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GEOPHYSICS

Sm–Nd Age of Dunite–Clinopyroxenite–Tylaite Association of the Kytlym Massif, the Platinum Belt of the Urals*

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The Platinum Belt of the Urals extends over 900 km in the meridional direction along the Paleozoic Tagil Rift and comprises 14 complexly built plutonic massifs [1]. The eastern portions of these massifs, prevalent in area, are occupied by gabbro. The bodies of platiniferous dunite and the surrounding clinopyroxenite adjoin the gabbroic plutons in the west. The geological facts testify that gabbro was emplaced later than dunite and clinopyroxenite. However, genetic relationships between dunite, olivine-, magnetite-, and plagioclase-bearing pyroxenites[1], on the one hand, and gabbro and gabbronorite, on the other hand, remain debatable. Some authors regard these rock groups as self-dependent igneous associations [2], whereas others consider them a common association [3]. To a great degree, the equivocal treatments are caused by absence of reliable data on the isotopic age of the ultramafic and mafic rocks. While gabbroic rocks are dated at 430–415 Ma (Silurian) quite definitely, the available fragmentary information on the age of the preceding rocks does not allow unambiguous interpretation [4].

In this communication, we present new data on the Sm–Nd age of clinopyroxene-bearing dunite, wehrlite, olivine clinopyroxenite, kosvite (including an apatite variety), and tylaite (including a pseudoleucite variety) that compose the Kosvinsky and Konzhakovsky blocks in the Kytlym Massif (Fig. 1). The results obtained substantially change the traditional view on the timing and geodynamic setting of ultramafic and mafic rocks in the Platinum Belt of the Urals.

Twenty representative whole-rock samples of the mafic and ultramafic rocks mentioned above (two series of ten samples from each geological block) were taken. Two samples of apatite kosvite kindly presented for analysis by E.V. Pushkarev (Institute of Geology and Geochemistry, Uralian Division, Russian Academy of Sciences) were used for the substantiation of a mineral isochron. Chemical compositions of the studied samples are given in Table 1, while the results of isotopic measurements are presented in Table 2. All analyzed samples demonstrate a common positive trend in coordinates $^{147}Sm/^{144}Nd$–$^{143}Nd/^{144}Nd$ (Fig. 2), which may be approximated by two rectilinear segments with different slopes. These segments correspond to the isochrons that characterize (1) clinopyroxene-bearing dunite, wehrlite, olivine clinopyroxenite, kosvite, and low-alkali tylaite from Kosvinsky Kamen and Konzhakovsky Kamen mountains ($^{147}Sm/^{144}Nd > 0.17$) and (2) pseudoleucite tylaite and apatite kosvite from Mt. Kosvinsky Kamen ($^{147}Sm/^{144}Nd < 0.16$) (Fig. 3).

Seventeen points with $^{147}Sm/^{144}Nd > 0.17$ make up an errorchron that corresponds to 531 ± 50 Ma (Nd_i = 0.512278 ± 67, MSWD = 9.1). If we omit three points (sample 4504, tylaite enriched in plagioclase and amphibole; samples 4514 and 4524, recrystallized coarse-grained olivine clinopyroxenite) (Fig.2), the remaining points yield an isochron age of 551 ± 32 Ma (Nd_i = 0.512252 ± 43, MSWD = 1.9) that corresponds to Late Vendian–Early Cambrian (Fig. 3). Other combinations of points lead to similar results but with a greater uncertainty.

In the region of $^{147}Sm/^{144}Nd > 0.18$ of the summary plot (Fig. 2), one can distinguish rectilinear segments that combine three to four points of rocks of the same type within narrow $^{147}Sm/^{144}Nd$ intervals. Slopes of these segments differ from the common trend. For example, four points of high-Mg clinopyroxenite (group *b* in Table 2) corresponds to an isochron age of

[1] More than a hundred years ago, L. Duparc named magnetite clinopyroxenite as k*osvite* (after Mt. Kosvinsky Kamen) and plagioclase-bearing clinopyroxenite as *tylaite* (after Mt. Tylai). These terms have been used until now, especially in the Urals.

