ISSN 2411-3336; e-ISSN 2541-9404

JOURNAL OF MINING INSTITUTE

Zapiski Gornogo instituta

Journal homepage: pmi.spmi.ru

Research article
UDC 550.93: 551.72 (481-922.1)

Vendian age of igneous rocks of the Chamberlain valley area (Northern part of the Wedel Jarlsberg Land, Svalbard Archipelago)

Aleksandr N. SIROTKIN[1], **Aleksandr N. EVDOKIMOV**[2]✉
[1] *VNII Okeangeologiya, Saint Petersburg, Russia*
[2] *Saint Petersburg Mining University, Saint Petersburg, Russia*

How to cite this article: Sirotkin A.N., Evdokimov A.N. Vendian age of igneous rocks of the Chamberlain valley area (Northern part of the Wedel Jarlsberg Land, Svalbard Archipelago). Journal of Mining Institute. 2022. Vol. 255. p. 419-434. DOI: 10.31897/PMI.2022.20

Abstract. The geological structure, structural relations with the underlying complexes, mineral composition, age and origin of sedimentary-volcanogenic and intrusive formations of the Chamberlain valley area (northern part of the Wedel Jarlsberg Land, Svalbard Archipelago) are considered. As a result of the studies, two stages of the Late Precambrian endogenous activity in this area have been identified. For the first time the Vendian ages (593-559 Ma) of intrusive (dolerites) and effusive (basalts, andesites, tuffs) rocks were determined by U-Pb-method (SHRIMP-II) for Svalbard Archipelago. At the same time, the Grenville ages for large bodies of gabbro-diorites, metadolerites bodies (1152-967 Ma), and metagranites (936 Ma) were determined for the first time for this area, which correlates well with the ages of magmatic formations obtained earlier in the southern part of Wedel Jarlsberg Land. A detailed petrographic and petrochemical characterization of all the described objects were compiled and the paleotectonic conditions of their formation were reconstructed. Based on these data, the Chemberlendalen series, which is dated to the Late Vendian, and the Rechurchbreen series, which the authors attribute to the Middle Riphean and correlate with the lower part of the Nordbucht series are distinguished. The data obtained indicate a two-stage Precambrian magmatism in this area of the Svalbard Archipelago and, most importantly, provide evidence for the first time ever of endogenous activity on Svalbard in the Vendian time. This fact makes it possible to reconsider in the future the history of the formation of folded basement of the Svalbard Archipelago and the nature of the geodynamic conditions in which it was formed.

Keywords: Svalbard; sedimentary-volcanogenic complex; basic magmatism; peridotites; gabbro; metavolcanic; the Vendian; the Middle Riphean; zircon; absolute age

Received: 04.04.2021 ***Accepted: 26.04.2022*** ***Online: 26.07.2022*** ***Published: 26.07.2022***

Introduction. For many decades, the age of the formation of Svalbard folded basement has been considered Caledonian and linked to the time and processes of the Scandinavian Caledonian formation [1-3]. Nevertheless, continuously, since the last third of the twentieth century, some authors, based on different materials, have argued for an earlier consolidation of this crust block [4-6]. Lately [7, 8] they have shown that the structural paragenesis of the Wedel Jarlsberg Land (WJL) Upper Cambrian complexes and adjoining areas of the archipelago is very similar to that of the Protouralian-Tymanian complexes of the Polar Urals and southern part of the Novaya Zemlya Archipelago. The apparent discrepancy in the spatial orientation of this paragenesis with the strike of the assumed Scandinavian Caledonian front continuation on the Barents Sea shelf [9, 10] suggests that the rock complexes of Svalbard folded basement are not Caledonian but represent a northwestern extension of the Protouralian-Tymanian complexes. Thus, there are strong grounds to suggest that the structure of ancient Svalbard folded basement contains both different-aged Early Precambrian and Grenvillean structural-compositional complexes [11, 12] and later Baikalian (or Protouralian-Timanian).

 DOI: 10.31897/PMI.2022.20

Figure 1. Svalbard Archipelago and work area – Chamberlain Valley area in the north of Wedel Jarlsberg Land (WJL)

At the same time, the absence of specific geological bodies of this age on the archipelago, primarily magmatic, does not allow to construct complete tectonic schemes. It should be also noted that there are conglomerate beds dating to the Vendian age and identified as metatillites in the main distribution areas of the Late Precambrian complexes in Svalbard [13-15]. The presence of this formation allowed B.P.Barkhatov [16] to describe for the first time Svalbard as an Epibaikal orogenic area.

Statement of the problem. The geological structure, petrological features, and age of the magmatic formations of the Chamberlain valley region in the northern part of WJL of the Svalbard Archipelago remain poorly understood to date. This work is a new attempt to determine the general sequence of Late Precambrian magmatism in the area and to clarify its geological structure.

The Wedel Jarlsberg Land is one of the key areas of the Svalbard Archipelago, which has been used as an example to form a modern view of the geological structure of the folded basement of the region. In the north of this area (Fig.1), Late Precambrian volcanogenic-sedimentary formations are exposed to the surface, hosting comagmatic intrusions, and overlapping them with a structural unconformity of Late Paleozoic and younger sediments [17-19]. The Late Precambrian complexes are dislocated into a series of large conjugate folded forms (Fig.2).

Within the folded basement, the Middle Riphean Verenscheldbreen complex (> 3 km thick), the Upper Riphean Sofiebogen series (> 3 km thick), and the Vendian Kapp Lee series (4 km thick) have been previously identified. There is a structural unconformity between the Middle and Upper Riphean stratones [20], and there is also an unconformity between the Upper Riphean and Vendian horizons. The strata age is confirmed by paleontological finds [21] and studies of detrital zircons [22-24]. An important specific feature of the area is that the structural-geological information obtained here allows us to identify mesostructural parageneseses in Upper Precambrian complexes oriented at a high angle to the structures of Precambrian blocks, which are known in the north of the archipelago and are defined as Caledonian. These materials have allowed several researchers to identify here the Late Precambrian stage of tectogenesis – Baikalian or Timanian-Protouralian [7, 17], but it has not been confirmed by isotopic dating of magmatic or metamorphic objects.

S.I.Turchenko and co-authors [17] have attributed the magmatic formations of the Chamberlain valley area to the single basalt-trachyandesitic formation of the Early Riphean. The geological map [19] shows these rocks as Late Proterozoic. A.M.Tebenkov [2] had the same opinion. Later, Middle Riphean isotopic dating was obtained for magmatic complexes of the southern part of WJL [25-27], and, accordingly, their formation period was attributed to the Middle Riphean [11]. Absolute ages of magmatic rocks in the northern part of WJL have not been determined by anyone until recently. At the same time, the dating of magmatic rocks in other areas of Svalbard should be noted: zircons in granites composing boulders in the Vendian conglomerates of the Nordenscheld Land (50 km to the north of the WJL), are dated at 656 Ma [28]; pegmatites from the Lower Riphean rocks in the southern part of the WJL contain zircons with ages of 615 Ma [24]. So far, this is the most reliable data proving the possibility of the Vendian endogenous processes on Svalbard. Importantly, the Polish geologists [29] suggested that the age of magmatic events in the northern part of the WJL could be about 600 Ma.

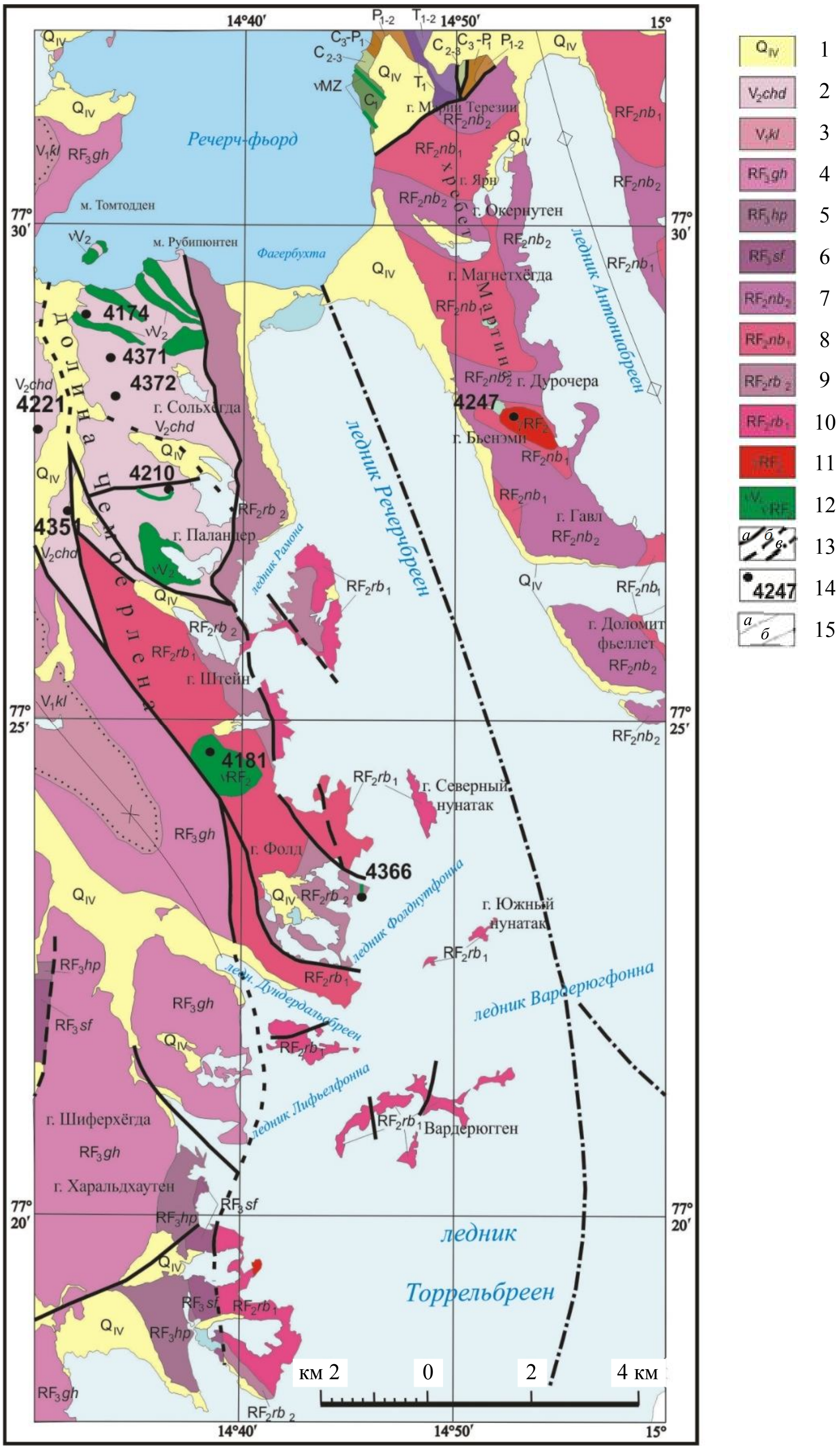

Fig.2. Scheme of the geological structure of the Chamberlain Valley area and its surroundings

