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New, Single Zircon (Pb-Evaporation) Ages from Vendian Intrusions in the Basement beneath the Pechora Basin, Northeastern Baltica

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THEME 8: Polar Urals, Novaja Semlja and Taimyr: The Northern Connection of the Uralides

Summary: The Precambrian basement beneath the Pechora Basin of northern Russia is known from deep (up to approx. 4.5 km) drill holes to be largely composed of Neoproterozoic successions, variously deformed and metamorphosed and intruded by magmatic suites of Vendian age. Presented here are new single-zircon, Pb-evaporation (Kober method) ages from eight intrusions across the Izhma, Pechora and Bolshezemel´skaya Zones, all from below the Lower Ordovician (locally Middle Cambrian) unconformity. The majority of the intrusions (six) yield remarkably similar ages of 550-560 Ma, apparently dating a widespread pulse of late- to post-tectonic magmatism. An early Vendian granite (618 Ma) has been identified in the northeasternmost region (Bolshezemel´skaya zone) and a Devonian granodiorite (380 Ma) in the Pechora Zone, where mid to late Palaeozoic magmatism has been previously reported. Evidence of inheritance in the zircon populations suggests the presence of Mesoproterozoic crust beneath the Neoproterozoic complexes.

INTRODUCTION

Thick Neoproterozoic successions occur throughout the two thousand kilometre long eastern margin of the East European Craton. Within the foreland fold belt of the Uralide Orogen, in the cores of major late Palaeozoic anticlines, these late Riphean successions generally occur beneath a major unconformity which separates early Palaeozoic platform (margin) successions of the continent Baltica (see Annex) from the underlying Neoproterozoic (and locally older) strata. The Proterozoic rocks within these anticlines provide evidence of folding and thrusting prior to Palaeozoic deposition. This pre-Palaeozoic deformation along the eastern margin of Baltica is referred to here as Timanian; it is generally accompanied by sub-greenschist to greenschist facies metamorphism and was approximately contemporaneous with the Baikalian deformation marginal to the Siberian Craton and the Cadomian deformation of western Europe.

Throughout the Southern and Middle Urals, the trend of Timanian-age structures is longitudinal. In the Northern Urals, the strike swings to the northwest, diverging from that of the Uralide Orogen (Fig. 1). This approximately Vendian-age fold belt continues into the Timan Range and thence, via the Kanin Peninsula, along the northern edge of the Kola Peninsula and the southern Barents Sea, to the eastern part of the Varanger Peninsula of northern Norway (TSCHERNYSCHEV 1901, ROBERTS 1995, 1996, BOGATSKY et al. 1996).

The Timan Orogen (TSCHERNYSCHEV 1901, SCHATSKY 1935, GETSEN 1987) is a SW-verging fold and thrust belt in which Neoproterozoic basin successions are thrust over platform facies deposits of the East European Craton. In the Timan Range, folded and cleaved basinal turbidites are overlain with major unconformity by Devonian sandstones and associated mafic volcanic rocks. Further northeast, the Phanerozoic succession (BELYAKOV 1994) thickens and, beneath the late Palaeozoic and Mesozoic sequences of the Pechora Basin, both Silurian and Ordovician platform successions occur – sandstones (quartzites), carbonates, and shales, deposited along continent Baltica's passive margin. Devonian rifting and associated largely mafic magmatism was followed by partial Permo-Carboniferous inversion, prior to the deposition of the thick foreland basin successions (LOBKOVSKY et al. 1996, ISMAIL-ZADEH et al. 1997) in the front of the Polar Urals.

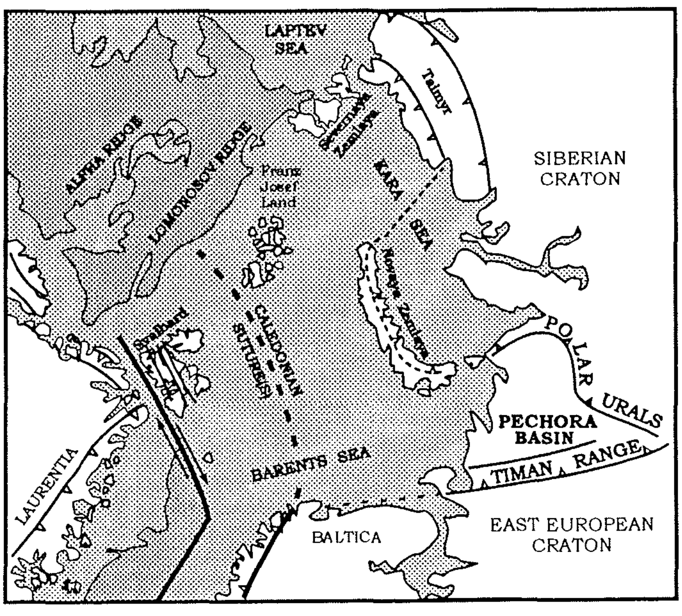

Fig. 1: Some of the main tectonic elements of the Arctic region in the early Tertiary and the regional setting of the study area.