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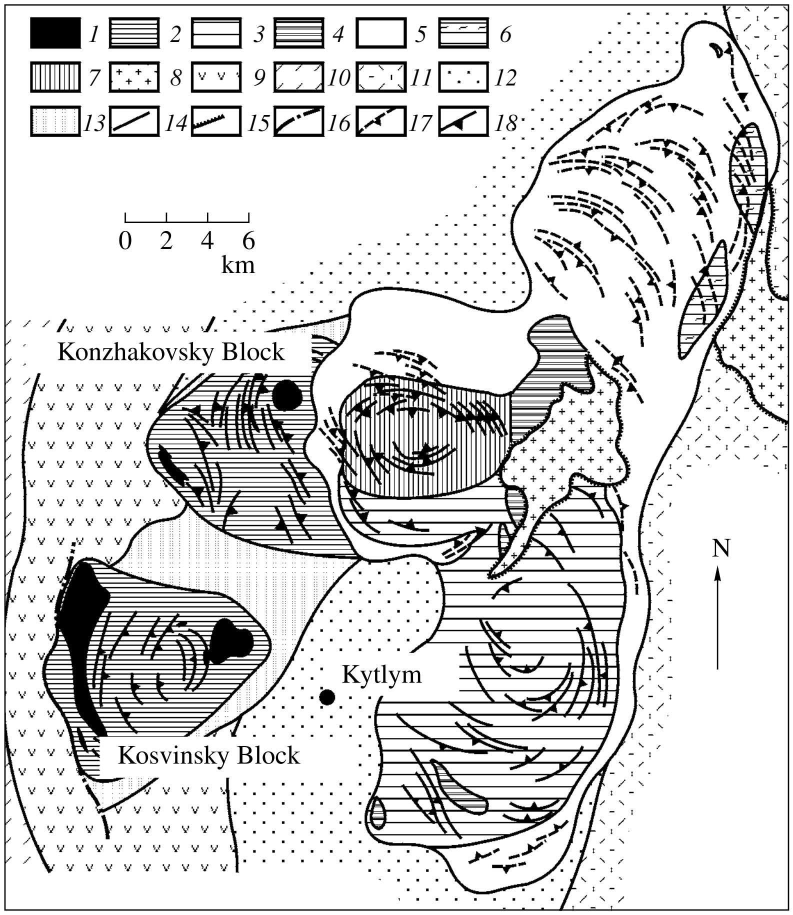

Fig. 1. Geological scheme of the Kytlym Massif, after [5]. The dunite–clinopyroxenite–tylaite association of the Konzhakovsky and Kosvinsky blocks: (*1*) dunite, (*2*) olivine clinopyroxenite, kosvite, and tylaite; Sukhogorsky pluton: (*3*) olivine gabbro, (*4*) remnants of dunite, wehrlite, and clinopyroxenite in gabbro; Valentorsky pluton: (*5*) gabbronorite and (*6*) olivine gabbro; (*7*) amphibole gabbro; (*8*) plagiogranite; (*9*) Ordovician metavolcanics; (*10*) Ordovician metaterrigenous rocks; (*11*) Silurian volcanics; (*12*) Ordovician and Silurian volcanics, unspecified; (*13*) kytlymite; (*14–18*) contour lines that demonstrate orientation of banding and mineral grains.

681 ± 82 Ma at $Nd_i = 0.51205 \pm 12$, whereas four points of clinopyroxene-bearing dunite, wehrlite, and cross-cutting clinopyroxenite veinlets (group *a*) yields 779 ± 160 Ma at $Nd_i = 0.51193 \pm 23$. A great uncertainty of age estimates and unrealistic low initial ratios of Nd isotopes suggest that these segments hardly have a geochronological meaning and are more likely a result of an accidental arrangement of points. If this is not the case, then an older (Late Riphean) age of groups *a* and *b* can only be suggested.

Line *2* in Fig. 3 is a mineral isochron based on six points (whole-rock samples 400 and 401 of apatite kosvite, apatite, and clinopyroxene separated from these samples). Whole-rock samples 4535 and 4544 of pseudoleucite tylaite and sample 4543 of apatite tylaite fall on the same isochron. The addition of these points does not change the parameters of the mineral isochron and only increases insignificantly the MSWD value. The isochron age of 441 ± 27 Ma, ($Nd_i = 0.512371 \pm 24$, MSWD = 3.9) corresponds to Late Ordovician–Early Silurian. Six points of the isochron mineral yielded 440 ± 27 Ma (MSWD = 2.7).

