ₂ O	(La/Sm)n	(Gd/Yb)n	(U/Nb)n	⁸⁷ Sr/ ⁸⁶ Sr	εNd
1	Ergalakhsky	Khalil	X-40	3.12	2.41	6.09	2.52	1.85	1.51	0.706034	−3.8
2		Norilsk area	n = 3 [67]							0.706459	−4.0
3		South Norilsk	n = 1 [69]	2.83	3.33	6.63	2.61	1.77	1.43	0.70758	−3.8
4	Kulyumbinsky	Kulyumber	Kul-12	7.72	1.36	4.9	2.00	2.12	1.17	0.706745	−1.0
		Intrusion 5								0.706773	−1.0
6	Daldykansky	Norilsk area	n = 5 [51]	6.00	1.72	3.43	1.51	1.25	2.26	0.705768	3.1
7	Kureysky	Kulyumber	K-2	8.3	1.29	2.64	1.40	1.23	3.04	0.704864	0.4
		Intrusion 4									
8		Khalil site, Khalil	X-6	6.99	1.31	4.21	1.35	1.25	2.58	0.705694	1.0
9	Norilsk-type	Khalil site	X-32	8.55	1.00	2.26	1.62	1.29	1.68	0.705275	1.0
		Intrusion 2									
10	Kruglogorsky	Kulyumber	PR-1/262.2	9.05	1.31	2.94	1.39	1.33	3.46	0.705222	1.7
11		Gabbrovy	PR-1/234	8.3	1.12	2.93	1.41	1.24	3.9	0.704887	2.2
12			PR-1/266	7.9	1.29	2.94	1.43	1.28	5.31	0.705206	2.1
13		Norilsk area	n = 8 [67]							0.707640	1.7
		MP-2b									
	Norilsk	Norilsk area	[67]								
14		Talnakh	n = 6, OUG-2							0.7071238	0.8
15		Norilsk 1	n = 9, MN-2							0.7067533	1.4
16	Gudchikhinsky	Norilsk area	n = 1.75/2 [51]	10.4	1.66	2.36	1.49	2.00	1.84	0.705435	3.9
17		Norilsk area	n = 5 CY-50, X-51/130							0.705343	4.2

Note. Oxides are given in wt. %.

The first rock variety, in fact, leucogabbro, formed oval or lenticular bodies (between few centimeters and few meters) with clear boundaries in gabbro-dolerites mostly in peripheral zones of ore-bearing intrusions or in their upper and lower parts. The mechanism of their formation was proposed by Likhachev [73,74] and suggests plagioclase accumulation and floatation during its early crystallization in magma when it rises to the surface in a conduit. In a chamber, magma pushes plagioclase mush into peripheral zones forming “inner leucogabbro”. Sometimes this mush fills fractures near a chamber and forms “outer leucogabbro”. Thus, Likhachev believes that “there was no significant break in the formation of these components of ore-bearing intrusions (i.e., leucogabbro and gabbro-dolerites of main intrusive body, N.K.), there is no doubt that they belong to a single magmatic system” (page 10 in [74]). Thus, inner leucogabbro bodies are not xenoliths (as it was written in [62]), because they are products of crystallization of the same magma. In this regard, external leucogabbro are apophyses of ore-bearing intrusions. The compositions of internal and external leucogabbro are identical in terms of the main components (Table 7).

Table 7. Weighted mean chemical compositions of the intrusions and leucogabbro (wt.%) and their isotope characteristics.

No.	1	2	3	4	5	6	7	8
No Sample	MP-2b	SF-7	ZF-37	ZF-39	1	2	3	4
SiO ₂	47.63	48.86	48.45	49.64	48.53	48.22	47.97	49.51
TiO ₂	1.07	1.04	1.16	1.04	0.50	0.82	0.74	0.58
Al ₂ O ₃	17.80	18.07	17.95	18.07	21.85	20.42	20.13	20.88
Fe ₂ O ₃	12.21	10.88	14.11	13.42	7.81	9.76	9.68	7.34
MnO	0.15	0.17	0.19	0.18	0.08	0.11	0.10	0.08
MgO	6.68	6.05	6.40	7.89	5.64	4.76	5.54	4.68
CaO	10.81	10.62	12.19	11.59	11.90	11.74	12.09	12.31
Na ₂ O	2.62	2.82	2.76	2.90	2.17	2.48	2.47	3.24
K ₂ O	0.92	1.34	0.67	0.55	1.47	1.60	1.07	1.19
P ₂ O ₅	0.11	0.15	0.13	0.11	0.05	0.09	0.21	0.19
Cr	120	141	235	221				
⁸⁷ Sr/ ⁸⁶ Sr	0.707028							
εNd	1.7							

