

Pre-Ordovician tectonic evolution and volcano-plutonic associations of the Timanides and northern Pre-Uralides, northeast part of the East European Craton

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Abstract

The Pre-Uralides and Timanides are Pre-Ordovician complexes, located at the east and northeast portion of the East European Craton. They combine two large groups of rocks of different composition: (1) The southwestern Timanides and southern Pre-Uralides consisting mostly of sedimentary rocks; (2) The northeastern Timanides and northern Pre-Uralides are composed of volcanic-sedimentary series and volcanogenic series, granitoids and rare ophiolites. The granitoids and associated volcanics of the second group are subdivided into I- and A-types. Rocks considered from the I-type are parts of a continuous basalt-andesite-dacite-rhyodacite and gabbro-granodiorite-granite series showing a calc-alkaline affinity. They are dated within a time range of 700 to 515 Ma and they are interpreted to be subduction-related and/or affected by collision magmatism. In contrast, A-type granitoids are parts of bimodal gabbro-granite and basalt-rhyolite associations, and dated from 565 to 500 Ma. A-type granitoid massifs show elongated shapes within linear tectonic zones and are interpreted to reflect an extensional/transensional setting.

The southwestern Timanides and southern Pre-Uralides were formed in the Neoproterozoic passive Timan margin of the Baltica. In contrast, the northeastern Timanides and northern Pre-Uralides were formed in the Late Neoproterozoic active Bolshezemel margin of Arctida and in the Baltica-Arctida collision zone during the Ediacaran-Middle Cambrian.

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1. Introduction

The East European Craton is bounded in the northeast by the Timan-Pechora basin and in the east by the Urals (Fig. 1). Pre-Ordovician granitoids are distributed over the northern Urals and within the basement of the Timan-Pechora basin. We present new compositional, geochemical and isotopic data for the granitoids of the North Urals (Lyapin anticline). Further, we summarize all available data of Pre-Ordovician granitoids in the Timan-Pechora region and the western flank of the northern Urals. We then interpret the combined geological–geophysical data to propose a new tectonic scenario for Neoproterozoic–

Middle Cambrian evolution of the northeastern part of the East European Craton.

We use the Geological time scale nomenclature after Gradstein et al. (2004).

2. Present-day geological setting of the east and northeast part of the East European Craton

2.1. The Urals and Timan-Pechora region

The Urals are a north-south trending Variscan fold-thrust belt subdivided into the Eastern-Uralian and Western-Uralian megazones by the Main Uralian Fault (Fig. 1). The Eastern-Uralian megazone consists predominantly of Paleozoic ophiolites and volcanic island-arc complexes. The Western-Uralian megazone consists of Upper Cambrian to Upper Paleozoic

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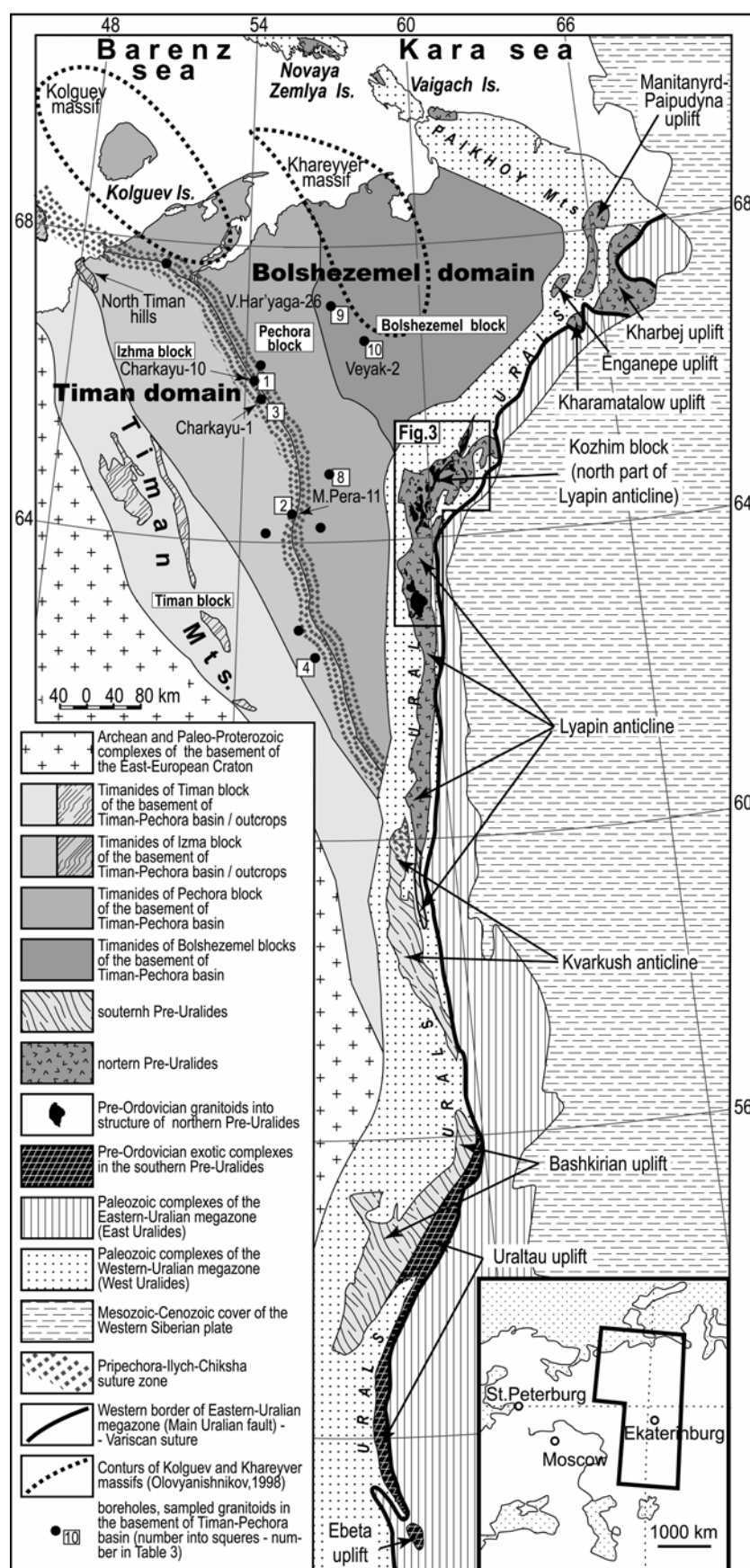


Fig. 1. Tectonic scheme of the distribution of Late Neoproterozoic/Cambrian complexes of the east (Uralian) and northeast (Timan-Pechora) frame of the East European Craton and its periphery to the east (based on Khain and Leonov, 1999). Insert: location of the tectonic scheme. Borehole locations after data of Dovzhikova et al. (2004) and Gee et al. (2000).

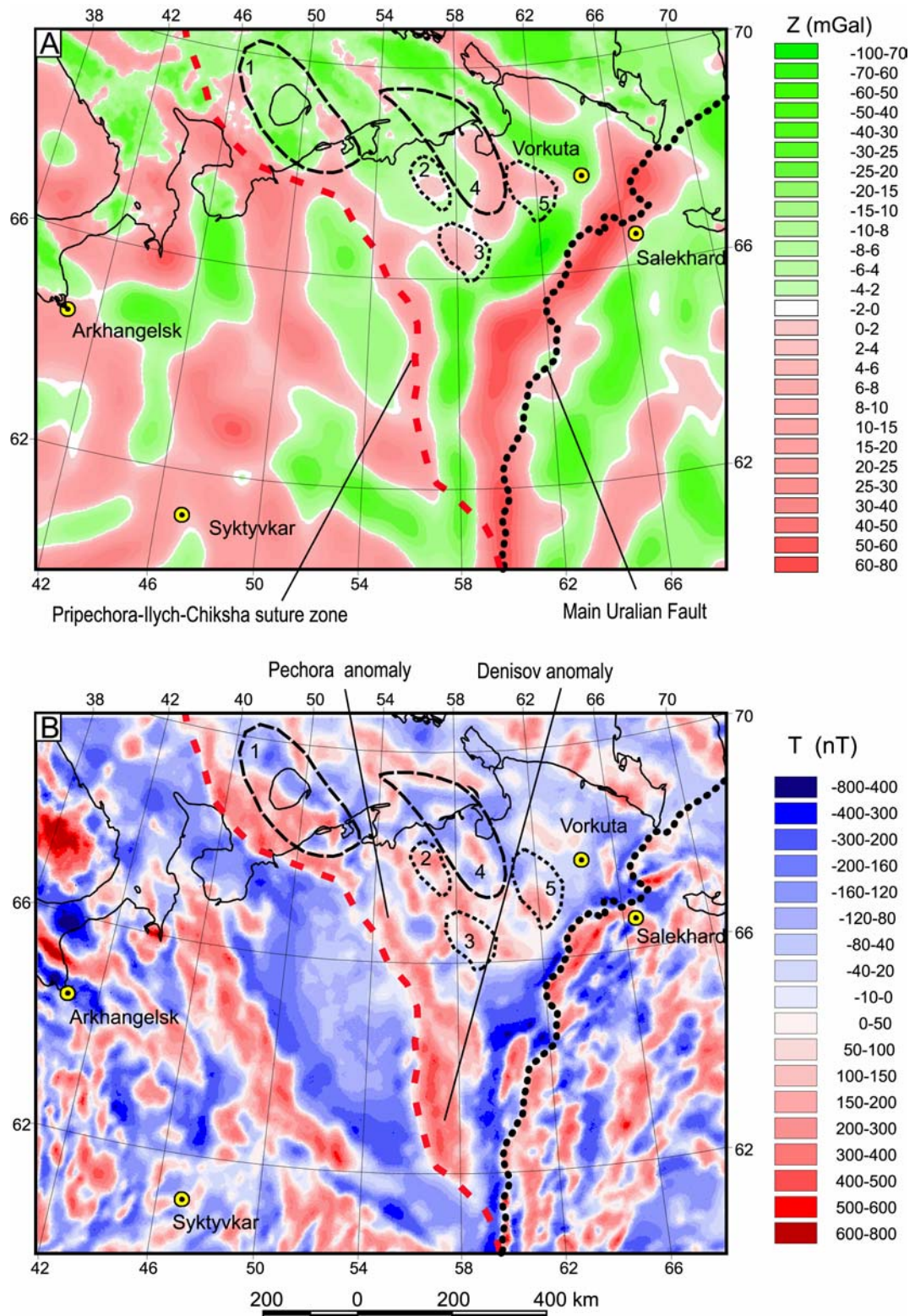


Fig. 2. The fragment of the (A) gravity (Bouguer anomalies, data taken from site http://topex.ucsd.edu/pub/global_grav_lmin/) and (B) magnetic (after Jorgensen, 1995) maps for the northeast East European Craton. The hyphens contour — Kolguev (1) and Khareyver (4) antiformal units of the basement of Timan-Pechora basin. The points contour — Khariyaga (2), Shariya-Makarikha (3), and Verhnyaya Adzva (5) synformal units of the basement of Timan-Pechora basin.

sedimentary (carbonate, siliceous and terrigenous) complexes. The basement of the Western-Uralian megazone consists of variably metamorphosed sedimentary, volcanic-sedimentary

and volcanogenic formations, intrusions (granites and gabbro), and rare ophiolites of Neoproterozoic to Middle Cambrian age that are collectively defined as the *Pre-Uralides*.