1 – Quaternary deposits; 2-3 – Vendian series (2 – Chemberlendalen (metavolcanics, phyllites, quartzites, limestones), 3 – Kapp Lee (conglomerates, sandstones, limestones); 4-6 – Upper Riphean, Sofiebogen series (formations: 4 – Goshamna (phyllites, quartzites), 5 – Heferpünten (marbleised limestones and dolomites), 6 – Slungfjellet (conglomerates, sandstones, limestones); 7-11 – Middle Riphean, Verenscheldbreen complex (upper (7 – marble, quartzite, schist) and lower (8 – quartzite, schists) strata of the Nordbuchta series, carbonate (9 – marble, greenstone) and terrigenous (10 – conglomerate, schist, greenstone) strata of the Rechurchbreen series) 11 – granites of the Martin Ridge (RF$_2$); 12 – metagabbroids (RF$_2$) and dolerites, Chemberlendalen ultrabasites (V$_2$); 13 – tectonic faults (*a* – reliable, *b* – inferred, *c* – inferred under glaciers); 14 – sampling points for dating; 15 – axes of the main structures of the area (*a* – anticlines, *b* – synclines). Rocks of the platform cover in the northern part of the scheme are shown with commonly used indices

Our work resulted in the first isotopic dating of volcanic and intrusive rocks of the Chamberlain Valley and its surroundings, which provided the basis for a new scheme of stratigraphic dissection of the Precambrian complexes of the area.

The overall structure of the Late Precambrian complexes in the northern WJL is characterized by a combination of three major folded forms, the Nordbuchta and Antoniabreen anticlines, and the Kapp Lee syncline separating them (Fig.2); the structures have a NW hinge strike. This fact points to the formation of the Late Precambrian complex structure under the compression conditions in the SW-NE direction with the general direction of tectonic motion to the NE [7].

A trough with the Vendian conglomerates is located in the Kapp Lyell syncline. To the east of the trough, the Chemberlendalen valley reveals a sedimentary-volcanogenic complex with intrusions of the basic-hyperbasic formation. The area of the Chemberlendalen and the adjacent parts of the Rechurchbreen and Antoniabreen glaciers is a junction of the anticline and syncline (Fig.2). The oldest rocks here are the rocks of the Verenscheldbreen complex, represented in the north of the WJL by the Rechurchbreen (> 1.5 km) and Nordbucht (> 2 km) series. The outcrops of the Rechurchbreen series are observed in the west face of the glacier of the same name, as well as in the southern part of the Chamberlain valley. The series is composed of conglomerates, gravelites, *Ser-Chl* schists, and piles of greenstones at the bottom; at the top, marbles with interlayers of schists and metavolcanics. The sides of the Antoniabreen Glacier are composed of sediments of the Nordbucht series (phyllites, quartzites, microgneisses, greenstones, and dolomites). The age of rocks of the Verenscheldbreen complex in the north of the WJL is determined, among others, by the age of the metamagmatic rocks intruding them (1187-936 Ma) and, when using materials from the southern part of the WJL, by a younger age – 1150-950 Ma [26, 27].

The Sofiebogen Series (RF_3) is exposed at the base of the west face of the Chamberlain Valley. Here they are represented by the upper Goshamn Formation (~2 km), which is composed of phyllites with interlayers of quartzite; the lower formations of this series, the Slungfjellet (conglomerates, up to 600 m) and Heferpünten (marbles, 500 m – with angular unconformity, overlie the Nordbucht Series outcrop). There is a clear structural unconformity between the Vendian conglomerates of the Kapp Lee series and the underlying phyllites of the Goshamn Formation.

The northern part of the Chamberlain valley is composed of a thick sedimentary-volcanogenic sequence of the Chemberlendalen series (~2 km), comprising volcanogenic rocks, phyllites, quartzites, limestones with conformable bodies of peridotites and dolerites. The sequence forms a northwest-trending syncline tilted northeastward. It is separated by discontinuities from the rocks of the Rechurchbreen series to the east and south and from the Goshamn Formation to the west. The age of the magmatic rocks of the Chemberlendalen series, based on absolute dating, has been determined by the authors of the article as Late Vendian (593-559 Ma).

Methods. Magmatic formations in the Chamberlain Valley and adjacent areas have been studied. Ten geochronological samples were taken from these rocks (Fig.2), each weighing about 5 kg. After crushing and sieving the samples, the heavy non-magnetic fractions, which contained zircon, were separated using electromagnetic separation and heavy fluids. Zircon monofractions were sampled at VSEGEI Central Laboratory, and their isotopic composition was analyzed at the Isotope Centre at VSEGEI. The zircons were aged by the local U-Pb method using the SHRIMP II ion microprobe under the standard procedure [30]. Optical (transmitted and reflected light) and cathodoluminescence (CL) images of zircon grains were used to select zircon dating points. The concentrations of elements in rocks and minerals from the samples taken by the authors were obtained at the VSEGEI Central Laboratory by X-ray fluorescence, microprobe, and ICP-MS analyses. When constructing the spectra of REE distribution their quantity was normalized to the content in chondrite CI [31]. Symbols of rock-forming minerals according to [32] are used in this work.

Results. The magmatic rock compositions of the Chamberlain Valley, the western side of the Recherche Glacier, and the Martin Ridge have been studied (Fig. 2, Tables 1-6).

For the first time *granite intrusion of Martin Ridge* [21] on Mount Bienemi was discovered and mapped. It is a tectonic remnant of granitoids with a total area of about 2 km^2 and a thickness of 150-200 m, lying flat (15-20°) with a slope to the west and NW. The plate is pushed on a folded phyllite sequence with interlayers of quartzites and greenstones, which has a NW strike and rock dip angles up to 30-40°. In the contact zone, granites are mylonitized and represented by fine-grained schistose *Bt-Ms-Qz-Kfs* rocks with small pink porphyroblasts. Among the rocks of the mylonitization zone, granitoid relics in the form of lenses of various sizes are constantly found.

Table 1

Chemical composition of Middle Riphean igneous rocks, wt.%

Components	Gabbroids of Fold Mountain and its surroundings					Martin Ridge granites	
	4181-3	4181-4	4366-5	4352-4	4355-4	4247-1	4332-1
SiO_2	43.20	52.10	44.10	46.80	47.10	59.10	68.60
TiO_2	4.26	2.14	2.89	5.62	5.47	0.92	0.46
Al_2O_3	13.60	18.20	9.05	13.70	13.60	15.50	14.20
Fe_2O_3	2.26	3.26	3.10	4.10	4.12	2.58	1.70
FeO	11.10	6.94	11.20	10.20	9.28	3.84	1.64
MnO	0.18	0.15	0.19	0.22	0.17	0.09	0.081
MgO	4.64	2.60	14.20	5.45	4.36	3.25	1.10
CaO	8.84	2.56	10.10	5.55	7.28	4.43	2.13
Na_2O	3.01	5.49	1.04	3.45	4.28	3.44	4.12
K_2O	0.061	2.69	1.59	1.52	1.39	3.14	3.66
P_2O_5	0.71	0.59	0.45	0.68	0.54	0.17	0.11
LOI	6.96	2.43	2.09	2.75	2.51	2.94	2.44
Summary	98.821	99.15	100.00	100.00	100.00	99.40	100.00
CI	12.6	9.50	3.12	7.54	9.11		
K_f	77.2	79.7	50.2	72.41	75.44		
F	0.17	0.32	0.22	0.29	0.31		
MgO*	0.26	0.21	0.50	0.28	0.25		
SI	22.0	12.4	45.6	22.04	18.62		

Note. CI – contamination index; K_f – fractionation factor; F – iron oxidation factor; MgO* – magnesia index; SI – Cuno solidification index.