No.	9	10	11	12	13	14	15
No Sample	PR-1	Katangsky 1	Katangsky 2	Kureysky (Khalil)	Norilsk-Type	MD-27	SF-10
SiO ₂	46.87	49.84	48.71	48.32	49.23	49.44	48.72
TiO ₂	1.33	1.44	1.52	1.59	1.00	0.90	0.89
Al ₂ O ₃	14.96	14.59	15.07	14.30	15.32	16.53	14.68
Fe ₂ O ₃	12.74	12.69	13.15	13.91	11.40	10.62	10.61
MnO	0.19	0.18	0.19	0.20	0.17	0.15	0.16
MgO	7.40	6.90	7.23	6.81	8.58	7.75	9.96
CaO	9.81	10.11	9.97	10.41	11.85	12.03	10.96
Na ₂ O	2.60	3.27	3.42	3.53	2.08	3.52	2.19
K ₂ O	0.58	0.76	0.55	0.71	0.25	0.40	0.71
P ₂ O ₅	0.19	0.14	0.17	0.21	0.09	0.24	0.12
Cr	128	166	165	181	379	524	698
⁸⁷ Sr/ ⁸⁶ Sr	0.705105			0.705694	0.705275		
εNd	2.01			2.34	1.01		

Note: Nos. 1–4, Kruglogorsky subcomplex, Norilsk area, after [62]; 5–8, leucogabbro (5, 6, Norilsk 1 inner, 6 outer; 7, Mount Chenraya, outer; 8, Talnakh, inner), after [72]; 9–13, intrusions of the Kulyumber river valley (9, Gabbrov; 10 Katangsky complex, Intrusion 1 in Figure 3, Kulyumber site; 11, Katangsky complex, Intrusion 2 in Figure 3; 12, Kureysky complex, Khalil intrusion, Khalil site [51]; 13, Norilsk-type intrusion, Khalil site [51]); 14–15, Norilsk complex, Norilsk area (14 Norilsk 1, 15 Talnakh).

A similar idea on the origin of the Kruglogorsky leucogabbro belongs to Rad’ko [72], who assumes that the occurrence of the Kruglogorsky intrusions in any places is evidence to the location of ore-bearing intrusions nearby. On the basis of this suggestion, the Kruglogorsky sills can be used for prospecting new Cu-Ni deposits. This approach formed a special geological method, which has been used by Norilskgeology Ltd. within the Kulyumber river valley. In this regard, the Gabbrov intrusion is an indicator of closely located mineralization.

The second variety of leucogabbro with ataxitic structure formed horizons in the lower and upper zones of intrusions. They had a large thickness and comprised economic PGE-Cu-Ni mineralization

in the ore-bearing intrusions (Talnakh, Norilsk 1). Their origin has been under discussion for many years [75,77,78].

Meanwhile, the geological mapping and exploration carried out in the 1960s and 1970s, demonstrated that the outer leucogabbro formed separate intrusive bodies [53]. Although the composition and structure of the Gabbrovy intrusion were similar to those of the Kruglogorsky sills, there are several differences with them. It is enriched in TiO_2 and MgO and depleted in Al_2O_3 in comparison with the leucogabbro sills of the Norilsk region (1.35 and 1.05 TiO_2 , 7.6 and 6.7 wt.% MgO , 14 and 17–18 wt.% Al_2O_3 , respectively) and has different weighted mean composition and isotopic characteristics (Table 6). In fact, the Gabbrovy intrusion takes an intermediate position between the Kruglogorsky subcomplex and Katangsky complex. We guess that it is possible to regard it within the latter as a weakly differentiated body.

In the case of the Kruglogorsky subcomplex sills in the Norilsk region, it was obvious that they were formed from magmas differing in chemical composition from magmas of ore-bearing intrusions. Their parental magmas were more leucocratic (5–6% wt.% MgO in comparison with 10–12 wt.% MgO for the Norilsk ore-bearing intrusions) and had higher ϵNd and lower Sr (Table 6). These features cannot be explained by the operation of fluids, as suggested in article [62]. The authors did not give any data on H_2O , Cl , or F contents in magmas that could support this theory. Furthermore, the occurrence of amygdals in leucogabbro does not account for the enrichment of these rocks by volatile components because amygdals are typical of any rocks in the upper parts of subvolcanic intrusive bodies, not only in the Norilsk region but around the Siberian trap province.