The Timan-Pechora basin consists of the dislocated Neoproterozoic-Middle Cambrian complexes (folded basement) named the *Timanides*, predominantly overlain unconformably by several kilometers of post-Cambrian cover. Because the basement is covered by sediments, it is poorly understood, though several boreholes have reached basement rocks (Beliakova and Stepanenko, 1991; Dovzhikova et al., 2004). Syntheses in English have recently been published (Gee et al., 2000; Roberts and Siedlecka, 2002; Dovzhikova et al., 2004; Pease et al., 2004). The basement outcrops in the southwest (known as the Timan mountains) and in the east (the Urals) of the Timan-Pechora basin.

2.2. Pre-Uralides and Timanides

The Pre-Uralides are mainly stratigraphically overstepped by a Late Cambrian (?)–Early Ordovician and later series of rocks. The exposed complexes of the Pre-Uralides of the Western-Uralian megazone are called the Central Uralian Uplifts (Fig. 1). In some local areas of Bashkir and Manitanyrd-Paipudyna uplifts, the Pre-Uralides were locally overthrust onto the more recent rocks during the Variscan times. Pre-Ordovician granitoids and associated volcanics are present only in the northern parts of the Central Uralian Uplifts. The Timanides of the Timan-Pechora region are subdivided into two large domains: (1) the Timan domain including the Timan and Izhma blocks, and (2) the Bolshezemel domain including the Bolshezemel and Pechora blocks (Fig. 1). The Pripechora-Ilych-Chiksha fault zone is a suture that separates the two domains, with a different Neoproterozoic character.

- (1) The Timanides of the Timan domain are composed of slightly deformed and weakly metamorphosed sedimentary formations (Olovyannishnikov, 1998; Gee et al., 2000; Roberts and Olovyannishnikov, 2004; Maslov, 2004). However, in the northwest, in the Kanin peninsula, the metamorphic grade reaches amphibolite facies, and intrusions of gabbro, granites and syenites occur (Kostyuhin, 1985; Andreichev, 1998; Olovyannishnikov, 1998; Lorenz et al., 2004). The Timan domain partly extends to the northwest in the Kil'din Island and Rybachi, Sredni, and Varanger peninsulas (the northern edge of the Baltic shield). It also extends to the southeast within the Kvarkush anticline of the Central Uralian Uplifts (Fig. 1).
- (2) The Timanides of the Bolshezemel domain are composed of intensely tectonized and metamorphosed volcanic and volcano-sedimentary complexes, and granitoids (Beliakova and Stepanenko, 1991; Olovyannishnikov, 1998; Gee et al., 2000; Dovzhikova et al., 2004; Pease et al., 2004). This domain extends to the southeast into the Lyapin anticline, and includes all the northern structural elements of the Central Uralian Uplifts.

A positive magnetic anomaly (Fig. 2) marks the triple junction of the Timan domain, Bolshezemel domain, and the Urals. Known as the Denisov anomaly, it is interpreted to reflect

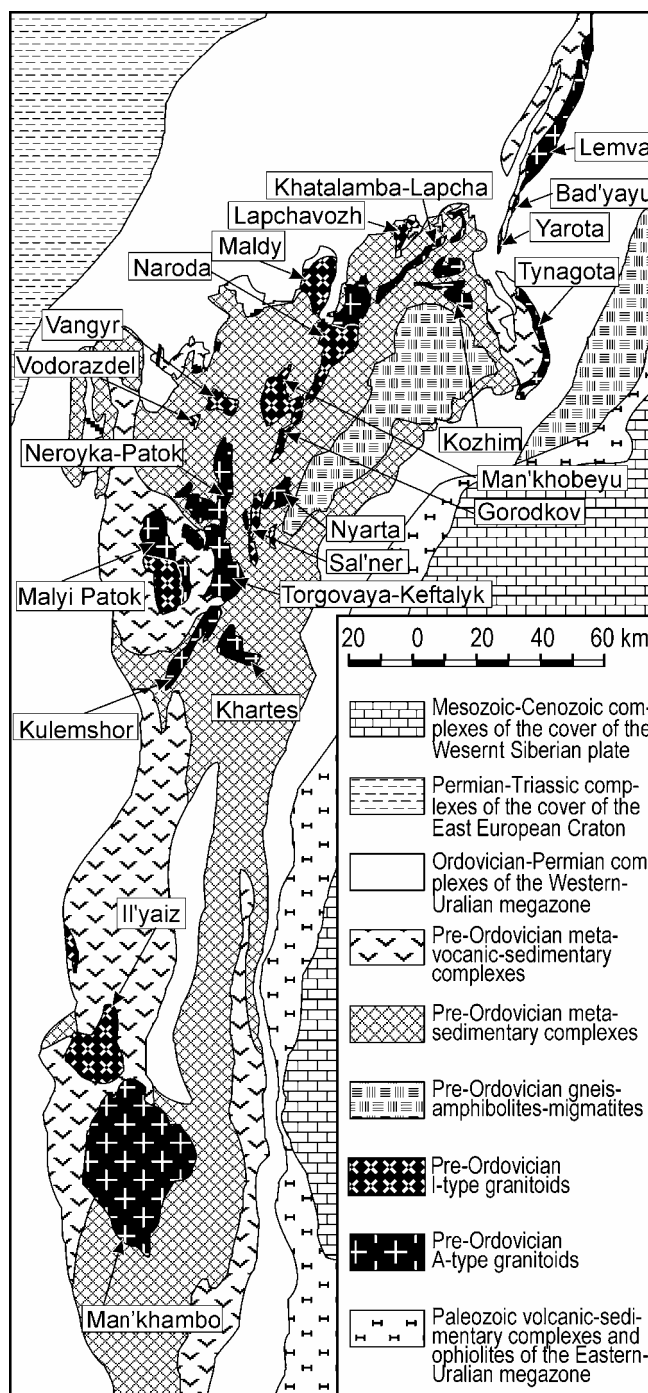


Fig. 3. Simplified geological scheme of the Kozhim block of the Lyapin anticline (for regional position see Fig. 1). Names of granitoids massifs are given in the rectangles.

basic and ultrabasic complexes within the Pre-Uralides overlain by Paleozoic and Mesozoic sedimentary rocks of the Western-Uralian megazone (Ivanov et al., 1986). The Denisov anomaly continues to the northwest into the Timan-Pechora basin as the Pechora and other positive magnetic anomalies. A high gradient zone in the magnetic field bounds the southwest slope of the magnetic anomalies' chain and correlates with an elongated positive gravity anomaly. This linear abnormal zone in potential fields coincides with the Pripechora-Ilych-Chiksha fault zone.

Table 1

Average compositions of Pre-Ordovician granitoids I-type of the North part of Urals

	Vangyr	Maldy	Lapchavoz		Il'yaiz	southern part of Naroda	
	Granites	Granites	Granites	Granodiorite	Granites	Granodiorite	Granites
	1	2	3	4	5	6	7
	n=10	n=5	n=7	n=27	n=46	n=6	n=3
SiO ₂	76,39	70,56	69,81	64,43	74,88	66,42	71,58
TiO ₂	0,16	0,42	0,36	0,57	0,27	0,61	0,55
Al ₂ O ₃	12,17	14,49	14,55	16,39	13,04	15,78	13,74
Fe ₂ O ₃	0,85	1,58	1,82	2,52	0,80	1,66	1,54
FeO	1,24	1,56	1,38	2,37	0,78	2,12	1,68
MnO	0,02	0,04	0,07	0,10	0,04	0,06	0,04
MgO	0,53	0,78	1,01	1,27	0,62	1,59	0,69
CaO	0,75	1,26	2,41	3,58	0,75	3,59	1,66
Na ₂ O	3,77	3,46	3,65	3,73	3,74	4,15	3,87
K ₂ O	3,51	4,31	3,40	3,02	4,37	1,75	3,46
P ₂ O ₅	0,06	0,12	0,07	0,11	0,06	0,15	0,08
nnn	1,08	1,42	1,18	1,85	0,84	2,04	0,97
H ₂ O-	0,17	0,2	0,18	0,19	0,18	0,28	0,31
CO ₂	0,08	0,20	0,16	0,4	0,09	0,43	0,14
La	26,01	49,9	35,5	31,18	39,67	22,23	40,60
Ce	48,58	95,3	54,02	55,14	71,62	39,325	71,03
Pr*	5,54	9,7	4,98	5,58	7,60	4,22	7,15
Nd	22,05	32,53	15,52	19,9	28,30	15,48	25,17
Sm	5,85	6,51	3,00	3,97	6,70	3,68	5,72
Eu	0,67	1,02	0,84	1,14	1,28	1,20	1,13
Gd*	7,57	7,07	3,90	5,08	8,34	4,48	6,47
Tb	1,18	1,09	0,59	0,76	1,24	0,65	0,93
Dy*	7,08	6,31	3,41	4,49	7,26	3,70	5,15
Ho*	1,65	1,36	0,75	0,98	1,56	0,77	1,11
Er*	4,7	3,75	2,08	2,74	4,36	2,03	2,85
Tm*	0,7	0,53	0,31	0,40	0,63	0,29	0,41
Yb	4,09	2,86	2,61	2,14	3,40	1,45	1,96
Lu	0,68	0,47	0,27	0,36	0,55	0,23	0,32
Cs	2,73	4,91	2,46	4,26	3,94	1,52	1,75
Ba	375	596	241	530	842	556	672
Sc	4,59	6,23	7,07	10,20	6,78	8,87	7,76
Cr	14	28,44	16,42	19,19	16,07	70,80	21,33
Co	3,75	4,77	6,29	9,61	2,47	10,48	6,60
Ni	63	18	70	41	39	141	19
Zn	66	80	56,5	113	18	60	37
Se	2,61	6,36	2,15	1,32	2,20	0,71	1,26
As	3,17	9,8	4,45	4,3	4,44	4,22	2,09
Sb	0,55	0,78	0,35	0,54	0,60	0,31	0,45
Th	17,6	25,33	16,44	12,47	11,97	8,71	15,43
U	1,76	4,45	1,67	2,55	1,84	1,46	1,80
Hf	4,92	5,23	3,69	4,03	5,00	3,83	4,84
Ta	1,71	2,31	3,63	1,2	2,22	0,79	0,82
Be	-	2,82	2,65	2,17	5,50	2,74	3,00
Pb	-	24,6	11,5	11,6	8,8	7,7	8,3
Ga	-	20,2	14	16,5	14,7	27,3	29,0
Cu	-	15,7	2,8	6,0	4,0	10,0	4,4
V	-	33	25	118	14	93	100
F	310	483	190	207	460	345	303
Y	-	37	28	30	25	15	23
Zr	190	141	108	131	165	165	193
Nb	15	12	8	12	60	<10	20
Rb	167	190	130	113	132	59	87
Sr	-	94	193	236	101	285	180

Comments. The oxide analyses were performed by conventional wet and X-ray fluorescence method at the Institute of Geology of Komi science Centre (IG KSC), Syktyvkar, Urals Branch, RAS. Trace elements were analysed by instrumental neutron-activation method and X-ray method at Vernadsky Institute of Geochemistry, Moscow and quantitative spectral method and atomic absorption method at IG KSC.

* — element concentration is defined by extrapolation method.