The evolution lines of Nd isotopic compositions of rocks and minerals used for the calculation of isochrons *1* and *2*, as well as a model age of inferred mantle sources, are shown in Fig. 4 in coordinates t–ε_{Nd}. Because the initial isotope ratios lie below the line of the depleted mantle DM [7], or primitive mantle PM (according to [8]), it may be supposed that the LREE-rich upper mantle served as a source, and source *2* was more enriched than source *1*. The model age of these sources depend on their $^{147}Sm/^{144}Nd$ ratio. This ratio shown in Fig. 4 has been chosen in such a way that it slightly exceeds the $^{147}Sm/^{144}Nd$ ratio of kosvite and tylaite, which are the solidified melts derived from the given sources. If we keep in mind that $^{147}Sm/^{144}Nd$ of PM (DM) is 0.2119, an estimate equal to 1366 Ma at $^{147}Sm/^{144}Nd = 0.20$ is close to the maximum possible model age. The minimum age at $^{147}Sm/^{144}Nd = 0.12$ equals ~600 Ma. Thus, an enriched source of the rocks

Table 1. Chemical composition of mafic and ultramafic rocks

Component	*a*		*b*		*c*		*d*		*e*	*f*
	4520	4522	4514	4524	4508	4542	4510	4526	4544	400
SiO_2	49.40	47.60	48.73	50.66	44.11	44.21	45.96	45.20	46.18	46.72
Al_2O_3	1.02	4.72	1.65	1.76	6.31	3.91	5.83	7.77	8.67	5.18
TiO_2	0.10	0.60	0.22	0.22	0.72	0.91	0.33	0.73	0.72	1.10
FeO_{tot}	6.34	8.15	9.26	6.64	15.84	15.50	11.62	13.04	12.47	12.27
MgO	26.84	19.97	22.78	19.94	13.68	16.40	20.70	15.10	14.62	12.58
CaO	16.02	18.70	17.03	20.45	18.68	18.54	14.92	17.23	14.41	18.81
Na_2O	0.06	<0.05	0.07	0.12	0.37	0.21	0.32	0.60	1.50	0.52
K_2O	0.04	0.05	0.05	0.04	0.07	0.05	0.07	0.08	0.93	0.28
P_2O_5	<0.05	<0.05	<0.05	<0.05	<0.05	0.07	<0.05	<0.05	0.27	2.38
Fe/Mg	0.13	0.23	0.23	0.19	0.65	0.53	0.31	0.48	0.48	0.55
Rb	0.46	0.55	0.66	0.43	1.25	0.07	0.27	0.07	110	5
Sr	8.87	17	28.4	52	130	77.1	130	530	940	490
La	0.17	0.3	0.31	0.097	1.03	1.66	0.65	2.65	14.5	26.43
Ce	0.41	1.84	0.64	1.16	2.97	5.86	1.78	8.23	32.9	57.71
Nd	0.39	2.85	1.31	2.31	4.07	6.21	2.2	9.51	22.5	36.27
Sm	0.21	1.06	0.54	0.9	1.5	2.15	0.95	2.96	5.16	7.63
Eu	0.057	0.43	0.2	0.29	0.48	0.64	0.35	0.99	1.59	2.05
Gd	0.17	1.26	0.65	0.84	1.62	1.9	0.98	2.74	4.26	6.41
Yb	0.073	0.55	0.27	0.31	0.6	0.66	0.48	0.72	1.16	1.13
Lu	0.019	0.095	0.051	0.037	0.1	0.095	0.085	0.11	0.2	0.17
Zr	4.3	11.4	4.6	5.17	9.32	14.8	5.17	30.4	56.5	36
Nb	0.11	0.07	0.098	<0.05	0.12	0.07	<0.05	0.054	1.06	1.6
Ni	450	190	310	210	240	220	360	190	220	208
Cr	2630	630	2100	1900	550	710	2370	680	790	321
V	35	200	99.6	59.2	380	450	150	370	290	542

Note: Rocks: (*a*) wehrlite (sample 4520), clinopyroxenite veinlets in dunite (sample 4522), (*b*) olivine clinopyroxenite, (*c*) magnetite clinopyroxenite (kosvite), (*d*) low-K tylaite; (*e*) pseudoleucite tylaite, (*f*) apatite clinopyroxenite. Samples 4520, 4514, 4508, and 4510 are from the Konzhakovsky Block; samples 4522, 4524, 4542, 4526, 4544, and 400, from the Kosvinsky Block. The major oxides (wt %) were determined with the XRF; minor elements, with the ICP-MS at the VSEGEI laboratory. Sample 400 was analyzed by E.V. Pushkarev.