The chemical compositions of rock-forming minerals from the studied intrusive complexes were very close to each other. In general, they reflected the composition of rocks, in particular, their magnesium number. The most significant mineral was olivine, since it is usually an early liquidus phase in rocks. Olivine varied significantly in differentiated intrusions. This has been established in numerous studies for the Norilsk ore-bearing intrusion, where its composition changes from 40 to 82 [24–26,43]. Most of the magnesium olivine compositions are typical of the picritic gabbro-dolerites and troctolites, in particular, for these rocks from the Norilsk 1 massif, studied by us in the core of the DM-27 borehole (Figures 14 and 15), where the forsterite component reached 80 mol.%. These olivines were similar to olivines from the Intrusive 2 of the Kureysky complex, changing from Fo_{38} to Fo_{75} (Table S1). Meanwhile, the Norilsk-type intrusion in the Khalil site, attributed preliminarily to the Norilsk complex, contained very ferruginous olivine Fo_{31-46} . Although the olivines from the Norilsk 1 intrusion were enriched in NiO (especially those from the picrite gabbro-dolerites containing sulfide ores), the olivines from the Intrusion 2 did not differ from them: They were even more nickel-rich at the same Fo . The minimum NiO occurred in the rocks from the Dzhatulsky massif and the trachydolerites of the Ergalakhsky complex. Most of the compositions of studied pyroxenes (Figure 16) almost all fell into the field of magnesium-rich augite and their points formed a small field in the En-Wo-Fs diagram. As in the case of olivine, pyroxenes from Intrusive 2 of the Kureysky complex were characterized by the greatest dispersion of compositions.

Figure 14. Inner structure of the Gabbrovy intrusion.

Figure 15. Diagram Fo-NiO for olivines from intrusive rocks.

Figure 16. Pyroxenes' compositions from the intrusive rocks in diagram En-Wo-Fs, (a) trapezium with fields of pyroxenes' compositions of the Kulyumber river valley, Norilsk 1, and Dzhaltulsky massifs; (b) the most widespread pyroxene compositions; (c) position of trapezium in diagram En-Wo-Fs.

5.3. Magma Sources

It should be assumed that the four groups of rocks mentioned above have various magma sources. The problem of the magma sources diversity has been considered for the Siberian platform for many years. Initially it was believed [1] that the diversity of all rocks in the province was due to the result

of crystallization differentiation of a single magma. By the end of the 1980s, the diversity of rock compositions was explained by the fractionation of the primary picritic magma, resulting from the assimilation of crustal rocks and the influence of mantle fluids on the initial melt [5]. New geochemical data, including a distribution of rare elements in magmatic rocks and their isotopic characteristics, led to a new interpretation of the origin of igneous rocks in the Siberian platform. They were regarded as a product of crust contamination (up to 25–30%) by primary mantle magma [35,36]. Later, the formation of different rocks was explained by simultaneous plume melting of at least two different lithospheric substrates [79,80] or as a result of the action of two different plumes [41]. The variety of rocks was also explained by the different amount of pyroxenite component in the source, formed as a result of the interaction of peridotite with the substance of recycled oceanic crust [81].

The most contrasting compositions of rocks formed at different depths and located in the same place represent tholeiitic basalts and kimberlites that are believed to have been formed from multilevel conjugated sources [82].

The difference in sources at various depths was explained by an action of fluids as well [83]. Results of nonisothermal equilibrium physicochemical dynamics modeling show the occurrence of the following sequence of zones in over-asthenosphere continental mantle: (1) a zone where initial rocks were intensively sublimated and depleted by most petrogenic components; the restite in this case becomes carbonated, salinated, and graphitized; (2) a zone of Si and Fe enrichment and carbon deposition in initial rocks depleted in Na, K, P, and Mn; (3) a zone of diamond-bearing lherzolites enriched with Na; (4) a zone of hydrated rocks enriched with K; (5) a zone of hydrated rocks not enriched with petrogenic components. Zone 2 can be responsible for the formation of kimberlite melts, zones 3 and 4 can be substrates of alkaline magma melting, and zone 5 can be the source of mafic tholeiitic magma. Unfortunately, amount of fluids was not estimated and their role in magma origin is disputable.

So, the spatial combination of rocks formed from different deep sources in the same blocks of crust remains completely unclear. We believe that the complex structure of the northwestern zone of the Siberian platform assumed the presence of faults of different depth which are the conduits for mantle and crustal magmas forming different igneous rocks.

On the basis of the geochemical and mineralogical data on igneous rocks at the Kulyumber river valley given in both parts of the article (Part I and Part II) we came to the following conclusions.