The southeast continuation of the Pripechora-Ilych-Chiksha fault zone is traced into the Urals, in the most northern part of the Kvar Kush anticline. High pressure and low temperature (HP/LT) metamorphic rocks found here imply that the fault zone is a suture. Available age dating of the rocks includes a K/Ar bulk-rock isotopic age of 500–550 Ma (Rusin, 1996) and Rb-Sr mineral isochronal data ~ 540 Ma (Beckholmen and Glondy, 2004).

3. Pre-Ordovician granitoids and associated volcanics of the western flank of the northern Urals and the basement of the Timan-Pechora basin

3.1. Location and geological setting

In the northeast edge of the Izhma block, granite massifs, presumably late- or post-tectonic have been reached by drilling (Gee et al., 2000; Dovzhikova et al., 2004; Pease et al., 2004). Within the Pechora block, calc-alkaline volcanic island arc complexes and intrusive complexes of intermediate and basic composition are recognized (Beliakova and Stepanenko, 1991; Gee et al., 2000; Dovzhikova et al., 2004; Pease et al., 2004). In the Bolshezemel block, volcano-sedimentary rocks, felsic volcanics and intrusions of two-mica granites and gabbro have been found in drill holes (Gee et al., 2000; Dovzhikova et al., 2004; Pease et al., 2004).

Pre-Uralides of the Polar Urals are represented by a differentiated volcanogenic series and associated sedimentary formations, granitoids, and ophiolites. In the Enganepe uplift on the western flank of the Polar Urals, they are exposed along with

unconformably overlying basal horizons of Ordovician to Permian sequences. This package forms the core of the Variscan Enganepe anticline (Mizin, 1988; Dushin, 1997; Scarrow et al., 2001; Khain et al., 2003; Pease et al., 2004).

In the Northern and Sub-Polar Urals, Pre-Uralian granitoids and associated volcanics are widespread in the northernmost part of the Lyapin anticline (Kozhim block) of the Central Uralian Uplifts (Fig. 3). Makhlaev (1996) showed that granitoids of the western flank of the Northern Urals include both I- and A-types. Both types of granites are associated with volcanic rocks (Soboleva, 2004; Kuznetsov et al., 2005a and references therein). The results are two magmatic series comprising: (1) differentiated calc-alkaline volcanics and granitoids (I-type), that form a continuously differentiated magmatic series, as in the Lapchavozh and Malotynagota continuous series (see location of the massifs in Fig. 3) and (2) normal and hyperalkaline rhyolites and granites (A-type), that form part of the gabbro-granite and basalt-rhyolite paragenetic associations, as in the Lemva and Tynagota series (Fig. 3).

3.2. Mineral and chemical composition

3.2.1. Mineral and chemical composition of the granitoids and volcanics of the western flank of the Northern Urals

The samples were analyzed for major oxides by wet chemistry, and by the X-ray fluorescence (XRF) method at the Analytical Laboratory of the Institute of Geology of Komi Science Centre RAS, (Syktyvkar, Russia). Concentrations of selected trace elements are obtained by the neutron-activation

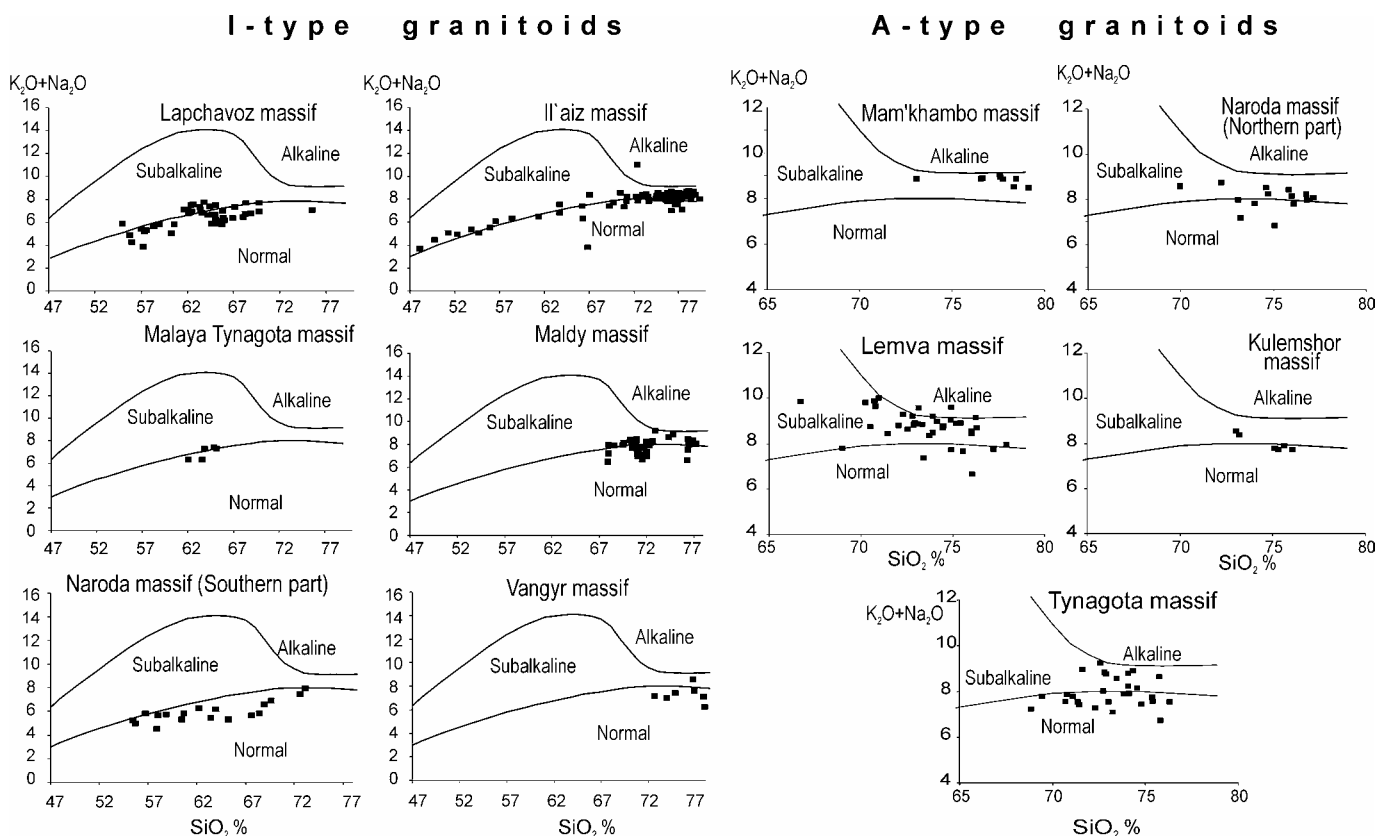


Fig. 4. Diagrams of total alkalinity versus SiO_2 (TAS-diagrams) for I- and A-types granitoids of the Pre-Uralides of the western flank of the North Urals.

method, and by the XRF method at the Analytical Laboratory of the Vernadsky Institute of Geochemistry RAS (Moscow, Russia), and by the quantitative spectral method and atomic absorption method, at the Analytical Laboratory in the Institute of Geology of Komi Science Centre RAS.

I-type granitoids and volcanics. I-type granitoids (Table 1) show a wide spectrum of compositions from quartz diorites to leucogranites with relatively abundant biotite-rich granites. Accessory minerals are represented by apatite, monazite, xenotime, tourmaline, zircon, allanite, and titanite. Opaque minerals are represented primarily by sulfides, and include some hematite and ilmenite. Magnetite is only found rarely.

Granitoids of I-type are characterized by normal or slightly increased alkalinity of K–Na type (Fig. 4). They are part of a continuous calc-alkaline series with a positive correlation between total alkalinity and the content of SiO_2 (Fig. 4). The I-type granites are enriched in high field strength elements (HFSE) and rare earth elements (REE), Th, Nb, Ta, Zr, Rb and are depleted in Sr, P, Ti (Fig. 5). Granitoids of I-type are enriched by the LREE with respect to HREE. The Eu deficiency is clearly seen in the most leucocratic differentiations of granitoids of I-type (Fig. 5). Average ratios: $\text{La}_n/\text{Sm}_n=4.57\pm1.47$, $\text{Sm}_n/\text{Yb}_n=2.16\pm0.66$, $\text{La}_n/\text{Yb}_n=9.59\pm3.04$.

I-type volcanics vary in composition from andesites up to rhyodacites. They typically have porphyritic textures. Pheno-

crysts in silicic volcanics are represented by plagioclase. Rocks with a lower content of SiO_2 are strongly altered by regional metamorphism. Porphyritic grains of plagioclase are totally saussuritized and mafic minerals are chloritized and epidotized. The granitoids and volcanics of I-type are parts of a continuous basalt-andesite-dacite-rhyodacite and gabbro-granodiorite-granite series.

A-type granites and volcanics. A-type granites (Table 2) are more homogeneous in composition and are dominated by leucocratic alaskite. Accessory minerals are primarily represented by allanite, zircon, apatite, titanite, and fluorite. Minerals with high abundances of rare earth elements — thorite, orangite, cyrtolite, aeschenite, columbite are found. Magnetite is most often found among the opaque minerals; and hematite and sulphides are also common.

A-type granitoids are usually hyperalkaline and referred to K–Na and K-types, they are characterized by restricted variations of composition and display an inverse relationship between total alkalinity and SiO_2 (Fig. 4). The A-type granites are characterized by higher total concentration of REE. A related enrichment in HREE is typical in A-type granites and they have a deficiency in europium. Average ratios: $\text{La}_n/\text{Sm}_n=3.08\pm0.72$, $\text{Sm}_n/\text{Yb}_n=1.51\pm0.24$, $\text{La}_n/\text{Yb}_n=4.53\pm0.58$.

A-type volcanics are mainly represented by porphyritic rhyolites. Among the phenocrysts, quartz and K-feldspar are