The character of the basement beneath the Palaeozoic successions of the Pechora Basin, between the Timan Range and the Polar Urals, has long been controversial (e.g. SIEDLECKA 1975). In the Urals foredeep, the Mesozoic and younger strata reach 10-12 km in thickness and "basement" is unknown. Further

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west, deep drilling for hydrocarbons has locally sampled basement (in 67 wells) on structural highs. These drill cores (Beliakova & Stepanenko 1991), many of the them several kilometres deep, together with potential field data and seismic profiling (Kostiuchenko 1994), have provided constraints on the interpretation of the basement. It remains an open question, however, whether the Timanian deformation is simply an expression of Vendian inversion along the southwestern margin of a Riphean aulacogen, or due to foreland folding and thrusting in the front of an orogen that involved substantial accretion of new lithosphere to the margin of the Archaean-Palaeoproterozoic East European Craton.

In the Polar Urals, 400 km northeast of the Timan thrust front, pre-Ordovician complexes occur both in the major Palaeozoic allochthons and in the cores of the Uralian foreland folds. In the Engenape Anticline, volcano-sedimentary successions and fragmented ophiolites are present, the latter dated to c. 670 ±5 Ma (U-Pb zircon, multigrain; E. Khain, oral. com.). Thus, there can be little doubt that Timanian accretion is a significant phenomenon along the northeastern margin of Baltica. Some authors have proposed that other latest Proterozoic sutures occur further to the southwest beneath the Pechora Basin. These interpretations have been based on geophysical data (Kostiuchenko 1994) and igneous petrology and geochemistry. Within the context of Europrobe´s Timpebar (Timan-Pechora-Barents/Kara Seas) project (Gee & Ziegler 1996), we have launched a programme to better constrain the age and provenance of the Neoproterozoic magmatism. This study summarises previously unpublished K-Ar isotope-age data and presents new ages on intrusions, generated using the Pb-evaporation (Kober) single zircon method.

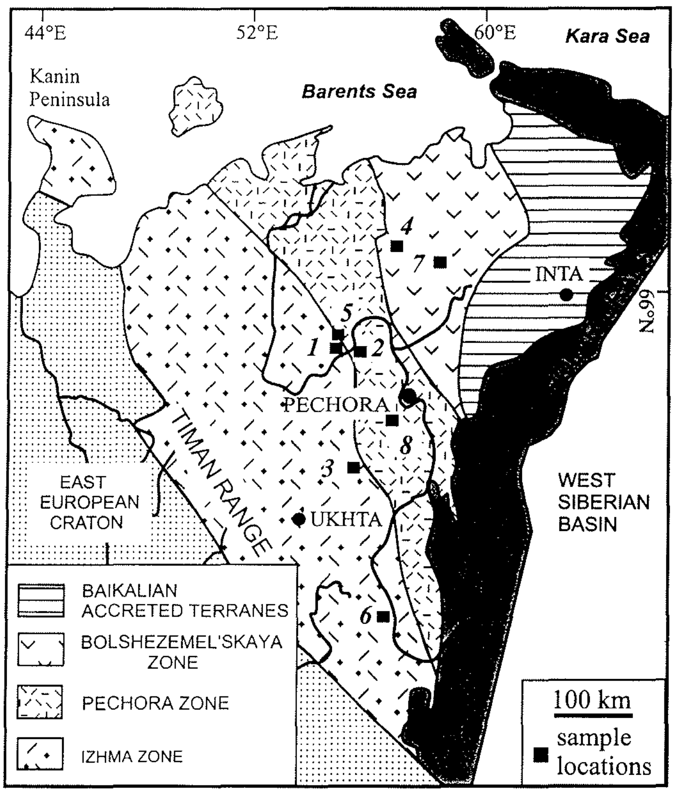

Fig. 2: Simplified geological map of the study area, with sample locations, (Baikalian = Neoproterozoic).

PRECAMBRIAN GEOLOGY OF THE TIMAN-PECHORA REGION

A great diversity of local names referring to different structures in the basement of the Timan-Pechora region occur in the literature (e.g. Bogatsky et al. 1996, Fig. 5). In this account it is convenient to refer to five major NW-trending belts - from southwest to northeast, the pericratonic region, the Timan Range, the Izhma Zone, the Pechora Zone, and the Bolshezemel´skaya Zone (Figs. 2 and 3).