6. Conclusions

- (1) The geochemical study of the volcanic rocks in the Kulyumber river valley allowed distinguishing the following formations similar to those of the Norilsk area: Syverminsky, Gudchikhinsky, Khakanchansky, and Nadezhdinsky. The absence of the Ivakinsky formation in the studied area implied that it pinched out from the north to the south. The tuffs of the Syverminsky formation were analyzed for the first time, and we have demonstrated how they differ from the Khakanchansky tuffs. Basalts of the Gudchikhinsky formation from the Kulyumber area were enriched in alkalis and depleted in U and Th, in comparison with the Gudchikhinsky basalts from the Norilsk area.
- (2) The studied intrusive rocks could be subdivided into three groups on the basis of major and trace elements' contents: (1) Subalkaline rocks ($\text{MgO} = 4 \text{ wt.}\%$, $\text{TiO}_2 = 3.3 \text{ wt.}\%$) with $(\text{La}/\text{Sm})_n = 2.5\text{--}2.8$ and $(\text{Gd}/\text{Yb})_n = 1.9\text{--}2.1$ (Ergalakhsky complex); (2) mafic rocks ($\text{MgO} = 6\text{--}9 \text{ wt.}\%$, $\text{TiO}_2 = 0.8\text{--}1.7 \text{ wt.}\%$) with strong negative Ta-Nb and positive Pb anomalies and varying ratios $(\text{La}/\text{Sm})_n = 1.3\text{--}1.0$, $(\text{Gd}/\text{Yb})_n = 1.2\text{--}1.5$ (Katangsky, Kureysky, and Norilsk complexes, Kruglogorsky subcomplex); and (3) mafic rocks ($\text{MgO} = 6\text{--}7 \text{ wt.}\%$, $\text{TiO}_2 = 1.4 \text{ wt.}\%$) without Ta-Nb and Pb anomalies with moderate $(\text{La}/\text{Sm})_n = 2.00$ and high $(\text{Gd}/\text{Yb})_n = 2.0$ ratios. The first two groups were similar to the rocks from the Norilsk area and Tunguska syncline, while the rocks of the third group were unknown earlier in the NW Siberian platform and have been attributed by the authors to a new intrusive complex named Kulyumbinsky complex.

- (3) Intrusive rocks of the second group formed massifs ranging in composition. The Norilsk complex was characterized by strong rock differentiation and elevated MgO and Cr, while Katangsky and Kureysky complexes of the Kulyumber river valley could not be distinguished from one another on the basis of geochemical data. A novel type of intrusion was recognized in the Khalil site. It takes an intermediate position between Norilsk and Katangsky complexes due to low TiO₂ and elevated Cr contents. Intrusions of the Daldykansky and Ogonersky complexes have not been found in the Kulyumber river valley.
- (4) Igneous rocks of the Kulyumber river valley originated from different sources: Mantle and crustal. The products of the first are the volcanic rocks of the Gudchikhinsky formation ($^{87}\text{Sr}/^{86}\text{Sr} = 0.706034$ and $\epsilon\text{Nd} = 4.0$) and gabbro-dolerites of the Kulyumbinsky complex ($^{86}\text{Sr}/^{87}\text{Sr} = 0.70675$ and $\epsilon\text{Nd} = -1.0$). A separate source is typical of the Ergalakhsky trachydolerites ($^{87}\text{Sr}/^{86}\text{Sr} = 0.706034$ and $\epsilon\text{Nd} = -3.8$), and another source is typical of the rocks of many complexes (Norilsk, Katangsky, Kureysky, $^{87}\text{Sr}/^{86}\text{Sr} = 0.70489\text{--}0.70702$, and $\epsilon\text{Nd} = 0.4\text{--}2.2$, respectively).
- (5) The diversity of igneous rocks within the Kulyumber river valley could be explained by the complex tectonic structure of the paleorift zone, which is characterized by a long tectonic evolution and the effect of deep faults.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2075-163X/10/5/415/s1>, Table S1: Composition of rock-forming minerals, wt.%.

Author Contributions: Conceptualization N.K., methodology B.B. and A.D.; investigation, B.G., A.L., formal analyses T.B.B. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the Russian Foundation for Basic Research, projects Nos. 18-05-70094 and 19-05-00654.

Acknowledgments: We are grateful to I. Sidorenko and M. Nesterenko for their help in the field trip and geologists of Norilskgeolgy Ltd. for the permission for cores' sampling. The authors thank N. Kononkova and V. Taskaev for microprobe analyses and N. Svirskaya and V. Turkov for samples' preparation.

Conflicts of Interest: The authors declare no conflict of interest.

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