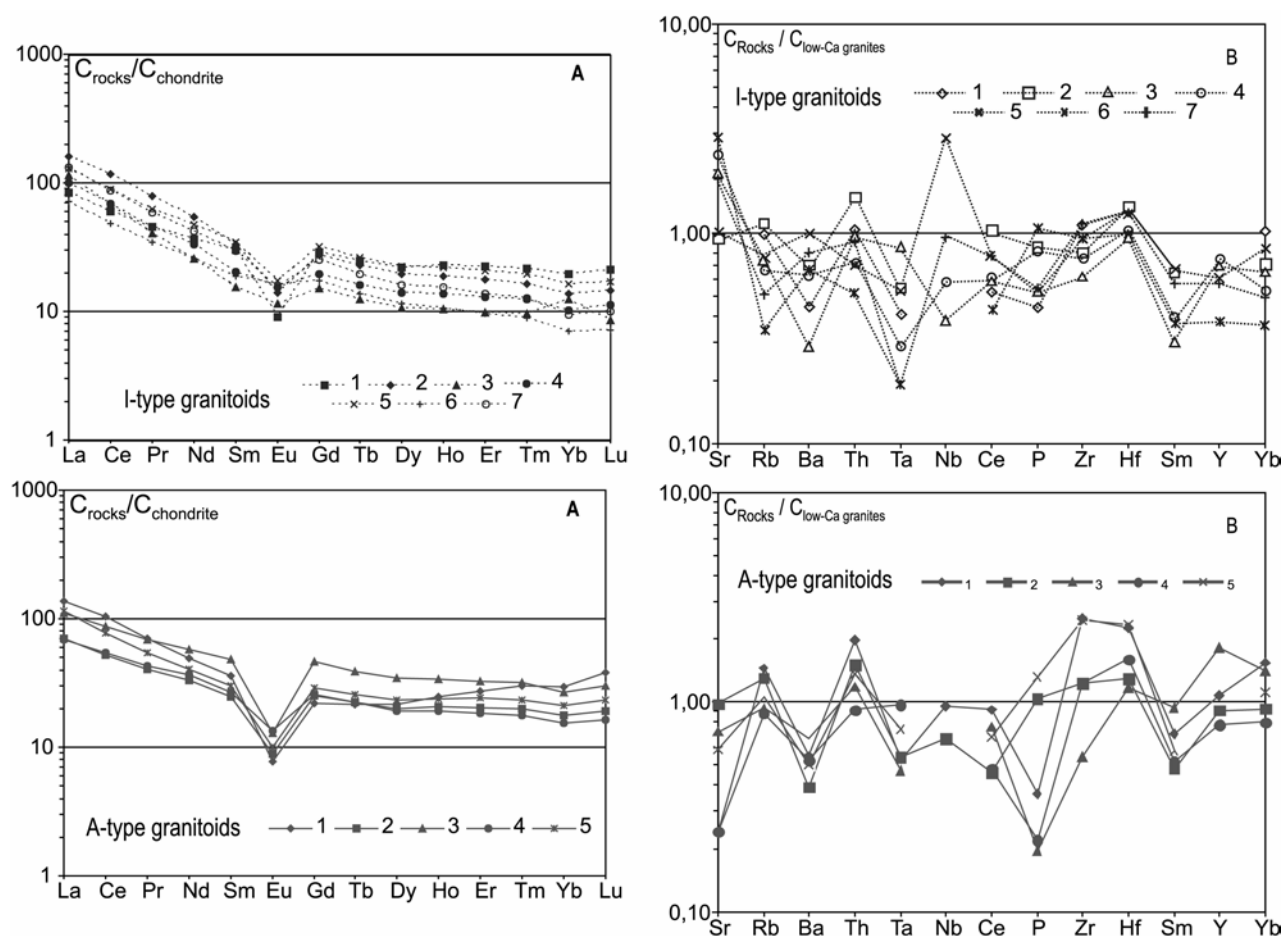


Fig. 5. REE diagram (A) and Spider diagram (B) of granitoids of the Pre-Uralides of the western flank of the North Urals. A: concentration of components normalized to chondrite (Boynton, 1984). B: concentration of components normalized to concentration of components of low-Ca granites (Turekian and Wedepohl, 1961). Numbers for I-type and A-type granitoids correspond to numbers in Tables 1 and 2, correspondently.

dominant, and plagioclase laths are less common. Volcanics of this type are close in chemical composition to their granitoid counterparts.

Granitoids and felsic volcanics of A-type are spatially associated with gabbro and basalts (Dorokhov and Soboleva, 2002; Soboleva, 2004), but the genetic relationship between the A-type felsic rocks and the mafic rocks is unclear. Genesis of the associations of A-type rocks is not yet understood. Comparison of the relative volumes of the spatially associated felsic and mafic rocks, suggest that felsic rocks are unlikely to have formed as a result of differentiation of basaltic magma.

Both A- and I-type granitoids share a shallow depth of crystallization for the magmas. The granites have hypidiomorphic, granular, porphyritic, and micropegmatitic structures peculiar to epizonal massifs. There is a gradual transition in the chemical composition of A-type granites and I-type leucocratic granites.

3.2.2. Mineral and chemical composition of the granitoids of the basement of the Timan–Pechora basin

The composition of the intrusive rocks that have been sampled from boreholes in the Bolshezemel domain and Pripechora-Ilych-Chiksha fault zone varies from gabbro to granite, and the rocks are related to the calc-alkaline series. Granitoids of the basement of the Timan-Pechora basin are characterized by geochemical signatures of typical I-type differentiates from basic magmas (Dovzhikova et al., 2004). The granitoid compositions range from quartz diorites up to granites (mainly biotite-bearing). In granitoids of the Izhma block, apatite and zircon occur as accessory minerals (Gee et al., 2000). In quartz diorites of the Pechora block, titanite, zircon, garnet and magnetite are present. In granites of the Bolshezemel block, apatite, zircon and magnetite are present. According to Dovzhikova et al. (2004), the granitoids are similar in chemical composition, are enriched with the LREE and are characterized by a negative europium anomaly. The low value of the initial ratio $^{87}\text{Sr}/^{86}\text{Sr}=0.708$, suggests that the magma was derived by anatexis of continental crust. Granitoids of the basement of the Timan-Pechora basin are interpreted to be derived from a mature island arc and/or formations in a collisional environment (Dovzhikova et al., 2004; Pease et al., 2004).

3.3. Isotopic ages

During the last decade, the authors have executed new U-Pb and Rb-Sr dating of Pre-Uralides-Timanides granitoids and associated volcanics by the Rb/Sr isochron method, and by different methods of zircon dating. We summarize our data for the western flank of the North Urals and the North Timan hills, and the results of Gee et al. (2000) for the basement of Timan-Pechora basin in Table 3. Results *N* 1–6, 8–10 in Table 3 were obtained by single zircons Pb-evaporation using Kober's technique, at the laboratory for Isotope Geology (Swedish Museum of Natural History). Results *N* 7, 24–29 in Table 3 were obtained by means of an ion microprobe SHRIMP-II at the Centre of Isotopic Research (VSEGEI, St-Petersburg, Russia). Results *N* 11–18 in Table 3 were obtained by the method of

Tabl. 2.

Average compositions of Pre-Ordovician A-type granitoids of the western flank of the North Urals

	Lemva	Tynagot	northern part of Naroda	Man'khambo	Morkulemshor
	Granite	Granite	Granite	Granite	Granite
	1	2	3	4	5
	n=62	n=12	n=14	n=11	n=5
SiO ₂	74,82	72,60	74,67	77,25	71,98
TiO ₂	0,2	0,43	0,35	0,12	0,26
Al ₂ O ₃	12,51	13,29	12,82	11,52	14,91
Fe ₂ O ₃	1,14	1,53	1,07	0,62	1,49
FeO	0,97	1,06	0,93	0,42	0,66
MnO	0,03	0,03	0,02	0,02	0,03
MgO	0,33	0,85	0,64	0,34	0,6
CaO	0,57	1,00	0,63	0,23	0,55
Na ₂ O	3,69	3,12	3,60	4,18	4,12
K ₂ O	4,98	4,62	4,43	4,64	4,08
P ₂ O ₅	0,05	0,14	0,03	0,03	0,18
LOI	0,49	1,31	1,05		1,14
H ₂ O ⁺	0,17	0,30	0,16	0,18	0,22
CO ₂	0,12	0,19	0,29	0,07	0,07
La	42,63	21,75	34,1	21,47	35,7
Ce	83,88	42,27	69,84	44,09	62,52
Pr	8,53	4,92	8,34	5,25	6,57
Nd	29,80	19,9	34,7	22,06	24,32
Sm	7,0	4,80	9,4	5,18	5,83
Eu	0,57	0,65	0,95	0,99	0,73
Gd	5,70	6,57	12,02	6,68	7,5
Tb	1,02	1,06	1,86	1,06	1,22
Dy	6,98	6,35	11,02	6,15	7,45
Ho	1,78	1,48	2,43	1,38	1,72
Er	5,70	4,3	6,9	3,87	5,06
Tm	0,98	0,64	1,03	0,57	0,76
Yb	6,15	3,71	5,62	3,2	4,43
Lu	1,22	0,62	0,96	0,53	0,75
Cs	2,19	4,47	3,31	0,62	2,25
Ba	463	329	560	441	420
Sc	4,53	5,39	14,04	2,95	4,82
Cr	40	16	39	3	7
Co	2,67	2,92	2,07	0,42	2,64
Ni	10	11	100	40	12
Zn	-	25	68	21	27
Se	-	2,35	2,26	6,1	4,81
As	1,10	3,37	10,58	2,36	13,94
Sb	0,58	0,26	0,27	1,77	0,57
Th	33,5	25,5	20	15,5	23
U	13,33	2,72	3,3	3,1	4,39
Hf	8,75	5,02	4,53	6,22	9,07
Ta	2,23	2,29	1,96	4,08	3,12
Be	4,30	4,6	3,4	2,9	4,7
Pb	21	22	7,8	6	104
Ga	14	17	15	14	14
Cu	37	11,1	5	6,6	7,9
V	17	26	6	8	21
F	175	197	396	-	-
Y	43	36	72	31	38
Zr	435	215	96	216	430
Nb	20	14	22	-	22
Rb	245	221	158	150	179
Sr	24	98	72	24	59

thermo-emission of Pb, at the Isotopic Laboratory of the Institute of Geology, Komi Science Centre (Syktyvkar, Russia). Results *N* 19, 21–23 in Table 3 were obtained by dating the U/Pb

in zircons at the Laboratory for geochronology and geochemistry of isotopes, Geological Institute, Kola Science Centre (Apatity, Russia). Results *N* 5–6, 20 in Table 3 were obtained by the Rb/Sr isochron method at the Isotopic Laboratory of the Institute of Geology, Komi Science Centre (Syktyvkar, Russia). Details of the analytic procedures for the isotopic geochronology studies are described in the papers referenced (Table 3) and on the official web-sites of the Laboratories.

Isotopic ages of Pre-Ordovician granitoids range over a time interval that spans from Cryogenian to Late Cambrian. During much of this time interval, I-type granitoids and felsic volcanics

formed. In particular, andesitic dacites and granodiorites of the Lapchavozh massif yielded ages of 695 ± 19 and 632 ± 7 Ma (Pb–Pb method) respectively. The age of the granites in the Maldy massif is 584 ± 9 Ma (Pb–Pb method). The age of the quartz diorites in the southern part of Naroda massif is 548 ± 5 Ma (U–Pb method), and for the granites we obtained a date of 515 ± 8 Ma (U–Pb method).