under consideration was formed in the Neoproterozoic. At $^{147}Sm/^{144}Nd$ of ~0.165, the initial isotope ratios for isochrons *1* and *2* fall on the same evolution line of the Sm–Nd isotopic system, so that the Late Vendian–Early Cambrian and the Late Ordovician–Early Silurian rocks may be regarded formally as derivatives of one enriched mantle reservoir that arose in the Late Riphean ~750 Ma ago. However, $^{147}Sm/^{144}Nd$ ratios of low-alkali kosvite and tylaite are higher than 0.17 (Fig. 2), and this makes the above suggestion less probable. Most likely, 750 Ma is a value close to the model age of the source of pseudoleucite tylaite and apatite kosvite that were formed ~440 Ma ago, whereas the source of low-alkali ultramafic and mafic rocks has an older model age.

Some geological implications. The low-alkali rocks of the dunite–clinopyroxenite–tylaite association of the Kytlym Massif have a Sm–Nd age of 551 ± 32 Ma. Hence, they predated not only the Silurian gabbro (415–430 Ma) but also the eruption of the Late Ordovician basalts. Thus, the dunite–clinopyroxenite–tylaite association belongs to the Cadomian (Vendian–Ordovician) rather than the Caledonian (Ordovician–Early Devonian) tectonomagmatic cycle that marks a transition from the platform evolution of the Protouralides to the development of the Paleozoic mobile belt. In light of these data, it becomes clear why ultramafic and mafic rocks in the Platinum Belt of the Urals reveal petrologic, geochemical, and metallogenic similarities with analogous platiniferous associations within cratons [9]. An intrusive belt of mafic and ultramafic bod-

Table 2. Isotopic characteristics of the studied samples

Group	Sample	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ	Location of samples
a	4520	0.263	0.748	0.21239	0.513012	14	Saddle between Mt. Konzhakovsky Kamen and Mt. Tylai
a	4536	0.479	1.403	0.20643	0.512983	18	Northern shoulder of the upper reaches of the Garevaya River
a	4516	0.216	0.585	0.22303	0.513064	24	Western slope of Mt. Konzhakovsky Kamen
b	4514	0.699	1.922	0.21999	0.513028	22	Ibid.
b	4505	0.682	1.823	0.22627	0.513069	19	Southern spur of Mt. Tylai (peak of 1403.0 m)
b	4517	0.619	1.593	0.23491	0.513099	16	Western slope of Mt. Konzhakovsky Kamen
c	4508	1.863	5.371	0.20969	0.513023	17	Mt. Tylai
d	4504	1.931	6.19	0.18857	0.512953	3	Southern spur of Mt. Tylai (peak of 1403.0 m)
d	4510	0.999	2.791	0.21647	0.513023	6	Mt. Tylai
d	4540	1.473	4.4	0.20243	0.51298	23	Southern slope of Mt. Konzhakovsky Kamen
a	4522	1.301	3.56	0.22099	0.513057	4	Eastern slope of Mt. Kosvinsky Kamen
b	4524	0.933	2.722	0.20718	0.512977	6	Ibid.
c	4542	3.331	10.84	0.18578	0.512923	23	Southern slope of Mt. Konzhakovsky Kamen
c	4525	3.668	12.9	0.17192	0.512874	5	Eastern slope of Mt. Kosvinsky Kamen
d	4526	4.182	13.73	0.18419	0.512912	21	Farkov Ridge
d	4531	2.764	9.386	0.17804	0.512903	20	Ibid.
d	4533	4.248	14.34	0.1791	0.512896	7	Ibid.
e	4535	5.349	22.63	0.14288	0.512786	2	Southern slope of Mt. Konzhakovsky Kamen
e	4544	7.436	31.62	0.14215	0.512777	3	Ibid.
f	400	7.341	34.49	0.12867	0.51274	4	Saddle between Mt. Kosvinsky Kamen and Farkov Ridge
f	401	6.351	26.15	0.14862	0.512795	1	
f	4543	4.46	18.96	0.14223	0.51279	9	Southern slope of Mt. Konzhakovsky Kamen
g	400cpx	6.027	24.13	0.15099	0.512826	3	Clinopyroxene from sample 401
g	401cpx	7.107	27.1	0.15857	0.51281	7	Clinopyroxene from sample 400
h	400ap	64.52	368.8	0.10575	0.512674	4	Apatite from sample 400
h	401ap	73.77	420.8	0.10599	0.512681	4	Apatite from sample 401