Table 2

Trace element composition of Middle Riphean igneous rocks, ppm

Elements	4181-3	4181-4	4366-5	4352-4	4355-4	4247-1	4332-1
Ba	48.7	1130	383	792	638	827	586
Sr	332	242	134	314	551	304	123
Rb	1	47.6	34.6	13	15.7	128	100
Nb	42.8	101	24.7	31.5	22.6	12.5	17.2
Zr	267	544	230	309	278	216	248
Hf	3.52	12.3	6.01	8.86	7.79	5.37	6.92
Th	0.92	8.08	1.36	1.06	0.92	8.62	19.3
Ga	22.5	29	15.4	20.9	21.1	19.5	18.2
La	31.9	98.5	20.5	20.1	17.6	41.2	71.6
Ce	76.4	192	48.9	58.3	47	80.2	132
Pr	11.1	23.6	6.65	8.57	6.77	9.94	12.6
Nd	52.3	87.8	33.1	43.2	35.7	35.4	42.1
Sm	11	15	7.46	10.1	9.14	6.87	5.92
Eu	3.86	5.6	2.48	3.59	2.9	1.6	1.33
Gd	10.5	12.9	5.96	9	8.23	6.59	4.92
Tb	1.53	1.83	0.88	1.46	1.32	1.01	0.78
Dy	7.63	9.28	4.37	7.24	6.75	5.58	3.7
Ho	1.41	1.85	0.8	1.24	1.25	1.18	0.68
Er	3.64	4.76	1.84	3.23	3.22	3.27	2.14
Tm	0.45	0.71	0.25	0.42	0.45	0.53	0.32

DOI: 10.31897/PMI.2022.20

End of Table 2

Elements	4181-3	4181-4	4366-5	4352-4	4355-4	4247-1	4332-1
Yb	2.48	3.81	1.53	2.58	2.77	2.79	2.38
Lu	0.39	0.58	0.19	0.36	0.35	0.47	0.3
Y	36	45.9	20.8	35	34.3	32.1	20.8
V	303	30.6	210	333	298	136	39.1
Cr	115	57.1	749	90.1	43.3	105	47.6
Co	86.2	35.1	73.5	67.9	34.1	27.7	5.94
Ni	39.6	4.31	436	47.7	24.9	21.4	11.2
Cu	31.2	5.06	98.5	34.8	13.3	37.5	6.34
Sc	25.9	9.57	31.6	50.1	26.6	15.9	6.17
U	0.32	3.95	n.d.	n.d.	n.d.	2.01	n.d.
TR	214.59	458.20	134.91	169.39	143.45	196.63	280.77
$(La/Sm)_n$	1.87	4.24	1.78	1.29	1.24	3.87	7.81
$(Gd/Yb)_n$	3.51	2.81	3.23	2.89	2.47	1.96	1.71
$(La/Yb)_n$	9.22	18.55	9.61	5.37	4.56	10.59	21.58
Eu/Eu*	1.10	1.23	1.14	1.15	1.02	0.5	0.51

According to their characteristics (Tables 1-2) granitoids correspond to moderately alkaline granodiorites and diorites (Fig.3). Petrochemical coefficients allow us to attribute them to the group of moderately alkaline and partially high aluminous rocks. The amounts of REE are low, and the degree of differentiation of light REE is higher than that of heavy REE. A prominent Europium minimum is clearly visible. Such trends of REE distribution are typical for the parental magmas of the deep origin connected with magmatic sources in the lower crust. The composition of the rocks indicates a weak differentiation of initial magma, which is reflected in its enrichment with light REE and depletion of Eu. The moderately alkaline type of the melt and other characteristics suggest its formation in intraplate conditions in the interval of the lower crust boundary horizons with the mantle.

Sample 4247-1 is a cataclased granitoid on Mountain Bienhami. Nine of the twelve points obtained gave a concordant age of 937±7 Ma. A discordant age (upper intersection) of 936±13 Ma (Greenville Stage) was also obtained. This age can be attributed to the magmatic stage of intrusion formation.

The group of gabbroids (*RF_2*) was identified by the authors of this article based on petrographic characteristics [33, 34] and isotopic dating obtained. The rocks of this group compose concordant bodies of varying thickness (from 10-15 to 60 m) among the *Ser-Chl* schists and dolomites of the Rechurchbreen series (see Fig.2). They are all localized in the southern part of the Chamberlain valley and on the western side of the Rechurchbreen glacier. Two bodies were sampled on the slopes of the Mountain Fold. The first one in outcrop 4181 is more than 40 m thick and is conformably deposited among shales, with hardening zones up to 1-1.5 m in the lower exocontact. A clear differentiation of rock composition

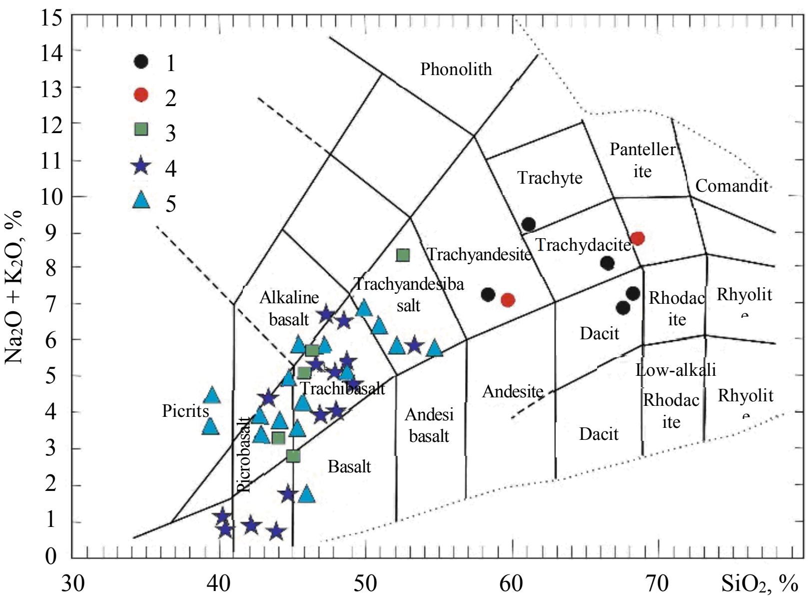

Fig.3. $Na_2O + K_2O$ – SiO_2 diagram for chemical classification of igneous rocks of the Chamberlain Valley region and its vicinity

1-2 – granitoids of the Martin Ridge (1 – according to S.I.Turchenko et al. [24]; 2 – according to authors); 3 – Middle Riphean gabbroids; 4-5 – Vendian magmatites (4 – intrusive 5 – volcanics) is observed: the lower half of the body is composed of gabbro (sample 4181-3) and in the center, gabbro-diorite (sample 4181-4), which is confirmed petrographically and by petrochemical data. The second gabbroid body (outcrop 4366) conformably lies among metamorphosed dolomites and is up to 30 m thick. It is a heavily altered basic rock with relics of a gabbroic structure.

These gabbroids have *Act-Ab-Chl* composition, *Cpx* relicts are present in amounts from 3-5 to 40-50 %, *Pl* up to 10-15 %. *Bt* and *Kfs* may present in small quantities, which makes it possible to define some varieties as monzogabbro. At a weak degree of alteration, the newly formed paragenesis is represented by *Ab* and *Chl*; at a higher stage of transformation, *Act*, *Chl*, *Ab*, *Ep*, and *Spn* appear.

The gabbroids correspond to picrobasalts, trachybasalts, and trachyandesibasalts in composition (Figure 3) and belong to tholeiitic rocks. They are sodic and potassic-sodic in alkalinity, moderately potassic, and moderately aluminous in potassium content. These rocks are typified by a lower iron oxidation factor (up to 0.17 %) and high K_f (up to 79.7), which indicates that the parental magma was formed at depth and is less water-impregnated. The value of the Cuno SI index (45.6-12.4) of gabbroids indicates deep differentiation of the parental magma.

Magma differentiation is reflected in the variability of trace element contents: Cr, Ni, V, Cu, and Sc successively decrease, and Zr, Hf, Ga, Nb, Sr, and Y increase. Total REE content in these rocks is low (135-458 ppm), with the lowest amount in metabasic of 4366 outcrop and the highest in gabbro-diorites. The nature of REE fractionation, determined by the values of $(Gd/Yb)_n$, $(La/Sm)_n$, $(La/Yb)_n$, is also maximum for gabbro-diorites, whereas in gabbro it does not change noticeably, being at the same level. The Eu/Eu* ratio is positive. The distribution of REE normalized to chondrite is uniform, the largest deviations are characteristic for gabbro-diorites by light REE content. According to the recommendations [33, 34], gabbroids are attributed to intraplate continental formations, formed in continental rifting conditions.

By analogy with the gabbroids known in the south of WJL [26, 27], the age of the magmatic rocks studied by the authors of this paper is considered to be Middle Riphean, which is confirmed by new data.

Sample 4181-4 is represented by gabbro-diorites. The rocks are weakly metamorphosed. The concordant age obtained by *Zrn* from these gabbro-diorites was 967±6 Ma (Fig.4, Table 6). The new result is in good agreement with the ideas about the Grenville tectonic-magmatic and tectonic-metamorphic events, which occurred on Svalbard 1150-950 million years ago [1, 35].

Sample 4366-5 is an altered basic rock with relicts of a gabbroic structure, allowing it to be classified as a metagabbroid. The *Zrn* sampled from the metabasites yielded a range of ages between 1611 and 858 Ma; most dates are grouped within the 1162-1026 Ma interval, and the concordant age of 1152±11 Ma is calculated from them. This corresponds to the age of the gabbroids in the southern part of the WJL – 1156-1154 Ma [26] and also provides information on the age of the Rechurchbreen series.

The Late Vendian hyperbasic-basic rocks have been encountered and studied in the northern part of the Chamberlain valley. Previously, rocks of this complex were described in detail and, together with the host volcanics, were classified as a single basalt-trachyandesitic series [17]. The thickness of intrusions can exceed 50-60 m. The intrusions are in constant association with metavolcanics of the basic composition. The metavolcanic rocks could be host rocks for the intrusives. Rocks of the complex have experienced regional metamorphism of the greenschist facies.

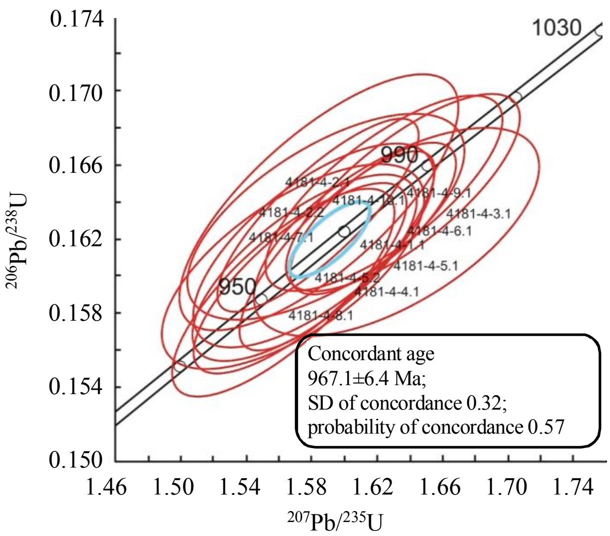

Fig.4. Concordia diagram for zircons from gabbro-diorites (sample 4181-4, n = 12)

The complex includes *Bt* wehrlites, metaperidotites, metapyroxenites, and metagabbroids. The host volcanogenic rocks of the Chemberlendalen series include metabasalts, metapicrites, metaandesites, and metatufs.