A-type granites and volcanics are characterized by Ediacaran–Cambrian dates. In particular, rocks of the Lemva massif exhibit ages of 526 ± 7 (rhyolites) and 564 ± 6 ; 558 ± 21 ; 530 ± 20 Ma (granites) (Pb–Pb method). The rhyolites of the Maldy

Table 3
The isotopic ages of Timanides and Pre-Uralides granitoids

№	Locations of sampling	Rocks type	Granitoids type	Age	method	referenses
Izma block						
1*	Borehole South Cherkayu-10	Granite	I-type	553 ± 6	Pb–Pb**	Gee et al., 2000
2*	Borehole Malaya Pera-11	Granite	I-type	551 ± 8	Pb–Pb**	Gee et al., 2000
3*	Borehole East Cherkayu-1	Granite	I-type	557 ± 15	Pb–Pb**	Gee et al., 2000
4*	Borehole Pyl'yu-21	Diorite	I-type	560 ± 15	Pb–Pb**	Gee et al., 2000
5	Krayny Kameshek massif	Syenite	I-type	$613 \pm 2 (603 \pm 6)$	Pb–Pb** (Rb/Sr)	Andreichev and Larionov, 2000 (Andreichev, 1998)
6	Bolshoj Kameshek massif	Granite	I-type	$612 \pm 3,5 (597 \pm 6)$	Pb–Pb** (Rb/Sr)	Andreichev and Larionov, 2000 (Andreichev, 1998)
7	Rumyanishny Cape massif	Syenite	I-type	613 ± 7	U–Pb SHRIMP	Larionov et al., 2004
Pechora block						
8*	Borehole Novaja-1	Diorite	I-type	565 ± 8	Pb–Pb**	Gee et al., 2000
9*	Borehole V. Khar'yaga-26	Granite	I-type	567 ± 36	Pb–Pb**	Gee et al., 2000
Bolshezemel block						
10*	Borehole Veyak-2	Granite	I-type	618 ± 6	Pb–Pb**	Gee et al., 2000
The Urals						
11	Maldy massif	Granite	I-type	584 ± 9	Pb–Pb	Soboleva, 2004
12	Frame of Maldy massif	Rhyolite	A-type	$516 \pm 19, 519 \pm 17$	Pb–Pb	Soboleva, 2004
13	Lemva massif	Granite	A-type	$530 \pm 20, 558 \pm 21, 564 \pm 6$	Pb–Pb	Soboleva, 2004
14	Frame of Lemva massif	Rhyolite	A-type	526 ± 7	Pb–Pb	Soboleva, 2004
15	Lapchvoz massif	Quartz diorite	I-type	632 ± 7	Pb–Pb	Soboleva, 2004
16	Frame of Lapchvoz massif	Andesidacite	I-type	695 ± 19	Pb–Pb	Soboleva, 2004
17	Northern part of Naroda massif	Granite	A-type	518 ± 10	U–Pb	Dorokhov and Kudryashov, 2002
18	Northern part of Naroda massif	Granite	I-type	557 ± 7	Rb–Sr	Anreichev and Ydovich, 1999
19	Southern part of Naroda massif	Granite	I-type	515 ± 8	U–Pb	Dorokhov and Kudryashov, 2002
20	Southern part of Naroda massif	Granodiorite	I-type	544 ± 4	U–Pb	Soboleva et al., 2004
21	Southern part of Naroda massif	Quartz diorite	I-type	548 ± 5	U–Pb	Soboleva et al., 2004
22	Southern part of Man'khambo massif	Granite	A-type	522 ± 6	U–Pb SHRIMP	Udoratina et al., 2006
23	Central part of Man'khambo massif	Granite	A-type	513.6 ± 5.6	U–Pb SHRIMP	Udoratina et al., 2006
24	Central part of Il'yaiz massif	Granite	I-type	510.1 ± 5.8	U–Pb SHRIMP	Udoratina et al., 2006
25	Tynagota massif	Granite	A-type	498 ± 4	U–Pb SHRIMP	Kuzenkov et al., 2004
26	Malotyngota massif	Granite	I-type	520 ± 4	U–Pb SHRIMP	Kuzenkov et al., 2004
27	Vangyr massif	Granite	I-type	598 ± 2.3	U–Pb SHRIMP	Udoratina et al., 2005

* - the number corresponde to borehole number in Fig. 2.

** - the Pb-evaporation Kober's technique by singl-zircon (207Pb/206Pb)

U–Pb SHRIMP - ion microprobe single zircon grain ages

massif are dated at 516 ± 19 and 519 ± 17 Ma (Pb–Pb method). Granites of the northern part of the Naroda massif have a crystallization age of 518 ± 10 Ma (U–Pb method).

In some cases, granitoids of both I- and A-types are spatially associated in composite granitoid massifs. In particular, granites of A-type and a wide spectrum of granitoids of I-type can be observed in the Naroda massif (Fig. 3). Biotite granites in the southern part of the Naroda massif are the latest differentiates of the calc-alkaline I-type series. They are dated at 515 ± 8 Ma. Leucogranites of A-type, composing the north part of the massif, were dated at 518 ± 10 Ma. Thus, they were formed at the same time within the error of isotopic dating.

Due to the remoteness of the Northern Urals, boreholes that extend down to the basement of Timan–Pechora basin are rare, and the dataset presented in Table 3 is the only information available at this time. Because the available geochronological data are poor and non-uniformly scattered over the region, they may not reflect details of geographic/temporary variations of

type of magmatism, nor volume of igneous rocks. But they do not show any essential temporal amagmatic gap, and we can conclude that magmatism lasted for approximately 200 Ma, specifically lasting about 185 Ma for I-type granitoids and about 65 Ma for A-type granitoids (Fig. 6).

Some zircons found within I-type granites have inherited cores. For example, in the Vangyr massif the inherited core of a magmatic zircon has an age of 1224 ± 9 Ma (Udoratina et al., 2005). Ages of inherited zircons' inclusions vary from ~ 0.9 to ~ 2.7 Ga in several granites of basement of Timan–Pechora basin (Gee et al., 2000). These inherited zircon cores are evidence for the involvement of the Archaean–Mesoproterozoic crust during the formation of granitoids in the basement of Timan–Pechora basin and the western flank of the Northern Urals.

3.4. Tectonic classification and palaeo-tectonic setting

Mineral and chemical compositions of the Pre-Ordovician granitoids and felsic volcanic rocks, reflect distinct structures of the crustal source (Makhlaev, 1996) and the tectonic setting during their formation (Soboleva, 2004). Granitoids of I-type have no geochemical signatures of a primitive island arc, and are interpreted to be subduction/collision-related. A-type granitoids are attributed to a late- and post-collisional intraplate origin (Fig. 7).

The formation of I-type granitoids and associated volcanic complexes spans an interval of ca. 700 to 515 Ma. The magmas giving rise to these rocks form a crustal-derived, continuously differentiated magma series. In general, their formation corresponds to crustal growth and thickening at an active continental margin and/or in a continental collision zone.

The formation of A-type granitoids and associated volcanic complexes spans an interval from ca. 565 to 500 Ma, and temporally overlaps with I-type magmatism. Magmatites of A-type are a part of contrasting gabbro-granitic and basalt–rhyolitic paragenetic associations. Their formation generally corresponds to localized extensional/transensional regimes that accompany regionally destructive tectonic settings.

4. The Neoproterozoic–Middle Cambrian tectonic evolution of the northeast part of the East European Craton

4.1. Review of previous tectonic concepts

By the Neoproterozoic, the skeleton of the East-European Craton – Baltica – consisted of three large blocks – Fennoscandia, Volgo-Uralia and Sarmatia (Bogdanova, 1993). Many tectonic scenarios for the Neoproterozoic–Middle Cambrian evolution of the east and northeast margins of Baltica (in modern coordinates) have been suggested (review in Kuznetsov et al., 2005a). We briefly summarize the most significant of these hypothetical tectonic scenarios.

A plate tectonic reconstruction for the basement of the Timan–Pechora basin was first proposed by Yudin and Dedelev (1987). Kostyuchenko (1994), Olovyanishnikov (1998), Scarrow et al. (2001), Pease et al. (2004), Dovzhikova et al. (2004), Roberts and Olovyanishnikov (2004), Cocks and Torsvik (2005) have

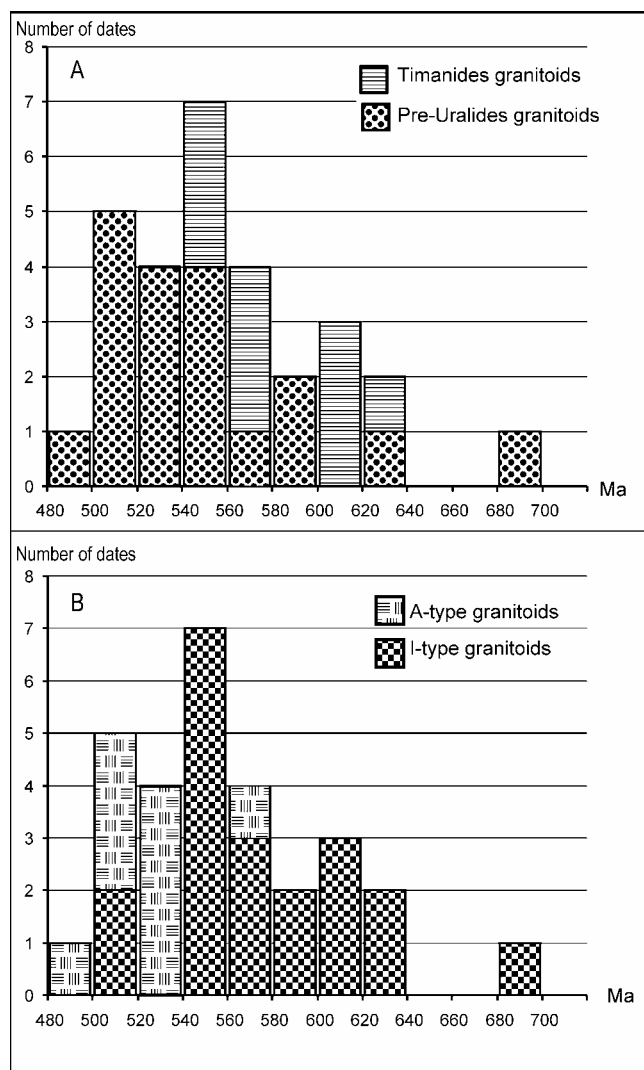


Fig. 6. Histograms of isotopic ages of the Pre-Ordovician granitoids and associated volcanics of the basement of the Timan–Pechora basin and the western flank of the North Urals (based on data from Table 3) subdivided (A) by location and (B) by types. Widths of the sliding window and step window are 20 Ma.