Note: Notations of rock and mineral groups are as in Table 1 and Fig. 2. 2σ is an uncertainty of measurements (the last decimal digits). The isotopic study was performed by B.V. Belyatsky on a Triton thermoionization mass spectrometer using the standard technique at the Center of Isotopic Studies, All-Russia Research Geological Institute (VSEGEI). Isochrons were calculated with the ISOPLOT program [6] at an average analytical reproducibility of 0.5% (2σ) for the $^{147}Sm/^{144}Nd$ ratio and taking into account the measured uncertainties of $^{143}Nd/^{144}Nd$ ratio (Table 2).

ies, which dissected a large Late–Vendian–Early Cambrian arch, likely existed at the site of the present-day Platinum Belt. These bodies were localized within the upper crust but still might have been unexposed at the day surface of that time.

The results obtained confirm a younger age of pseudoleucite tylaite and apatite kosvite (441 ± 27 Ma) relative to ultramafic and mafic rocks with low contents of alkali metals and correlative minor elements (Table 1). Pyroxenite and kosvite enriched in alkali metals and phosphorus crop out on the western slope of Mt. Kosvinsky Kamen [10] as sheetlike bodies conformable to the structure of the Kosvinsky Block. Judging from isotopic data, these bodies have been emplaced into the older clinopyroxenite and tylaite almost synchronously with the opening of the Late Ordovician–Early Silurian rift, the axis of which is traceable a few kilometers eastward [11]. This magmatic episode may be regarded as an onset of the Caledonian rifting and at the same time as a final stage of the Cadomian tectonomagmatic cycle. It is hardly accidental that pseudoleucite tylaite and apatite clinopyroxenite are coeval with miaskite and carbonatite that occur in the Vishnevy and Ilmeny mountains [12].

The present-day structure of the Kytlym and other massifs in the Platinum Belt was ultimately formed in the transpressive tectonic setting after the emplacement of the Silurian gabbro. The older dunite, clinopyroxen-

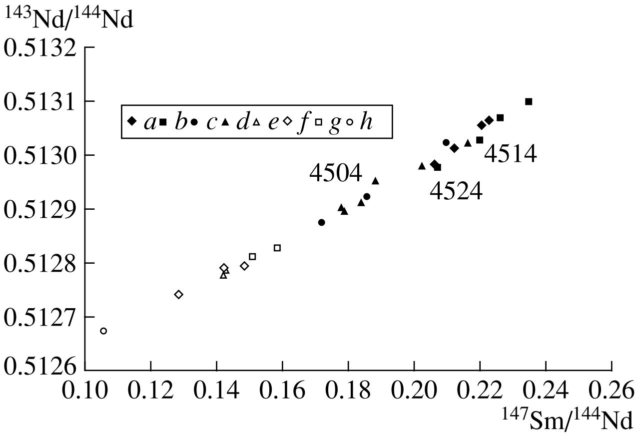

Fig. 2. Isotopic compositions of the studied rocks plotted in coordinates $^{147}Sm/^{144}Nd$–$^{143}Nd/^{144}Nd$. (*a*) Clinopyroxene-bearing dunite, wehrlite, and clinopyroxenite veinlets in dunite; (*b*) olivine clinopyroxenite with Fe/Mg < 0.24; (*c*) magnetite clinopyroxenite (kosvite) with Fe/Mg > 0.42; (*d*) low-K tylaite; (*e*) pseudoleucite tylaite; (*f*) apatite kosvite containing (*g*) clinopyroxene and (*h*) apatite. Numerals in the plot denote sample numbers (Table 2) omitted from the calculation of isochron (*1*), see Fig. 3.