Table 3

Chemical composition of the Vendian intrusive rocks of the Chamberlain Valley, wt.%

Components	Biotitic wehrlite		Peridotite	Metapiroxenite			Dolerite		Gabbro-dolerite			Metagabbro		
	4151-1	4187-2	4187-3	4213-3	4174-4	4189-2	4174-1	4174-3	4210-2	4186-1	4189-1	4188-1	4214-1	4187-4
SiO_2	39.30	38.1	38.40	42.80	44.70	47.00	49.20	53.3	48.50	47.9	48.60	48.00	48.00	48.40
TiO_2	1.22	1.36	1.18	5.79	1.33	2.95	2.18	1.60	2.18	3.81	2.66	3.17	2.97	2.74
Al_2O_3	6.80	5.76	4.95	11.90	10.10	14.00	14.50	15.50	11.80	16.80	15.30	15.30	11.90	16.30
Fe_2O_3	7.83	6.05	4.45	2.55	1.91	1.99	1.66	1.48	1.97	2.47	3.29	1.46	1.79	2.43
FeO	4.06	6.49	6.64	10.00	10.3	8.71	9.15	6.05	8.27	7.23	6.94	8.12	7.75	7.97
MnO	0.15	0.15	0.12	0.16	0.19	0.17	0.15	0.16	0.15	0.13	0.14	0.16	0.15	0.18
MgO	24.70	27.20	26.00	5.77	16.00	8.43	8.81	5.29	9.39	4.03	5.56	6.77	8.64	7.26
CaO	7.85	3.09	4.44	11.70	8.28	6.56	5.70	8.28	9.83	5.99	9.07	6.11	11.10	4.76
Na_2O	0.17	0.05	0.05	3.36	1.34	2.46	4.11	5.19	3.22	4.85	3.30	3.03	2.75	4.70
K_2O	0.85	0.74	0.64	1.08	0.21	2.58	0.33	0.54	0.67	1.90	1.82	3.25	1.00	0.14
P_2O_5	0.26	0.34	0.27	0.51	0.25	0.88	0.23	0.28	0.29	1.22	0.69	0.87	0.54	0.71
LOI	6.08	9.38	11.8	2.96	4.01	2.89	2.81	1.67	2.82	2.70	1.84	2.42	2.41	3.51
Summary	99.27	98.71	98.94	98.58	98.62	98.62	98.83	99.34	99.09	99.03	99.21	98.66	99.00	99.10
CI	1.75	1.53	1.59	7.34	3.42	4.68	7.17	11.6	5.93	8.90	7.30	5.00	5.9	9.20
K_f	32.5	31.6	34.0	68.5	43.3	55.9	55.1	58.7	52.2	70.7	64.8	58.6	52.5	58.9
F	0.66	0.48	0.60	0.20	0.16	0.19	0.15	0.20	0.19	0.26	0.32	0.15	0.19	0.23
MgO*	0.69	0.70	0.71	0.32	0.57	0.45	0.45	0.42	0.48	0.30	0.36	0.42	0.48	0.42
SI	65.7	67.1	68.8	25.4	53.8	34.9	36.6	28.5	39.9	19.7	26.6	29.9	39.4	32.3

Table 4

Trace elements composition of the Vendian intrusive rocks of the Chamberlain valley, ppm

Elements	4151-1	4187-2	4187-3	4213-3	4174-4	4189-2	4174-1	4174-3	4186-1	4210-2
Ba	462	303	368	707	135	2270	165	253	1010	735
Sr	239	264	381	411	121	1330	170	305	1040	650
Rb	25.5	24.9	20.8	30.2	5.78	30.9	4.61	6.49	15.5	4.17
Nb	28.6	31.2	27	21.1	14.9	55	12.8	16.7	85.9	21.8
Zr	133	158	136	250	130	415	130	128	653	129
Hf	3.52	4.11	3.43	7.41	3.26	9.74	3.7	3.31	14.5	3.49
Th	2.53	2.49	1.97	0.88	1.11	3.8	0.77	1.08	6.12	1.22
Ga	12.6	12.6	10.9	21	14.5	25.3	20.4	18	28.5	19.3
La	24.9	30.2	24.3	21.1	15.5	63.3	12.5	15.4	81.5	16.8
Ce	48.8	61.6	47.7	56.8	33	136	31.7	33.9	178	38.9
Pr	6.08	7.62	5.73	8.98	4.4	18.1	4.97	4.7	23.8	5.67
Nd	26.2	30.4	22.9	43	19.7	72.1	23.7	20.3	98.9	25.1
Sm	5.3	6.13	5.05	9.48	4.5	13.6	5.23	4.45	18.9	5.65
Eu	1.87	2.09	1.37	3.33	1.66	5.1	1.96	1.79	6.02	2.01
Gd	4.36	5.1	3.9	8.98	4.59	11.7	5.51	4.68	14.4	5.86
Tb	0.6	0.79	0.57	1.24	0.64	1.64	0.86	0.67	2.08	0.9
Dy	2.76	3.3	2.62	6.04	3.36	7.59	4.54	3.7	9.56	4.72
Ho	0.53	0.62	0.53	1.11	0.73	1.29	0.91	0.7	1.72	0.89
Er	1.27	1.34	1.14	2.78	1.66	3.24	2.37	1.78	4.01	2.29
Tm	0.14	0.19	0.14	0.34	0.25	0.37	0.28	0.24	0.56	0.32

End of Table 4

Elements	4151-1	4187-2	4187-3	4213-3	4174-4	4189-2	4174-1	4174-3	4186-1	4210-2
Yb	1.02	1	0.62	2.01	1.31	2.29	1.76	1.46	2.96	1.86
Lu	0.13	0.17	0.13	0.3	0.21	0.34	0.29	0.21	0.39	0.24
Y	13.6	15.3	12	29.1	17.2	34	22.7	18.8	43	24.3
V	198	206	179	427	164	220	240	182	216	261
Cr	2090	2540	2070	150	867	333	326	341	62.8	406
Co	105	115	103	99.9	88.4	68.9	63.5	44.2	67.7	72.2
Ni	896	1140	1120	50.4	472	134	166	84	19	223
Cu	52.1	28.5	47	19.3	63.7	25.3	36.7	6.13	43.3	69.6
Sc	20.8	17.1	17.4	32.6	20.1	18.7	25.5	23.7	9.3	25.3
U	0.71	0.76	0.65	0.28	0.36	1.37	0.32	0.33	2.22	0.34
TR	123.9	150.55	116.7	165.49	91.51	336.96	96.58	93.98	442.80	111.21
$(La/Sm)_n$	3.03	3.18	3.11	1.44	2.22	3.02	1.54	2.23	2.78	1.92
$(Gd/Yb)_n$	3.55	4.23	5.21	3.71	2.90	4.24	2.60	2.66	4.03	2.61
$(La/Yb)_n$	17.51	21.67	28.09	7.53	8.48	19.92	5.10	2.85	19.75	6.48
Eu/Eu*	1.19	1.14	0.94	1.10	1.12	1.24	1.12	1.20	1.11	1.07

Gabbroids are the most common rocks in this complex. They are medium-grained varieties consisting of *Cpx* and *Pl*, with *Ilm* and *Mag*, *Py,* and *Ap* present (up to 10 %). *Cpx* is represented by salite with 60-75 % *Di* minal; *Aug*, enriched in Fe and Ti, is also noted in these rocks. Primary minerals are partially replaced by metamorphosed minerals: *Act*, *Chl*, *Ab* (N 0-7), *Ep*, *Ch*, *Spn.* Among *Amp*, along with metamorphogenic *Act*, kaersutite is noted. Rock structures change from ophitic to gabbroic, therefore dolerites and gabbro-dolerites can be distinguished.

Peridotites are distinguished by their black color, fine-grained structure, and massive appearance. They are attributed to the wehrlite group: they consist of *Cpx* and *Ol*, with constantly associating chromspinel, brownish *Hbl,* and *Bt*. Peridotites are metamorphosed: *Srp*, *Chl*, *Act*, *Cal*, and *Tlc* are noted. *Mag*, *Cr-Ti-Mag*, *Ilm,* and sulphides *Po*, *Py*, *Ccp*, *Pn* are permanently present. Microprobe analysis indicates that *Cpx* is represented in these rocks by *Di* (ferruginicity within 10-23 %) with increased, up to 5-6 %, Al_2O_3 content and the constant presence of small amounts of Cr, Ti, Mn. *Bt* is present in two generations. The early, magmatic generation, is *Phl* with ferruginicity in the range of 21-30 %, as well as high Ti content (0.33-0.48 f.u.) and low Al^{VI} (0 to 0.19 f.u.). The late biotite generation is metamorphogenic and is represented by annite with ferruginicity 64-66 % and high Al^{VI} (0.41-0.46 f.u.) and low Ti (0.03-0.05 f.u.). Chromspinels are characterized by a variable amount of Cr_2O_3 (from 5-13 to 40-41 %) and the constant presence of Fe, Al, Ti, and Mn; half of the studied grains lack Mg. The grains of this mineral are often zonal: the core is represented by chromspinel, and the periphery of the grain is pure *Mag.* Primary *Amp* is represented in metaperidotites by magnesio-hornblende with ferruginicity 25-30 %, where a part of Ca is substituted by K (up to 0.25 f.u.), and Si content is 6.15-6.25 f.u. This *Amp* is also characterized by a high content of Ti and Al. Metamorphogenic *Amp* is represented by *Act* with high magnesia.