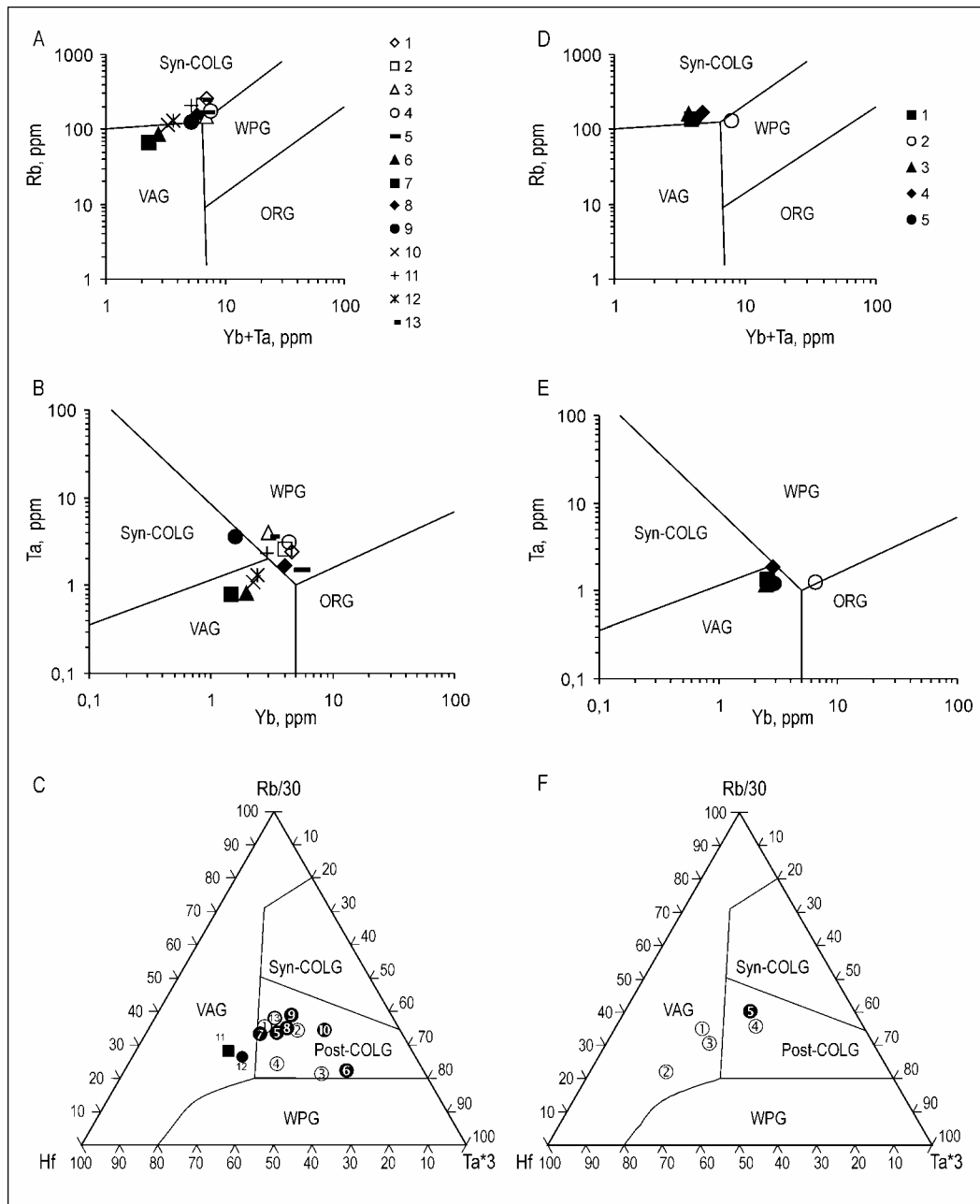


Fig. 7. Tectonic classification of granitoids of the Pre-Uralides (A, B, C) and Timanides (D, E, F). A, B, D, and E — diagrams after Pearce et al. (1984), C and F — diagrams after Harris et al. (1987). Symbols for A, B, C diagrams: granitoids A-type: 1 - Lemva massif, 2 - Tynagota massif, 3 - Man'khambo massif, 4 - Kulemshor massif, 5 - Naroda massif, north part; granitoids I-type: 6, 7 - Naroda massif, south part, granites (6), granodiorites (7), 8 - Vangyr massif, 9-10 Lapchavozh massif, granites (9), granodiorites (10), 11 - Malydy massif, 12-13 - Il'yaiz massif, granites (12), leucogranites (13). Symbols for D, E and F diagrams: granitoids of the basement of Timan-Pechora basin from boreholes: 1 - Charkayu-1, 2 - Veyak-2, 3 - Charkayu-10, 4 - M.Pera-11, 5 - V.Har'yaga-26 (Dovzhikova et al., 2004). For location of boreholes see in Fig. 1. VAG - volcanic island arc granitoids, Syn-COLG - syncollisional granitoids, WPG - intraplate granitoids, ORG - mid-oceanic ridge granitoids, Post-COLG - post-collisional granitoids. Granitoids corresponding to granitoids I-type are shown by filled symbols, A-type — by open symbols.

developed different models, and all interpret the northeastern margin of Baltica (Timan margin) as an active continental margin with inward subduction during the Late Neoproterozoic-Middle Cambrian, or during at least a part of this time span. An alternative interpretation considers that the Timan margin of Baltica represents a passive margin during the Neoproterozoic (Maslov, 2004; Beckholmen and Glondy, 2004). Later, at the boundary between the Ediacaran and Cambrian, the margin is thought to

have been involved in outward (northeast in modern coordinates) subduction (Beckholmen and Glondy, 2004).

In spite of the different interpretations on the nature of the Timan margin of Baltica (passive or active), the models imply an accretionary style of tectonics for the basement of Timan-Pechora basin. A palaeo-ocean (Timan-Pre-Uralian, after Yudin and Dedeev, 1987) is thought to exist to the northeast of Baltica during the Neoproterozoic and Cambrian.

With regards to the Pre-Uralides of the Western-Uralian megazone, there is a consensus that the Pre-Uralides were formed on the eastern margin of the East European Craton in the Neoproterozoic-Cambrian. Ivanov et al. (1986) consider the Pre-Uralides to be complexes of the mid-continental Mesoproterozoic-Cambrian rift while others consider the Pre-Uralides to be active continental margin complexes (Dushin, 1997; Scarrow et al., 2001; Linnemann et al., 2004; Ruzhenzev and Samygin, 2004). In particular, Linnemann et al. (2004) and Scarrow et al. (2001) believe that the Pre-Uralides were formed in the continuation of the Avalonian-Cadomian subduction-related belt. Other authors consider Pre-Uralides to be complexes from a passive continental margin (Samygin and Leites, 1986; Puchkov, 1997, 1998). However, Puchkov (1997, 1998) believes that a passive margin regime changed to a collision of Baltica and Proto-Gondwana (approx. 630–570 Ma), and consider the Pre-Uralides and Timanides as a part of the Cadomian-Avalonian collisional orogen.

It is important to note, that Pre-Uralian complexes display basic differences in the north and south of the Central Uralian Uplifts (Fig. 1). The existing tectonic models have not explained this fact. In this paper a different interpretation of Neoproterozoic-Cambrian tectonic evolution of the northeast and east region of the East European Craton has been proposed including the collision of two palaeo-continents, Baltica and Arctida.

4.2. *Arctida palaeo-continent*

Shatsky (1935) first mentioned an ancient continent in the Arctic region. Later, Zonenshain et al. (1990) carried out the first plate tectonic reconstruction of this ancient continent (named Arctida) which was inferred to have existed as a separate continent up into Middle Paleozoic, unrelated to the East European Craton. Arctida paleogeography has been restored (Borisova et al., 2002; Kuznetsov et al., 2005a,b) on the basis of new geological (Egorov et al., 2002), paleomagnetic (Metelkin et al., 2000), and geophysical data (Jorgensen, 1995).

In the Late Mesozoic to Early Cenozoic, Arctida was fragmented as a result of spreading in the North Atlantic and Arctic oceans, as oceanic basins opened (the Makarov, Amerasian, and Eurasia basins) (Fig. 8). Generally, the tectonic reconstruction of Arctida is poorly constrained, because the Arctic region is not well studied. There are many details that are under discussion. For example, the Spitsbergen block is referred to as Laurentia (Gee and Teben'kov, 2004; Cocks and Torsvik, 2005). However, old stratigraphic complexes and granitoids of the Spitsbergen archipelago are the northeast continuation (in a structural sense) of the Scandinavian Caledonides. The complexes are allochthonous in Scandinavia and there is reason to believe that the Spitsbergen Caledonides are also allochthonous. The autochthonous basement of the Scandinavian Caledonides is Baltica, but the autochthonous basement for the Spitsbergen Caledonides is Arctida. We propose that the Neoproterozoic

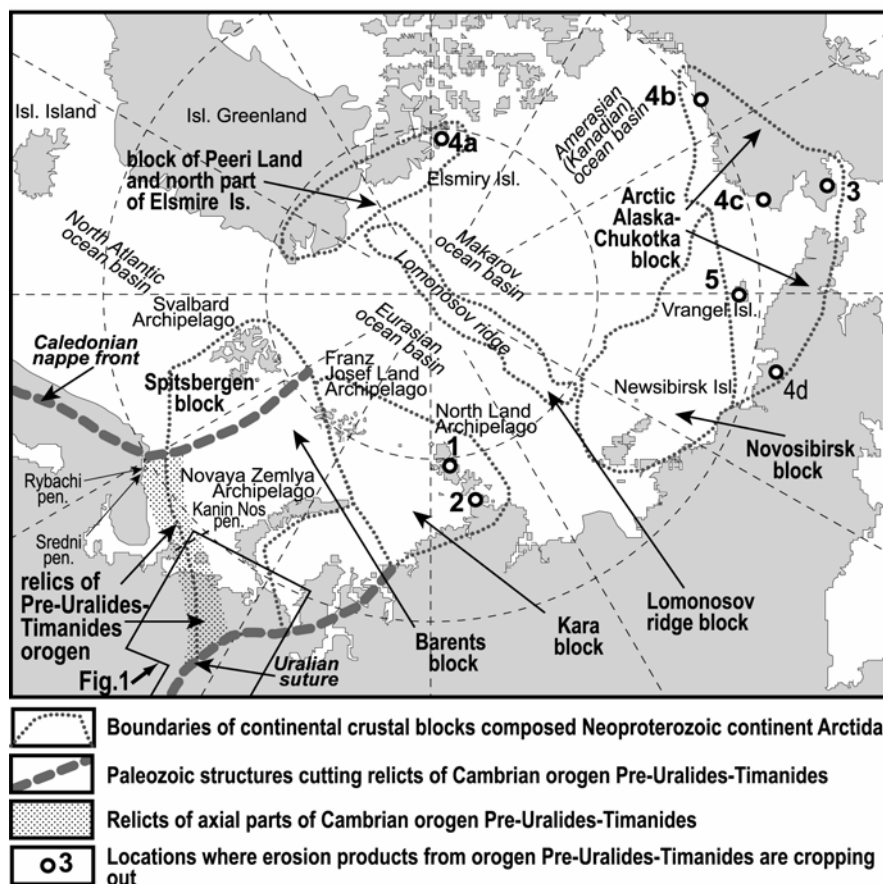


Fig. 8. Some tectonic elements of the Arctic sector.

complexes in Wedel Jasberg Land area, in the southwestern Spitsbergen might be an elevation of the Arctida autochthonous basement. The Neoproterozoic complexes are dislocated into a large northwest-southeast trending anticline with northeast vergence. Smaller asymmetrical folds at different scales with the same axes trend and vergence are overprinted. They are interpreted to record deformations driven by northeast-southwest directed compression (Bjornerud et al., 1991). The fold axes trend orthogonal to the Caledonian deformational front. However, the same fold axes show that trend and vergence of the megascopic structural paragenesis were fixed in the complexes of Pre-Uralides-Timanides in Enganepe uplift (Kuznetsov et al., in press). This fold axes trend is also typical of Timanian dislocations in the Sredni and Rybachi peninsulas (Roberts, 1995), but the folds here have southwest ("mirror" relative to the Wedel Jasberg Land area) vergence, as if they originated from the opposite flank of a divergent orogen.

It has been known for a long time that the Paleozoic complexes unconformably overlie the dislocated and eroded relicts of the Timanides that now form the basement of Timan-Pechora basin. The complexes continue northward into the Paikhoi mountains and the archipelago Novaya Zemlya (Bogolepova and Gee, 2004). These complexes are geophysically (via seismic stratigraphy) traced onto the shelves of the Barents and Kara seas. This means, that by the beginning of Paleozoic, the whole area had become part of Baltica.

The recent paleomagnetic definition of the October Revolution Island (North Land Archipelago) for the Late Cambrian-

Early Ordovician (Metelkin et al., 2000) indicates that the Kara block had the same paleomagnetic poles as the East European Craton at the least from the Late Cambrian (Fig. 9). These data are consistent with an Arctida-Baltica collision before the Cambrian.