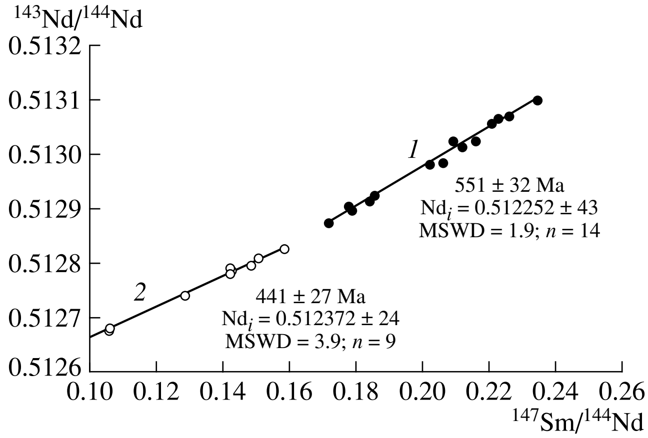

Fig. 3. Sm–Nd isochrons. See text for explanation.

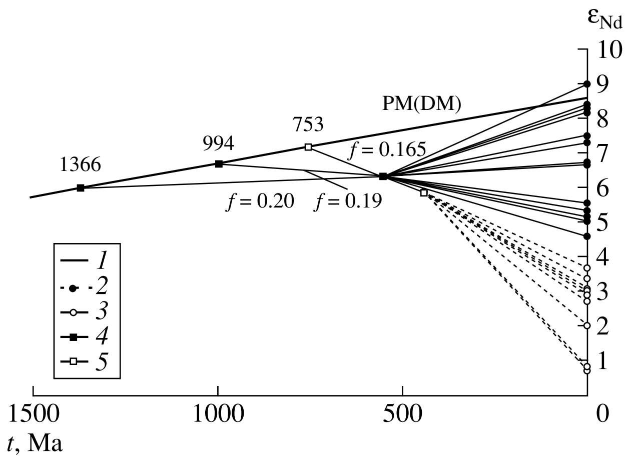

Fig. 4. Evolution of Nd isotopic compositions in coordinates t–ε_{Nd} for rocks and minerals used in the calculation of isochrons (*1*) and (*2*) and the model age of their sources. (*1*) Primitive mantle PM [8] that corresponds to the depleted mantle DM, after [7]; (*2*) points on isochron (*1*) shown in Fig. 3 and corresponding to rock groups *a*–*d*; (*3*) points on isochron (*2*) shown in Fig. 3 and corresponding to rock groups *e*–*h* (Fig. 2); (*4*) lines of evolution for sources of rocks *a*–*d* at different f = $^{147}Sm/^{144}Nd$ values; (*5*) the same for rocks and minerals *e*–*h*. Numerals on line PM (DM) denote model age of sources, Ma

ite, and tylaite were tectonically transported (squeezed) to the present-day denudation level to make up a complex structural assemblage together with still uncooled gabbro (hot melange, after Efimov [1]). They are retained in some places as relict blocks at shoulders of the Late Ordovician–Early Silurian basaltic rifts. One cannot rule out that the vertical extent of the ultramafic rocks in the Kytlym Massif is limited, as was suggested by Ivanov [13] for the Kachkanar Massif, whereas the deep roots of this and other massifs of the Platinum Belt are composed largely of the Silurian gabbro, which also served as the main source of heat for the ductile flow and recrystallization of ultramafics.

The conformable attitude of the Late Vendian–Early Cambrian and Late Ordovician–Early Silurian rocks in the Kosvinsky Block supports the superimposed formation of this structural feature as a single whole.

The question about country rocks that initially hosted the main mass of dunite, clinopyroxenite, and tylaite remains open. It is commonly assumed that the Ordovician volcanic and volcanosedimentary rocks transformed into peculiar banded hornfels (known as "kytlymite" in the Urals) served as the country rocks [1, 5]. However, if the ultramafics are pre-Ordovician rocks, either the protolith of hornfels was older or hornfels were formed as a result of the thermal impact of the Silurian gabbro. The occurrence of dikes and relatively large bodies of gabbroic rocks, which crosscut kytlymite in the Katyshor Range that separates ultramafic rocks of the Konzhakovsky and Kosvinsky blocks (Fig. 1), and some other observations compel us to give preference to the second version.

Deformation and metamorphism of ultramafic and gabbroic rocks of the Platinum Belt were multiple. The last episode probably occurred in the Carboniferous, as follows from the involvement of the Lower Carboniferous sedimentary rocks of the Polar Urals into the thrusting [14]. The Rb–Sr age of pseudoleucite tylaite (340 ± 22 Ma) at Mt. Kosvinsky Kamen [10] is likely a record of this final episode.

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