Metapyroxenites differ from metaperidotites only petrochemically; in thin sections, they contain the same set of metamorphogenic minerals, and the primary minerals, *Cpx* and *Bt,* are preserved everywhere. The only difference is the appearance in metapyroxenites of *Ab*, evolving by *Pl*.

All the described rock types have been petrochemically characterized previously [17] as basic and ultrabasic varieties of normal alkalinity, as well as alkaline basic and alkaline-ultrabasic varieties. They, in turn, form a single comagmatic series with alkaline and normally alkaline ultrabasic and basic volcanics of the Chemberlendalen series. Tables 3-6 present the petrogenic and trace element compositions of the meta-intrusive and meta-effusive rocks from the Chamberlain valley area.

DOI: 10.31897/PMI.2022.20

Table 5

Chemical composition of metavolcanic rocks of the Chemberlendalen series, wt.%

Components	Basic tuffs			Basalts and trachybasalts						Picrobasalts		Andesibasalts and trachyandesites				
	4174-18	4164-4	4372-1	4164-5	4174-7	4191-1	4211-2	4212-4	4213-4	4164-1	4221-1	4174-10	4174-11	4211-1	4351-1	4371-1
SiO_2	43.30	34.50	45.40	44.80	41.50	49.00	45.50	43.00	47.80	39.70	37.20	51.30	39.60	46.00	49.30	45.40
TiO_2	3.86	3.87	3.52	2.38	1.06	3.48	3.10	3.91	2.91	4.01	2.96	2.49	2.97	3.54	3.36	3.52
Al_2O_3	17.20	13.10	13.10	16.20	8.53	14.30	11.70	11.90	14.70	14.20	11.40	16.30	13.50	17.40	15.40	13.10
Fe_2O_3	2.96	2.02	3.60	1.25	5.16	2.61	2.37	2.14	1.98	0.30	4.56	2.08	1.32	1.98	3.06	3.60
FeO	11.70	7.63	5.58	8.86	6.20	9.22	9.59	10.60	9.00	9.56	5.68	8.12	8.12	9.37	9.44	5.58
MnO	0.11	0.20	0.22	0.17	0.15	0.14	0.16	0.18	0.13	0.21	0.18	0.077	0.32	0.091	0.14	0.22
MgO	8.58	6.72	4.60	4.19	15.70	6.70	11.50	10.90	8.24	5.94	7.13	4.04	4.69	5.96	6.36	4.60
CaO	1.46	14.30	9.76	7.64	7.24	6.09	8.21	8.92	5.63	16.30	14.30	3.93	12.40	3.82	3.70	9.76
Na_2O	3.65	3.16	5.08	4.34	0.86	4.38	2.36	1.74	3.48	4.34	1.07	5.04	3.92	3.64	4.13	5.08
K_2O	0.23	0.20	0.82	0.56	0.38	0.50	1.09	1.54	1.68	0.25	1.70	0.30	0.29	2.58	0.94	0.82
P_2O_5	0.88	1.02	1.39	0.89	0.21	0.37	0.52	0.69	0.44	0.96	1.05	0.87	0.81	0.96	0.66	1.39
LOI	4.89	12.30	6.84	7.74	12.10	2.20	2.74	2.93	2.90	4.12	11.50	4.64	11.00	3.56	3.51	6.93
Summary	98.82	99.02	99.91	99.02	99.09	98.99	98.84	98.45	98.89	99.89	98.73	99.19	98.94	98.90	100.00	100.00
CI	7.09	7.13	10.2	12.32	3.09	8.78	4.36	4.05	5.69	9.05	4.72	15.65	10.82	6.03	8.36	18.57
K_f	63.1	59.0	66.64	70.7	42.0	63.8	51.0	53.9	57.1	62.4	59.0	71.7	66.8	65.6	66.3	74.28
F	0.20	0.21	0.39	0.12	0.45	0.22	0.20	0.17	0.18	0.03	0.45	0.20	0.14	0.17	0.25	0.17
MgO*	0.37	0.42	0.34	0.30	0.59	0.37	0.50	0.47	0.43	0.38	0.42	0.29	0.34	0.35	0.34	0.26
SI	31.6	34.0	23.36	21.8	55.5	28.6	42.7	40.5	33.8	29.1	35.4	20.6	25.6	25.3	26.6	17.8

Table 6

Trace element composition of metavolcanic rocks of the Chemberlendalen series, ppm

Elements	4174-18	4164-4	4372-1	4164-5	4174-7	4191-1	4211-2	4212-4	4164-1	4351-1
Ba	109	59.8	112	147	71.9	272	426	960	170	372
Sr	125	535	359	334	491	753	468	469	189	428
Rb	2.27	2.2	17.1	18.5	2.27	6.68	22.6	24	17.4	17.1
Nb	45.7	49.1	44.3	55.7	44.8	14.2	26.2	34	13.7	32.8
Zr	365	410	531	459	373	169	297	300	119	358
Hf	9.66	9.84	3.2	12.9	8.89	4.81	6.89	7.28	3	9.26
Th	2.54	3.09	2.5	6.79	2.76	0.54	1.7	1.92	1.06	1.97
Ga	33.4	17.9	23.2	25.9	16.8	21.4	19.8	20.7	13.5	27.1
La	49.8	42.9	49.2	49.9	35.1	12.7	26	33.9	12.1	29.4
Ce	109	103	110	111	82.8	34.1	63.7	80	27.5	71.4
Pr	14.8	15.2	16.5	15.3	11.8	5.43	9.77	12.1	3.9	9.6
Nd	65.4	37.2	75	67.2	55.9	27.5	44	54.2	17.9	44.6
Sm	14.2	15.4	14.1	13.4	12.2	6.93	9.51	11.3	3.81	9.99
Eu	3.76	4.45	4.35	3.25	3	2.84	3.32	4.04	1.36	3.14
Gd	11.7	13.8	10.8	11.5	11.1	6.89	8.85	10.8	3.86	8.16
Tb	1.75	1.75	1.49	1.39	1.51	1.13	1.29	1.51	0.62	1.28
Dy	8.31	8.47	6.89	7.33	7.24	5.68	6.2	7.19	2.83	6.48
Ho	1.56	1.48	1.19	1.39	1.27	1.14	1.09	1.3	0.58	1.1
Er	3.58	3.4	3.09	3.53	2.93	2.66	2.86	3.14	1.48	3
Tm	0.44	0.4	0.37	0.42	0.4	0.34	0.36	0.44	0.22	0.4
Yb	2.36	2.27	2.24	2.88	1.98	2.06	2.11	2.34	1.21	2.46
Lu	0.36	0.33	0.27	0.36	0.28	0.31	0.28	0.32	0.19	0.36
Y	38	37.4	375	35.6	32.1	28.3	30	34.7	15.1	31.1
V	284	248	201	141	219	268	251	296	144	223
Cr	284	356	174	95.1	316	62.5	631	428	914	248
Co	81.7	62.1	28.2	32.8	72.3	77.2	101	107	86	34.6
Ni	162	202	95.1	61.3	179	37	306	199	500	98

End of Table 6

Elements	4174-18	4164-4	4372-1	4164-5	4174-7	4191-1	4211-2	4212-4	4164-1	4351-1
Cu	18.9	50.7	38.6	27.8	47.7	15.1	81.6	39.3	59.9	16.7
Sc	20.8	19.1	12.8	9.07	16.1	27.6	27.5	28.4	16.9	23.2
U	0.37	1.02	n.d.	2.07	1.03	0.2	0.58	0.55	0.29	n.d.
TR	287.02	286.05	295.49	288.85	227.51	109.71	179.34	222.58	77.56	191.37
$(La/Sm)_n$	2.26	1.80	2.25	2.40	1.86	1.18	1.77	1.94	2.05	1.90
$(Gd/Yb)_n$	4.11	5.04	3.99	3.31	4.65	2.77	3.48	3.83	2.65	2.75
$(La/Yb)_n$	15.14	13.56	15.73	12.43	12.72	4.42	8.84	10.39	7.17	8.57
Eu/Eu*	0.61	0.64	1.08	0.55	0.54	1.26	1.13	1.12	0.74	1.06

In the $SiO_2 – Na_2O + K_2O$ diagram (see Fig.3), figurative points of intrusive and volcanogenic rocks form a single cloud and fall into the fields of picrites, picrobasalts, alkaline basalts, trachybasalts, and trachyandesibasalts. According to their alkalinity, these rocks can be classified as potassic, sodic, and potassium-sodic. At the same time, in terms of potassium content, most of these rocks belong to the moderately potassic and high-potassic series. In terms of aluminosilicate nature, moderately aluminous and low aluminous rocks sharply predominate

Biotite wehrlites and metaperidotites are characterized by the lowest silica content (36.8-39.3 %) and the highest magnesia content (23.3-27.2 %); Al_2O_3 and $Na_2O + K_2O$ at $K_2O > Na_2O$ are characterized by low values. The iron oxidation coefficient F is 0.38-0.66; the fractionation coefficient K_f is 31.6-44.7. The rocks are characterized by the lowest CI (1.53-1.81), indicating a minimal presence of crustal material in the parent magma.

Metapyroxenites are characterized by SiO_2 (from 42.8-47.0 %), MgO (5.77-16.0 %), have an increased alkalinity ($Na_2O + K_2O$ to 5 %) and titanium (to 5.79 %). The *F* oxidation coefficient is low (up to 0.16), and the contamination coefficient is significantly higher than that of peridotites (up to 7.34).

The most numerous group of rocks are metagabbroids, represented by dolerites and gabbro-dolerites, differing in the degree of metamorphism and the character of relict structures. These rocks are characterized by a low iron oxidation coefficient (up to 0.15) and high K_f (up to 77.2).

The compositions of the metavolcanics are identical to the intrusive varieties, which may indicate their genetic unity. At the same time, the CI contamination index in the volcanic rocks is significantly higher, indicating the presence of a significant portion of crustal material in the magmas, while the Cuno SI index is lower, which may be an indication of significant crystallization fractionation.