4.3. Baltica-Arctida collision

4.3.1. Pre-Ordovician granitoids as tectonic indicators of the Baltica-Arctida collision

The Timan edge of Baltica is commonly interpreted to have grown by accretion during the Late Neoproterozoic-Middle Cambrian. In particular, the Kolguev and Khareyver and a few smaller massifs, which are allocated in the Bolshezemel domain of the basement of Timan-Pechora basin (Fig. 1), are interpreted as accreted microcontinents or terranes (Olovyanishnikov, 1998; Roberts and Olovyanishnikov, 2004). The massifs are spatially divided by zonal development of the Neoproterozoic (?) melanocratic rocks (basic-ultrabasic) and intermediate and felsic volcanogenic and/or volcanogenic-tuffogenic rocks and their associated sedimentary (clastic) complexes. They are generally interpreted to be suture zones, formed during the accretion of terranes.

However, if the growth of the Timan margin of Baltica (modern basement of Timan-Pechora basin and western flank of the North Urals) occurred by accretion of terranes, there should be a northeast-younging trend in age of I-type granitoids and associated volcanics reflecting the migration of a magmatic

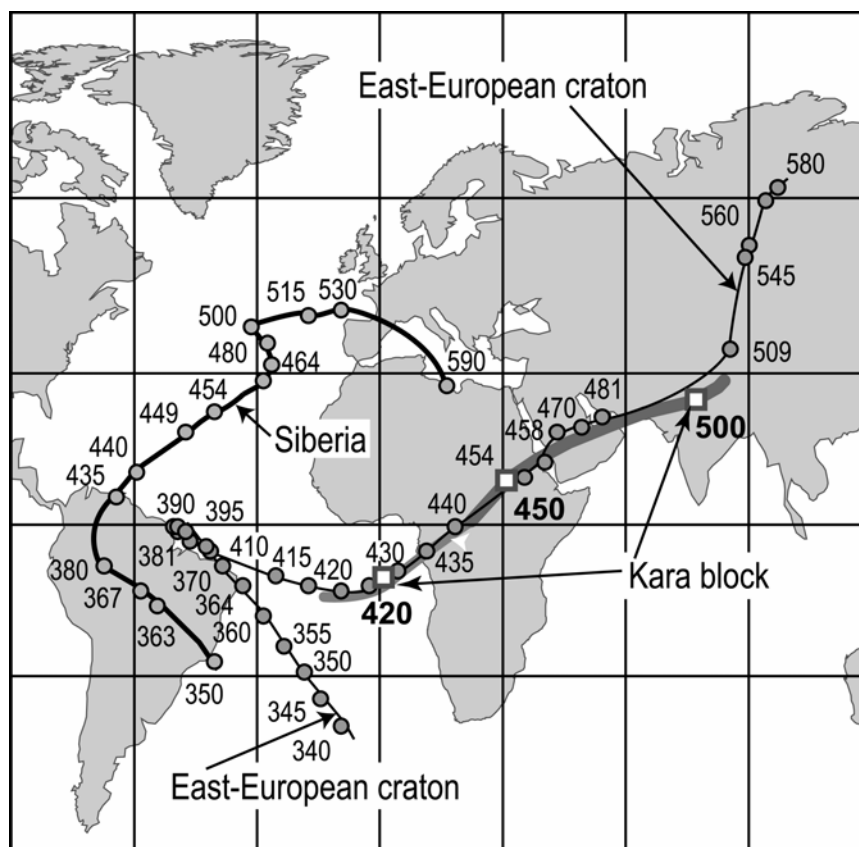


Fig. 9. Comparison of the Late Neoproterozoic-Middle Paleozoic segments of the Polar Wander Curves for Siberia and East European Craton in accordance to Hramov et al. (1999) and Kara block (Metelkin et al., 2000). The figure was plotted with help of the GMAP computer program (Torsvik and Smethurst, 1999).

front. However, the available I-type granitoid age data (Table 3 and Fig. 6) do not show any obvious space-time relation both for the whole Timan-Pechora - North Urals region, and for the Kozhim block. The oldest and the youngest of I-type granitoids are found in the Northern Urals. The ages ~ 565 Ma and ~ 618 Ma were obtained for I-type granites from adjacent boreholes in Bolshezemel domain (Fig. 1, numbers 9 and 10), and ages ~ 612 Ma for the North Timan hills region, whereas granitoid ages in Pripechora-Ilych-Chiksha fault zone yield ages of ~ 555 Ma. A tendency for random ages, together with the change in type of granitoid magmatism over time (I- and A-types), and the compositional-structural features of the Pre-Uralides-Timanides, all indicate that the northeastern margin of

Baltica was involved in a more complicated tectonic scenario than a simple (step by step) accretion of terranes.

In our interpretation the northeastern and eastern margins of Baltica were passive continental margins in the Mesoproterozoic and Neoproterozoic (excluding Ediacaran), during which thick sediments were accumulated. These sedimentary rocks are exposed in the Timan mountains, and the Timan domain of the basement of the Timan-Pechora basin (Olovyanishnikov, 1998; Roberts and Olovyanishnikov, 2004), the Kvarukh anticline and the Bashkir uplift (Maslov, 2004) (Fig. 1). In contrast to the Bashkir uplift, the Uraltau and Ebeta uplifts in the southern Central Uralian Uplifts include Neoproterozoic subduction-related volcanics, and rare ophiolites (Ruzhenzev and Samygin,

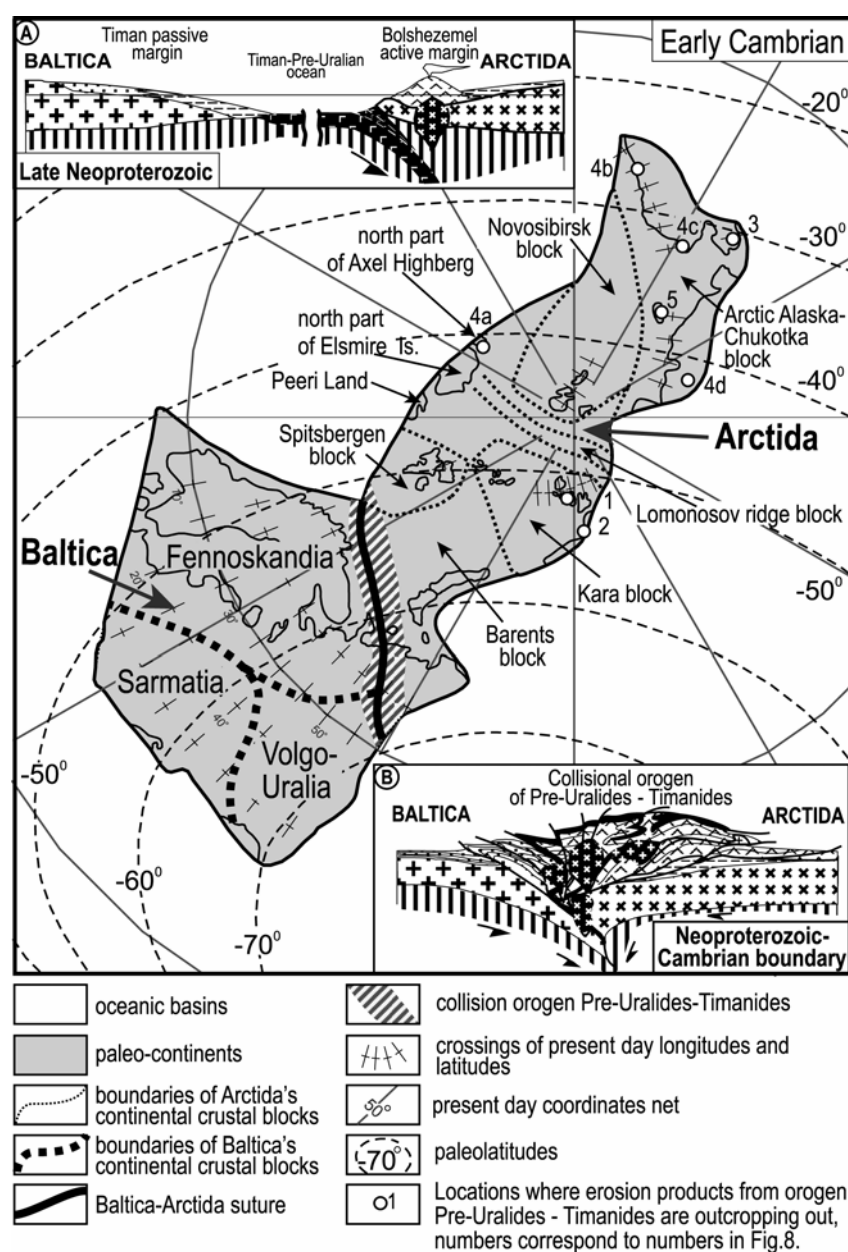


Fig. 10. A plate tectonic reconstruction for the Early Cambrian after Borisova et al. (2002) and Kuznetsov et al. (2005a) with changes and additions. (A) Schematic geodynamic section (southwest—northeast, modern orientation) across the passive Timan margin of Baltica and active Bolshezemel margin of Arctida for Late Neoproterozoic time. (B) Schematic section (southwest-northeast, modern orientation) across the Cambrian collisional orogenic belt of the Pre-Uralides-Timanides.

2004), intruded by Varangian (discordance U–Pb age 590 ± 4 Ma) granitoids (Fedotova et al., 2006). But they do not constrain the geodynamics of the passive eastern margin of Baltica, because these tectonic units did not originate on Baltica and instead have a peri-Gondwanan (Cadomian) origin (Puchkov, 1998; Kuznetsov, 2005; Kuznetsov et al., 2005b).

The Timanides of the Bolshezemel domain of the basement of the Timan-Pechora basin, and the Pre-Uralides of the Lyapin anticline, and all other units of the Central Uralian Uplifts to the north from the Lyapin anticline consist of volcanic-sedimentary rocks, granitoids and rare ophiolite complexes. We propose that they formed at the Bolshezemel active margin of Arctida during Neoproterozoic (Fig. 10A). The early phase of the calc-alkaline granitoid magmatism of I-type ranges from ~ 700 Ma to ~ 560 Ma and indicates an active marginal tectonic setting.

A collision of the Timan passive margin of Baltica and the Bolshezemel active margin of Arctida, occurred during the Ediacaran–Middle Cambrian (Fig. 10B). The most important, substantial expression of the collision is the I-type granitic magmatism dated at ~ 560 Ma.

Late episodes of coeval syncollisional I-type granitic magmatism, A-type granitoids and comagmatic volcanics formed between ~ 565 and ~ 500 Ma. A-type magmatites are spatially associated with gabbro and basalts, forming bimodal associations. A-type granitic magmas were formed in zones affected by intrusion of continental tholeiitic mafic rocks. A-type granites form elongated intrusive massifs in linear tectonic zones (Fig. 3) and probably mark a local extensional setting, with faulting of the continental crust.

4.3.2. *Structural features of the collisional orogenic belt of the Pre-Uralides-Timanides*

A structural expression of the Arctida-Baltica collision was the formation of an asymmetrical divergent orogenic belt of the Pre-Uralides-Timanides of Cambrian age (Fig. 10B). Relicts of the axial part of the orogenic belt are the Izhma and Pechora blocks. The relicts of the orogenic belt are now traced to the southeast in the Central Uralian Uplift structures as the Kozhim block of Lyapin anticline. To the northwest, the orogenic belt can be traced into the Rybachi and Sredni peninsulas and partially into Varanger peninsula where the belt is called the Timan-Varanger folded system (Roberts and Olovyanishnikov, 2004; Cocks and Torsvik, 2005).

The southwest (in modern coordinates) flank of the orogenic belt was mostly composed of Mesoproterozoic–Neoproterozoic complexes of the Timan passive margin of the Baltica. But several allochthonous complexes of the Bolshezemel active margin of Arctida are recognized in the southwestern flank of the orogenic belt, known as the Lyamcha and Lunvozh (Olovyanishnikov, 1998) suites and their correlatives. Seismic reflection sections across the Timan domain (southwest flank of the belt) clearly show that the fold and fault systems here are southwest verging (Kuznetsov et al., 2005a). Roberts (1995) recognized similar structures in the Sredni and Rybachi peninsulas.

Complexes of the Bolshezemel active margin of Arctida were located in the axial zone and the northeastern flank of the orogenic belt. Most complexes on the northeastern flank have

been involved in a large amplitude nappe transport which destroyed older accretionary structures. This flank of the orogenic belt is characterized by the folds that have northwest trending axes and northeast vergence. Similar structural patterns are observed in the Pre-Uralides-Timanides complexes exposed in the Enganepe uplift (Kuznetsov et al., in press). The Neoproterozoic complexes of the Wedel Jasberg Land area in Spitsbergen, where Bjornerud et al. (1991) recognized analogical structural patterns, might be a northwest prolongation of the northeastern flank of the orogenic belt of the Pre-Uralides-Timanides. The nappes of the allochthonous complexes of Bolshezemel margin of Arctida were transported inside Arctida and they tectonically overlie the back arc complexes of the margin.

The nappe structure was dislocated into simple fold patterns. Later in the Cambrian, the orogenic belt was tectonically reworked and eroded. Structures on the northeastern flank of the belt were fragmented and are now observed as elongated zones of melanocratic (basic/ultrabasic) volcanic series, and volcanic-sedimentary and sedimentary complexes. The zones are large synforms — the Nizhne-Pechora and Kozhim-Vangyr synforms, and smaller ones (Fig. 2) in the basement of Timan-Pechora basin. There is also the Enganepe uplift in the Polar part of Central Uralian Uplifts (Fig. 1) where the allochthonous Neoproterozoic complexes are exposed.

In the present-day structure of the basement of the Timan-Pechora basin, synforms alternate with antiforms. The antiforms are the Kolguev, Khareyver and other similar smaller uplifts (Figs. 1 and 2). In the core parts of these antiforms, Neoproterozoic complexes correspond to the back arc portion of the Bolshezemel margin of Arctida and older rocks occur. Olovyanishnikov (1998) interpreted these uplifts as exotic tectonic blocks (terrane) bounded by wide fault zones (sutures) that contain basic-ultrabasic complexes. But the uplifts are not necessarily accreted terranes. We consider them to be large antiforms, and the zones of basic-ultrabasic complexes to be large synforms. The synformal structures (Khariyaga, Shariya-Makarikha, and Verhnyaya Adzva (Fig. 2), and smaller ones) are composed of Neoproterozoic allochthonous ophiolitic and differentiated volcanic and volcanic-sedimentary complexes from the frontal portions of the Bolshezemel active margin of Arctida. The autochthonous sedimentary complexes (approximately coeval to allochthonous complexes of the synforms) and their old basement are located in the cores of the antiforms.

4.3.3. *The erosion products of the collisional belt of the Pre-Uralides-Timanides*

The collisional orogenic belt of the Pre-Uralides-Timanides was exposed during the Late Cambrian–Early Ordovician (some parts up to Middle Ordovician) and generated erosion products which were transported throughout the Arctida palaeo-continent. The following populations of detrital zircons and others minerals found in different regions of the Arctic sector, with ages around ~ 560 Ma (Figs. 8 and 10):

- (1) According to Gee et al. (2005) who have collected samples on October Revolution Island, Cambrian turbidites yield

- an 545 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age for detrital muscovite. Lorenz (2005) reported that the Ordovician igneous rocks on October Revolution Island contain zircons with 566.6 ± 9.3 , 544.6 ± 9.0 , 579.7 ± 9.6 , and 578.9 ± 6.4 Ma ages xenocrysts (inherited cores).
- (2) Pease (2001) reported on detrital zircons populations in two Neoproterozoic/Cambrian greywacke samples from the easternmost Taymyr. These yielded ages mostly between ca. 550 and 700 Ma, with pronounced cumulative frequency peaks in both samples at ca. 560 Ma. It is emphasized that comparable ages are obtained for granites in the basement of the Timan-Pechora basin (Gee et al., 2000).
 - (3) Amato (2004) reported on orthogneiss (Thompson Creek) from the Seward Peninsula (Western Alaska) with metamorphic rims growing on igneous cores. The ages from the core are 565 ± 6 Ma (average of three $^{206}\text{Pb}/^{238}\text{U}$ ages) or 583 ± 17 Ma (upper intercept, 9 grains) with $\text{Th}/\text{U} > 0.4$. The rim ages are 94 ± 2 Ma. It is emphasized that the obtained ages are atypical for Laurentia, and that Barentsia/Baltica is indicated as a possible source.
 - (4) Zircons with ages of ca. 560 Ma were reported from the Sverdrup Basin, Isl. Axel Heiberg (Figs. 8 and 10, point 4a), Sadlerochit mountains (Figs. 8 and 10, point 4b) and Lisburne Hills (Figs. 8 and 10, point 4c), North Alaska, and Margovaam basin (Figs. 8 and 10, point 4d), North Chukotka (Miller et al., 2004, 2006).
 - (5) Two zircons from Triassic sandstones on Vrangell Island yield ages of 510.7 ± 15.7 and 667.6 ± 17.7 Ma (Miller et al., 2006).

The Arctic Alaska—Chukotka block was separated from Siberia during the Paleozoic up to the Early Mesozoic by the Anyui Ocean (Miller et al., 2006 and references therein), therefore all zircons found in Triassic sandstones of the Arctic Alaska-Chukotka block could not be from a Siberian source. On the other hand, according to a summary by Hoffman (1989), who reviewed the ages of the Precambrian bedrocks of the North American continent, the Late Neoproterozoic magmatic/metamorphic rocks are known only in a few small locations in the Appalachian mountains. So, there is a low probability that Laurentia was a source province for the zircon populations in the Arctic with ~ 560 Ma ages. We suggest that the most probable sources of the zircon populations for the entire Arctic sector are the magmatic and metamorphic complexes from the Bolshezemel active margin of Arctica and from the collisional orogen belt of Pre-Uralides-Timanides.

5. Summary

Pre-Ordovician complexes of the eastern and northeastern region of the East European Craton, the Pre-Uralides-Timanides, are divided into two large groups with different compositions. (1) The southwestern Timanides (including the Timan domain of the basement of Timan-Pechora basin) and the southern Pre-Uralides (including the Kvarkush anticline and Bashkir uplift) consist predominantly of sedimentary rocks.

(2) The northeastern Timanides (including the Bolshezemel domain of the basement of the Timan-Pechora basin) and the northern Pre-Uralides (including the Lyapin anticline and all of the other northern units of Central Uralian Uplifts) are composed of the volcanic-sedimentary and volcanogenic series, granitoids, and rare ophiolites.

The southwestern Timanides and southern Pre-Uralides were formed at the passive Timan margin of Baltica, and the northeastern Timanides and northern Pre-Uralides were formed on the active Bolshezemel margin of Arctica and in the collision zone between Arctica and Baltica (Fig. 10).

Pre-Ordovician granites and associated volcanics of the second group of the Pre-Uralides-Timanides are subdivided into I- and A-types.

Granitoids and volcanics of I-type associations are part of a continuous differentiated magmatic series. I-type volcanics vary in composition from andesites up to rhyodacites. I-type granitoids include a wide spectrum of rocks ranging from quartz diorites up to leucogranites. They are characterized by normal or slight alkalinity, and by the presence of alkali feldspars. I-type granitoids are parts of the differentiated calc-alkaline series with a positive correlation between total alkalinity and the SiO_2 content. They have geochemical signatures typical of an island arc, an active continental margin and/or collisional zones.

Granitoids and comagmatic volcanics of A-type are parts of the bimodal gabbro-granite and basalt-rhyolite paragenetic associations. A-type volcanics are mainly represented by rhyolites with porphyritic textures. A-type granites are homogeneous in composition. Leucocratic alaskite varieties prevail among them. A-type granitoids are usually hyperalkaline and contain alkali feldspars. They are characterized by more restricted variations in the major element composition and an inverse relationship between total alkalinity and SiO_2 .

The formation of I-type granitoids corresponds to the processes of growth and thickening of the continental crust in either an active continental margin and/or in a zone of continental collision. The formation of A-type granitoids and associated volcanics corresponds to extensional/transensional regimes within a convergent tectonic setting. Isotopic ages for I granitoid magmatism cover a time interval of ca. 185 Ma (700–515 Ma), and A-type granitic magmatism ca. 65 Ma (565–500 Ma) (Fig. 6).

The calc-alkalic I-type magmatism with ages from 700 to 515 Ma, corresponds to subduction-related (Bolshezemel active margin of Arctica) and collision-related (Baltica-Arctica collision) magmatism. In contrast, A-type granites with ages from 565 to 500 Ma are members of a bimodal sequence. A-type granitic magmas could be formed in zones that were warmed by ascending mafic magma. A-type granites form elongated intrusive massifs within linear tectonic zones, and mark a local extensional setting with faulting in the continental crust.

A crucial time in the Neoproterozoic-Cambrian tectonic evolution of the northeastern portion of the East European Craton was the collision between Baltica (Timan passive margin) and Arctica (Bolshezemel active margin) during the Ediacaran-Middle Cambrian. The collision was accompanied

by Alpine-style nappes, which were extensively transported during continental collision and overlapped the complexes in the marginal regions of the both continents. Later, the collisional belt of Pre-Uralides-Timanides was tectonically reworked and eroded. Some fragments of the northwest flank of the orogenic belt are now observed as elongated synformal structures in Bolshezemel domain. These synforms are adjacent to antiforms. The synforms and antiforms demonstrate a three-layered architecture in the basement of Timan-Pechora basin. The upper layer consists of the allochthonous Neoproterozoic formations of the active Bolshezemel margin of Arctida. The second layer consists of autochthonous, mostly sedimentary complexes, of an epi-continental margin basin. The lower layer consists of pre-Neoproterozoic basement rocks of the consolidated crust of the Arctida palaeo-continent.

We suggest that the most probable sources of the zircon populations with ages around ~ 560 Ma for the entire Arctic sector are the magmatic/metamorphic complexes from the collisional orogen belt of Pre-Uralides—Timanides.

The proposed Baltica-Arctida collision concept adds new constraints to global-scale tectonic syntheses. In particular, the most recently known plate motion reconstructions (Hartz and Torsvik, 2002; Murphy et al., 2004; Cocks and Torsvik, 2005; etc.) do not take into account the Neoproterozoic continent Arctida, but separate the Timan, Pechora, Barents, Kara and other blocks. Future modifications to these reconstructions have to: (1) account for Arctida's landmasses during the Neoproterozoic (? in Rodinia), and specify the Cambrian composite continent (Arctida+Baltica) in the Paleozoic plate configurations; (2) take into account a passive margin tectonic regime for the Timan and Uralian margins of Baltica during the Neoproterozoic; and (3) imply not a simple accretion of small terranes, but instead complicated collision tectonics (? involving an oblique collision with a change of direction, a 'slab break' during collision, etc.) for the Timan margin of Baltica during the Ediacaran-Middle Cambrian.

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