Peridotites are characterized by the maximum values of transit elements (Cr, Ni, Co) and minimum – Y, Zr, Hf, Ga, V, etc. Pyroxenites occupy in such cases an intermediate position between peridotites and gabbroids. The content of Cr, Ni, and Co is variable but generally higher for gabbroids and for peridotites – Zr, Hf, Ga, Nb, V, Ba, Sr, etc. However, gabbroids are characterized by low concentrations of Cr, Ni, and Co and much higher concentrations of Zr, Hf, Ga, Nb, V, Ba, and Sr. The REE distribution in these rocks is also important. Minimum values of the sum of REE are characteristic for peridotites and pyroxenites, maximum – for gabbroids. The fractionation character of LREE and HREE is remarkable in that for all rock types $(Gd/Yb)_n > (La/Sm)_n$, i.e. HREE spectrum is more fractionated. At the same time, the $(La/Yb)_n$ ratio has the greatest values for peridotites (up to 28.09) and gabbroids – minimal, but with large variations (2.85-20.46). This indicates an uneven enrichment of light REE in rocks of the Chemberlendalen complex. Eu/Eu* shows a weak positive anomaly (to 1.24-1.27) or its absence (1.02-0.97) for all investigated intrusive rocks. At the same time, a significant overall enrichment of rocks with light REE – $(La/Yb)_n$ up to 21.67-28.09 – brings the studied rocks closer to the basalts of oceanic islands and continental rifts, i.e. to the intraplate complexes.

Journal of Mining Institute. 2022. Vol. 255. P. 419-434
DOI: 10.31897/PMI.2022.20

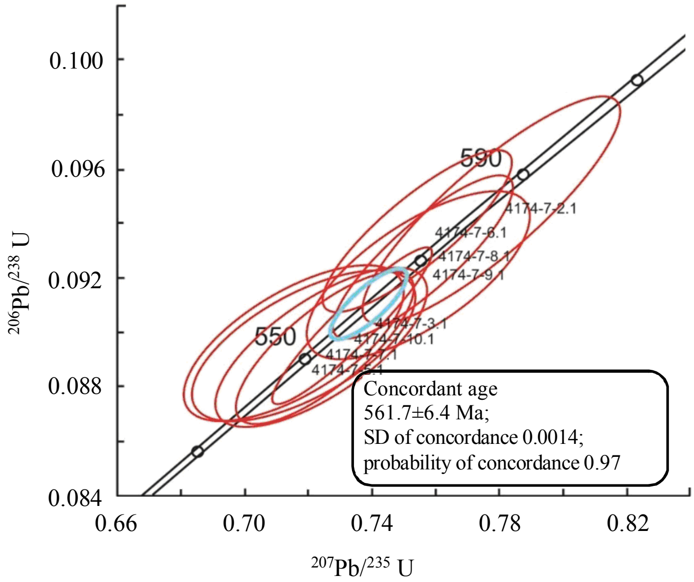

Fig.5. Concordia diagram for zircons from metabasalt (sample 4174-7, *n* = 9)

The distribution of trace elements in metaeffusives of the Chemberlendalen series is largely similar to that of the meta-intrusive rocks. For several rocks, there is a noticeable Europium minimum – up to 0.51. They are also characterized by significant enrichment of light REE compared to heavy ones. In general, for REE from metavolcanic rocks, there is a high level of fractionation.

In previous publications [11, 36] the figurative points of meta-intrusive and meta-effusive rocks according to [17] were put on the diagram of L.S.Borodin [37]. Most of the points fall into the fields of moderately alkaline and alkaline-basalt series. Therefore, taking into account all the presented data, the Chemberlendalen basic-ultrabasic complex should be attributed to the moderately alkaline potassium-sodium series, trachybasalt-trachyandesite formation and with a high degree of confidence – to intraplate formations.

The isotopic age of zircons from these rocks, collected by the authors, made it possible for the first time to obtain data on their absolute age. Seven samples were collected and studied: five from metavolcanogenic rocks interbedded with metasedimentary rocks, and two from concordant bodies of gabbroids deposited in the sedimentary-volcanogenic sequence. The metasedimentary rocks were diagnosed by comparing thin sections and chemical analysis data.

Sample 4174-7 is represented by metabasalts. It is a greenish-grey platy rock deposited as a concordant horizon up to 30 m thick in the sedimentary-volcanogenic sequence. Microscopically, these are *Ab-Chl-Cal* schists with a porphyroblastic structure; phenocrysts are represented by large *Cal* grains or aggregates of *Cal* and *Qz*. The fine-grained main mass is composed of *Cal*, *Chl*, *Ab*, *Qz*, *Spn*, *Mag*. From the sample 10 *Zrn* grains were analyzed; all calculated points lie on the Concordia. The obtained figures belong to the same age range from 509.5 to 582 Ma. Concordant age was calculated from nine measurements and was 562±5 Ma (Fig.5).

Sample 4221-1 – metapicrite: metavolcanic layer up to 7 m thick, concordant embedded in dark grey phyllites. Rocks are greenish-grey and fine-grained; in thin sections, they are described as *Cal-Ser-Chl* shales with *Ab* and *Cal* phenocrysts. The main shale fabric is represented by *Chl*, *Ser*, *Cal*, *Ab*, *Qz*, *Spn*, and *Opq*. 13 isotopic ratios were obtained for *Zrn* from the sample, all measurements fit into two age ranges: 1674-1897 and 506-627 Ma. The concordant age for *Zrn* of the second group was calculated from six grains and made 570±6 Ma (Fig.6).

Sample 4371-1 – metaandesibasalts: a layer up to 4 m thick of greenish-grey platy fine-grained rocks, conformably deposited among dark grey phyllites. The thin sections show phenocrysts *of Pl*; the main mass is composed of *Pl*, *Chl*, *Cal*, *Ser*, *Kfs*, and *Opq*. 15 points of *Zrn* grains from this rock have been studied. The results obtained can be divided into two age groups: 678-836 and 483-622 Ma. The concordant age was calculated from 10 measurements and amounted to 559±4 Ma (Fig.6).

Sample 4372-1 is the basic metatuf: greenish-gray platy rock with a porphyritic structure. The main mass is represented by *Chl*, *Bt*, *Cal*, *Ms*, *Qz*, *Pl*, and *Opq* with lenses of *Cal-Qz* composition; *Pl* is present as small elongated prisms, indicating its primary magmatic nature. Eleven analyses were made for *Zrn* from this sample, and the obtained figures give four age groups: 2862±21; 1403±9; 845-975; 543-596 Ma. For *Zrn* of the last group (six measurements), a concordant age of 593±6 Ma was obtained.

Sample 4174-1 is dolerite: a concordant body over 60 m thick, which is composed of medium-plate, medium-grained rocks. Under the microscope, it is weakly altered dolerite. The main minerals

DOI: 10.31897/PMI.2022.20

Journal of Mining Institute. 2022. Vol. 255. P. 419-434

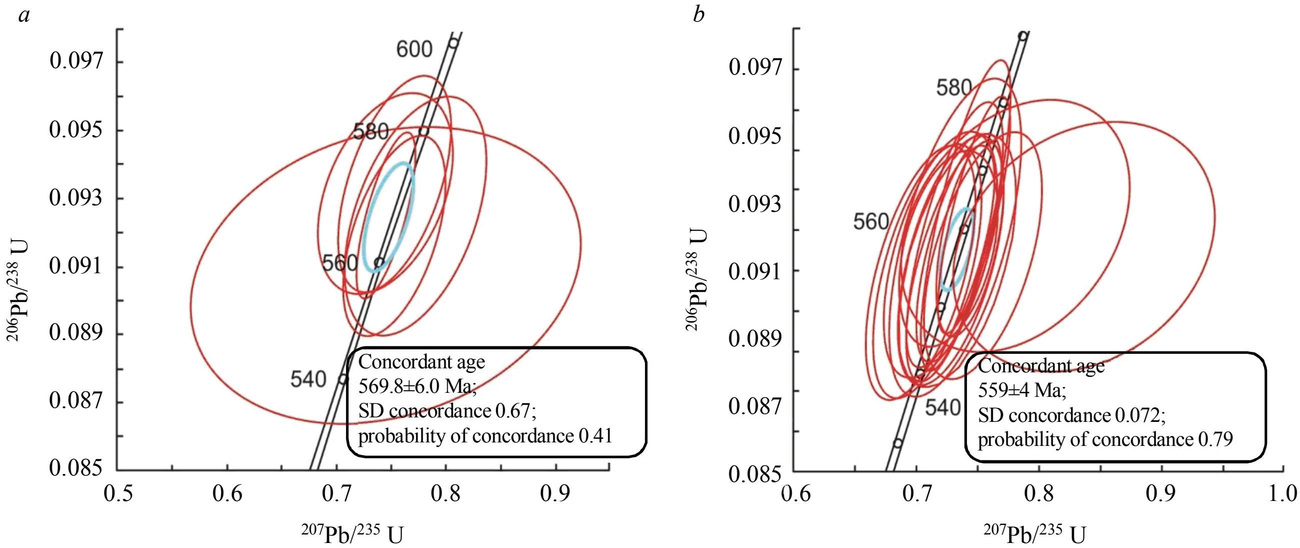

Fig.6. Concordia diagram for zircons from metapicrite (sample 4221-1, *n* = 6) (*a*) and metaandesibasalt (sample 4371-1) (*b*)

are *Cpx* and *Ab*, *Ilm* and single grains *of Kfs* are present; *Chl*, *Act*, *Cal*, and *Spn* are also noted. Eleven measurements were made for *Zrn* from the sample, and the isotopic ages obtained are in the range of 546-607 Ma. The Concordant age of dolerite calculated from this sample was 590±3 Ma (Fig.7).

Sample 4210-2 is gabbro-dolerite (a layered body of thick, coarse-grained rocks with a clearly visible magmatic structure and up to 10 m thick). The thin sections show fragments of ophitic structure, weakly pronounced cataclasis, and chloritization. Mineral composition: *Pl*, *Cpx*, *Opq*, *Chl*, *Act*. Five *Zrn* grains were taken from the sample, and the results give two age groups: 1744-1868 and 950-1006 Ma, which allows us to consider these *Zrn* as xenogenic (?), trapped by magma from older underlying complexes.

Sample 4351-1 – metaandesite: a more than 20 m thick horizon of greenish-grey, indistinctly platy fine-grained rocks, conformably interbedded with phyllites. The rock is described as metaandesitic with relicts of porphyritic structure, phenocrysts represented by *Pl.* The main fine-grained mass is composed of *Pl*, *Cal*, *Chl*, *Opq*, *Qz*, *Ser*, *Spn*. Eleven *Zrn* grains were isolated from the sample; the results are distributed in two groups: 2332-3309 and 1130-1436 Ma, i.e. they should be also considered magma-captured xenogenic crystals (?).

As a result of the geochronological studies, the majority of the studied rocks are dated between 559 and 593 Ma, corresponding to the Vendian, the formation period of the Chemberlendalen series sedimentary-volcanogenic section, and the comagmatic basic and ultrabasic intrusions of the Chemberlendalen complex. The occurrence of older dated *Zrn* in some of the samples allows them to be considered xenogenic, trapped by magma during upward movement through rocks of the underlying crust.

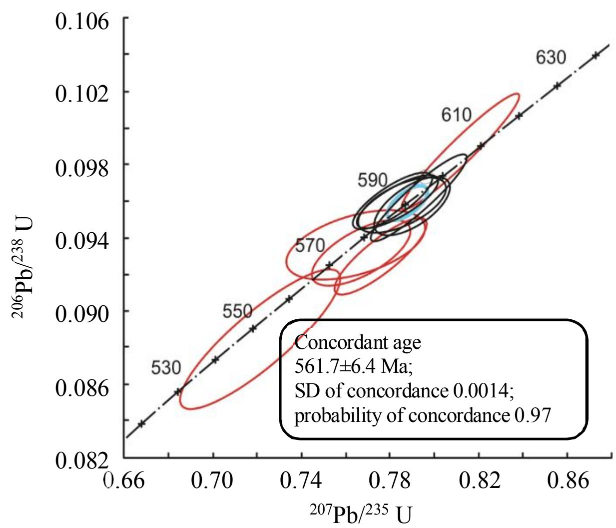

Fig.7. Concordia diagram for zircons from dolerite (sample 4174-1, *n* = 11)

Discussion. The results of the presented studies of magmatic complexes in the north of the WJL allow us to confidently discern two intervals of magmatic activity: Middle Riphean (1157-936 Ma) and Vendian (593-559 Ma).

Events of the Middle Riphean (Grenvilleian) age are widely observed on Svalbard. Several works have proved that this is the time of consolidation of the ancient basement of the archipelago [6, 11, 22]. In particular, in the southern part of WJL, the formations of this tectonic stage include the Skolfjellet gabbro-granite complex with rocks aged 1156-1072 Ma [26] and metaryolites of the Wimsodden formation (Verenscheldbreen complex) aged 1198-933 Ma [27]; in the northern part of WJL, to the east of Antoniabreen glacier, zircons aged 950±5 Ma [38] were obtained from gneisses of uncertain genesis. Taken together, these materials indicate magmatic and metamorphic events in this area in the 1200-950 Ma age interval, which is consistent with data from other areas of the archipelago [3, 35].

Important data for understanding the age correlation of endogenous processes in the basement rocks of the archipelago were published in [39], where the material of crustal and mantle xenoliths from basanites of Quaternary volcanoes in the northern part of the archipelago was analysed using U-Pb, Pb-Pb, Sm-Nd, Re-Os analytical methods. More than 560 zircons from crustal xenoliths (granitoids, gneisses, granulites) and 300 grains of sulphides from mantle xenoliths (peridotites) resulted in the sharp peak in the interval 1200-900 Ma with a maximum 963±30 Ma, corresponding to the Grenville events. The second dating peak is dated to the interval 750-524 Ma, corresponding to the Baikal events. A slight peak is also obtained in the interval 1900-1600 Ma (Late Karelian time). Archean and especially Caledonian events are represented by sporadic dating.

Our new dating complements this picture, allowing us to identify a new straton of the Middle Riphean age within the Verenscheldbreen complex in the north of the WJL – the Rechurchbreen series, whose rocks contain consonant bodies of metagabbroids with ages of 1152±11 and 967±6 Ma. The age and petrological characteristics of these rocks (intraplate continental formations) allow them to be compared to gabbro and diorites of the Skolfjellet complex in the south of the WJL [10, 26]. At the same time, the data obtained by the authors on age (936±6 Ma) and composition of metagranitoids of the Martin Ridge allow us to correlate them with granitoids and metaryolites also known in the south of WJL. These results make it possible to supplement the modern understanding of the tectonic structure of the whole area and the leading role of the Grenville (Middle Riphean) events in the formation of the archipelago basement.

The most important result is the Vendian dating obtained for the first time for Svalbard for metavolcanic rocks of the Chemberlendalen series, and the gabbroid bodies that break through them. It should be noted that some authors have paid much attention [7, 36, 40] to the Vendian time on Svalbard. According to them, it is marked by rare dating (Rb-Sr, Ar-Ar, K-Ar, U-Pb) on metamorphogenic rocks, mainly in the southwest of the archipelago [10, 41]. The first group of dating (660-580 Ma) corresponds to the Vendian period marked on Svalbard by widespread tillites, including the conglomerate strata of the Kapp Lee series. The second group of dates (553-505 Ma) corresponds mainly to the Cambrian period, which is characterized on Svalbard by the widespread absence of Early-Middle Cambrian sedimentation and structural unconformity with the Late Precambrian sequence [10].

The Baikal stage, which coincides with the Late Proterozoic-Early Paleozoic boundary, remains largely debatable for Svalbard, although it is associated with a change in tectonic regime, formation series, and partial structural restructuring of areas. For this reason, the Vendian tillite-like formation is of special attention [13, 15]. Scientists have different opinions about the tectonic regimes in the Late Proterozoic and Early Paleozoic. They have been considered as both miogeosynclinal [13, 42] and platform [5, 16]. The sections of this period are characterized by regional faulting, low sedimentation rates, amagmatic nature of the Baikal interval of the Ny Friesland Peninsula section as a basement tectonotype of the archipelago, presence of the appreciable amount of metavolcanics and small intrusive bodies in the western sections of Svalbard, low metamorphism of Baikalian age sediments on Ny Friesland, where a low-temperature subfacies of the greenschist facies and prehnite-pumpellyite facies are observed, higher metamorphism, fixed in the high-temperature subfacies of greenschist facies and higher, in western areas, proceeding under the conditions of increased pressures

[11, 41]. Note that in Svalbard, the Upper Precambrian and Lower Paleozoic layered complexes are separated by a hiatus in sedimentation and unconformity [10, 13, 17], which are quite comparable in character and duration to the Protouralian-Timanian unconformity [9, 10].

Conclusion. The occurrence of the Vendian dating of magmatic objects on Svalbard was expected and is not an accident. The dating interval of 559-593 Ma, determined by the authors of the article, corresponds to the Vendian period, which confirms the existence of geodynamic conditions generating intraplate volcanism on Svalbard at that time. The nature of the ultrabasic and basic magmatic rocks, as well as the predominantly pelitic composition of the metasedimentary rocks of the Chemberlendalen series, indicate that the sedimentary-volcanogenic sequence was formed during a single tectonic-magmatic cycle when moderately alkaline ultrabasic-basic volcanism was combined with a high degree of chemical weathering of rocks in the sources of the Vendian age material. Therefore, we can assume that the environments of sedimentary-volcanogenic series formation were similar to continental rifting.

The age correlation between two Vendian strata of the archipelago, the Kapp Lyell conglomerate series, and the Chemberlendalen sedimentary-volcanogenic series, allows to consider the former as an earlier one because boulders and pebbles of volcanic rocks are completely absent in the conglomerate horizons, widely represented in all formations of this series (up to 4 km in total thickness). Therefore, we propose to consider the Kapp Lyell series as Lower Vendian and the Chamberlandallen series as Upper Vendian (see Fig.2), which allows us to predict the identification of Upper Vendian analogues in other areas of the western part of the archipelago.

REFERENCES

1. Krasilshchikov A.A., Tebenkov A.M. Precambrian history of Svalbard caledonides. Geologo-geofizicheskie kharakteristiki litosfery Arkticheskogo regiona. St. Petersburg: VNIIOkeangeologiya, 1996. Iss. 1. Part 1, p. 70-82 (in Russian).

2. Tebenkov A.M. Late Precambrian magmatic formations of western Svalbard. *Vestnik LGU*. 1983. N 24, p. 88-93 (in Russian).

3. Tebenkov A.M., Dzhi D.G., Iokhanssen U., Larionov A.N. Tectonic history of Svalbard foundation (according to geochronological data). *Kompleksnye issledovaniya prirody Shpitsbergena*. Is. 4. Apatity: Izd-vo KNTs RAN, 2004, p. 90-100 (in Russian).

4. Sirotkin A.N. Nikitin D.V. Peculiarities of geodynamic development of Devonian graben of Svalbard. *Journal of Mining Institute*. 2011. Vol. 194, p. 104-111 (in Russian).

5. Turchenko S.I. Pre-Caledonian stage of the tectonic development of the folded basement of the Svalbard archipelago as the basement of an ancient platform. Geologiya i perspektivy rudonosnosti fundamenta drevnikh platform: Sbornik nauchnykh trudov. Leningrad: Nauka, 1987, p. 222-231 (in Russian).

6. Khain V.E., Filatova N.I. From Hyperborea to Arctida: to the problem of Pre-Cambrian craton of the Central Arctic. *Doklady RAN*. 2009. Vol. 428. N 2, p. 220-224 (in Russian).

7. Baluev A.S., Kuznetsov N.B., Zykov D.S. New data on lithosphere structure and formation history of the West Arctic shelf (The White and Barents Seas). Stroenie i istoriya razvitiya litosfery (Seriya “Vklad Rossii v Mezhdunarodnyi polyarnyi god”). Moscow: Paulsen, 2010, p. 252-292 (in Russian).

8. Kuznetsov N.B. The Cambrian Baltica-Arctida Collision, Preuralian-Timanian Orogen, and its erosion products in the Arctic. *Earth Sciences*. 2006. Vol. 411. N 9, p. 1375-1380 (in Russian).

9. Kuznetsov N.B. The Cambrian Protouralian-Timanian Orogen: Structural Evidence of Collisional Nature. *Doklady RAN*. 2008. Vol. 423. N 6, p. 774-779 (in Russian).

10. Kuznetsov N.B. Svalbard basement: north-eastern continuation of the Scandinavian Caledonian or north-western continuation of the Protouralian-Timanian. *Byulleten Moskovskogo obshchestva ispytatelei prirody. Otdel geologicheskii*. 2009. N 84 (3), p. 23-51 (in Russian).

11. Sirotkin A.N., Evdokimov A.N. Endogenous modes and evolution of regional metamorphism of folded basement complexes of Svalbard Archipelago (on the example of the Ny Friesland Peninsula). St. Petersburg: VNIIOkeangeologiya, 2011, p. 270 (in Russian).

12. Akbarpuran Haiyati S.A., Gulbin Y.L., Sirotkin A.N., Gembitskaya I.M. Compositional Evolution of REE- and Ti-Bearing Accessory Minerals in Metamorphic Schists of Atomfjella Series, Western New-Frisland, Svalbard, and Its Petrogenetic Significance. *Geology of Ore Deposits*. 2021. Vol. 63. N 7, p. 634-653. DOI: 10.1134/S1075701521070047

13. Krasilshchikov A.A. Stratigraphy and palaeotectonics of the Precambrian-Early Paleozoic of Svalbard. Leningrad: Nedra, 1973, p. 119 (in Russian).

14. Krasilshchikov A.A. General scheme of stratigraphic and tectonic dissection of the Svalbard Pre-Cambrian. Geologiya Svalbard. Leningrad: NIIGA, 1976, p. 56-62 (in Russian).

15. Harland W.B. The geology of Svalbard. Memoir N 17. Oxford. London: Geological Society, 1997, p. 521.

16. Barkhatov B.P. Main stages of tectonic development of Svalbard Archipelago. *Vestnik Leningradskogo gosudarstvennogo universiteta*. 1970. Vol. 6 (1), p. 157-159 (in Russian).

17. Turchenko S.I., Tebenkov A.M., Barkhatov D.B., Barmatenkov I.I. Geological structure and magmatism of the Chamberlain valley region, West Svalbard. Geologiya Shpitsbergena. Leningrad: Sevmorgeologiya, 1983, p. 38-48 (in Russian).
18. Birkenmajer K. Caledonian basement in NW Wedel Jarlsberg Land south of Bellsund, Spitsbergen. *Polish Polar Research*. 2004. Vol. 25. N 1, p. 3-26.
19. Dallmann W.K., Hjelle A., Ohta Y. et al. Geological Map of Svalbard 1:100,000, B11G Van Keulenfjorden. Norsk Polarinstitutt Temakart, 1990, p. 15.
20. Bjornerund M. An Upper Proterozoic unconformity in northern Wedel Jarlsberg Land, southwest Spitsbergen: lithostratigraphy and tectonic implications. *Polar Research*. 1990. Vol. 8. N 2, p. 127-140. DOI: 10.3402/polar.v8i2.6809
21. Soviet geological research in Svalbard 1962-1992. Extended abstracts of unpublished. Oslo, 1996, p. 103.
22. Sirotkin A.N., Marin Yu.B., Kuznetsov N.B. et al. On the age of Svalbard basement formation: U-Pb dating of detrital zircon from Upper Precambrian and Lower Carboniferous clastic rocks of the northwestern part of the Nordenscheldland. *Doklady RAN*. 2017. Vol. 477. N 3, p. 1-6. DOI: 10.7868/S0869565217330143
23. Kośmińska K., Schneider D., Majka J., et al. Detrital zircon U-Pb geochronology of metasediments from southwestern Svalbard's Caledonian Province. EGU General Assembly 2015, 12-17 April 2015, Vienna, Austria. Geophysical Research Abstracts. 2015. Vol. 17. N 11805.
24. Majka J., Gee D.G., Larionov A.N. Neoproterozoic zircon age from anathectic pegmatite, Isbjornhamna Group (Wedel Jarlsberg Land, Spitsbergen). NFG, N2. Abstract and Proceedings of the Geological Society of Norway. 2007. Abstr. NISP-041, p. 266.
25. Gavrilenko B.V., Balashov Yu.A., Tebenkov A.M., Larionov A.N. Early Proterozoic U-Pb age of "relict" zircon from high-potassic quartz porphyries of the Wedel Jarlsberg Land (Svalbard). *Geokhimiya*. 1993. N 1, p. 154-158.
26. Balašov Yu.A., Peucat J.J., Teben'kov A.M., et al. Rb-Sr whole-rock and U-Pb zircon datings of the granitic-gabbroic rocks from the Skalfjellet Subgroup, southwest Spitsbergen. *Polar Research*. 1996. Vol. 15. N 2, p. 167-181. DOI: 10.3402/polar.v15i2.6645
27. Balašov J. A., Teben'kov A.M., Ohta Y., et al. Grenvillian U-Pb zircon ages of quartz porphyry and rhyolite clasts in a metaconglomerate at Vimsodden, southwestern Spitsbergen. *Polar Research*. 1995. Vol. 14 (3), p. 291-302. DOI: 10.3402/polar.v14i3.6669
28. Larionov A.N., Tebenkov A.M. New SHRIMP-II U-Pb zircon age data from granitic boulders in Vendian tillites of the southern coast of Isfjorden, West Spitsbergen. *Abstracts and Proceedings of the Geological Society of Norway*. 2004. Vol. 2, p. 88-89.
29. Majka J., Kośmińska K. Magmatic and metamorphic events recorded within the Southwestern Basement Province of Svalbard. *Arktos*. 2017. Vol. 3(1), p. 1-7. DOI: 10.1007/s41063-017-0034-7
30. Williams I.S. U-Th-Pb geochronology by ion microprobe. *Reviews In Economic Geology*. 1998. Vol. 7, p. 1-35. DOI: 10.5382/Rev.07.01
31. McDonough W.F., Sun S.-s. The composition of the Earth. *Chemical Geology*. 1995. Vol. 120, p. 223-253. DOI: 10.1016/0009-2541(94)00140-4
32. Whitney D.L., Evans B.W. Abbreviations for names of rock-forming minerals. *American Mineralogist*. 2010. Vol. 95, p. 185-187. DOI: 10.2138/AM.2010.3371
33. Dolivo-Dobrovolskii V.V. Principles of Rational Classification of Magmatic Rocks. *Journal of Mining Institute*. 2009. Vol. 183, p. 181-186 (in Russian).
34. Practical Petrology: Methodological Recommendations on Study of Magmatic Formations applied to the Tasks of State Geological Mapping. Saint Petersburg: VSEGEI Press, 2017, p. 168 (in Russian).
35. Tebenkov A.M., Krasilshchikov A.A., Balashov Yu.A. Main geochronological boundaries and stages of Svalbard basement formation. *Doklady RAN*. 1996. Vol. 346. N 6, p. 786-789 (in Russian).
36. Sirotkin A.N., Skublov S.G. U-Pb age of zircon from metabasites of the Svalbard Archipelago crystalline basement and its formation history. *Regionalnaya geologiya i metallogeniya*. 2015. N 63, p. 47-58 (in Russian).
37. Borodin L.S. Petrochemistry of magmatic series. Moscow: Nauka, 1987, p. 260 (in Russian).
38. Majka J., Be'eri-Shlevins Y., Gee D.G. et al. Torellian (c. 640 Ma) metamorphic overprint of Tonian (c. 950 Ma) basement in the Caledonides of southwestern Svalbard. *Geological Magazine*. 2014. Vol. 151. Is. 4, p. 732-748. DOI: 10.1017/S0016756813000794
39. Griffin W.L., Nikolic N., O'Reilly S.Y., Pearson N.J. Coupling, decoupling, and metasomatism: Evolution of crust-mantle relationships beneath NW Spitsbergen. *Lithos*. 2012. Vol. 149, p. 115-135. DOI: 10.1016/j.lithos.2012.03.003
40. Evdokimov A.N., Sirotkin A.N., Chebaevskii V.S. Late paleozoic alkaline-ultramafic magmatism in Spitsbergen archipelagoes. *Journal of Mining Institute*. 2013. Vol. 200, p. 201-209 (in Russian).
41. Majka J., Mazur S., Manecki M., et al. Late Neoproterozoic amphibolite-facies metamorphism of a pre-Caledonian basement block in southwest Wedel Jarlsberg Land, Spitsbergen: new evidence from U-Th-Pb dating of monazite. *Geological Magazine*. 2008. Vol. 145. Is. 6, p. 822-830. DOI: 10.1017/s001675680800530x
42. Harland W.B. Caledonide of Svalbard. The Caledonian orogeny – Scandinavia and related areas. Chichester, New York: Wiley, 1985, p. 999-1016.

***Authors*: Aleksandr N. Sirotkin,** *Doctor of Geological and Mineralogical Sciences, Head of the Sector, https://orcid.org/0000-0003-2433-3953 (VNIIOkeangeologiya, Saint Petersburg, Russia)*, **Aleksandr N. Evdokimov,** *Doctor of Geological and Mineralogical Sciences, Professor, evdokimov48@list.ru, https//orcid.org/0000-0002-8121-0426 (Saint Petersburg Mining University, Saint Petersburg, Russia)*.

The authors declare no conflict of interests.