Pericratonic region

Southwest of the Timan Range, the East European Craton is covered by Neoproterozoic platform successions. These are known from drill holes and in exposures on the Kanin Peninsula, where so-called pericratonic carbonates, shales, and sandstones are in fault contact with basinal shales and turbidites. Devonian strata overlie, with near-parallel unconformity, Upper Vendian pericratonic red sandstones and shales ("molasse"), which in turn rest unconformably on the underlying Neoproterozoic successions (Olovyanishnikov et al. 1995).

Timan Range

Exposures in the Timan Range are dominated by basinal facies sediments with steep NE-dipping cleavages (Olovyanishnikov et al. 1997). Exposures on Chetlasky Kamen´ have provided the best control of lithostratigraphy and the basis for regional correlation. The base of the succession is not exposed and the deepest structural levels are seen in the core of a major anticline in the northernmost part of the Timan Range and on the adjacent Kanin Peninsula, where a thick succession has been described to increase in metamorphic grade downwards to amphibolite facies; gabbro, granite and syenite intrusions occur in the core of this structure (Olovyanishnikov et al. 1997, Andreichev 1998) and no basement has been recognized. The existing seismic data (Olovyanishnikov et al. 1995) indicate that the Timan basinal facies is thrust southwestwards at least some tens of kilometres and that the East European Craton extends northeastwards beneath the Timan Range an unknown distance towards the Pechora Basin.

Izhma Zone

The basinal facies of the Timan Range is known from drill holes to extend northeastwards beneath the Palaeozoic cover of the Izhma Zone (Fig. 2). It is variously intruded by both diabase-gabbro suites and granites. The former are generally pre-tectonic and thought to be late Neoproterozoic in age; the latter, at least locally, can be demonstrated in drill cores to be late- to post–tectonic and probably Vendian in age (Raznitzyn 1965). In one drill hole (Mala Pera–11), shales unconformably overlying granite have yielded Middle Cambrian microfossils.

Pechora Zone

Potential field data and, particularly, aeromagnetic anomaly maps (KOSTIUCHENKO 1994) show a marked change in the character of the pre-Palaeozoic basement along the northeastern margin of the Izhma Zone. A major fault zone has been inferred to separate the Izhma and Pechora Zones (BELIAKOVA & STEPANENKO 1991). Strong positive magnetic anomalies in the Pechora Zone are related to pre-Ordovician basement magmatism, which increases in magnitude and changes in character (both extrusive and intrusive) and chemistry (intermediate to mafic). Detailed analyses of seismic profiling (mainly wide angle), in combination with the potential field data, have defined significant changes in the deeper basement; in combination with petrological data (BELIAKOVA & STEPANENKO 1991), these have been interpreted by both geologists and geophysicists to define a subduction-related complex dominated by volcanic arc magmatism in the basement of the Pechora Zone. The lack of characteristic ophiolite-related lithologies in the Pechora Zone drill cores may simply reflect the limitations of the drill core database.

The Pechora Zone intrusive complexes are intermediate to mafic in composition and of calc-alkaline affinity (BELIAKOVA & STEPANENKO 1991). For example, the Novaya-1 drill hole located near Pechora penetrated c. 270 m of gabbro-diorites with associated plagiogranites. The volcano-sedimentary host rocks are tightly folded and metamorphosed at greenschist facies; mafic intrusions are altered to amphibolites. On-going geochemical investigations seek to better define the origin and tectonic setting of this magmatism.

Bolshezemel´skaya Zone

Northeast of the Pechora Zone, the basement deepens towards the Polar Urals. However, a broad uplift has been located that reaches to within c. 3 km of the surface – the Bolshezemel´skaya arch. This structure gives its name to a zone that differs greatly in character from those to the southwest. Several drill holes in the Bolshezemel´skaya arch have penetrated the pre-Ordovician basement, providing evidence of a volcano-sedimentary sequence of red sandstones and shales, volcaniclastic conglomerates, various tuffs, rhyolites, and subvolcanic porphyritic and granophyric intrusions. Two-mica granites and gabbros intrude this volcano-sedimentary association and carry xenoliths of the latter.

PREVIOUS ISOTOPE-AGE STUDIES

A wide range of Pechora basement lithologies have been analysed for K/Ar whole rock and mineral dating by various Russian laboratories. Some of these ages have been published (e.g. MAL'KOV 1992, MAL'KOV & PUCHKOV 1963, RAZNITZYN 1965), but much of the data comes from the unpublished internal reports of various institutes (Table 1). Some of these reports lack sufficient analytical detail (decay constants, composition, etc.) to permit assessment of the accuracy of the data. Certainly the older (prior to the 1970's) data would not have been calculated using currently accepted decay constants of DALRYMPLE (1979). Recalculated ages using the decay constants of DALRYMPLE (1979) would generally be 4-5 % older than the originally reported c. 400-600 Ma ages. Nevertheless, this considerable unpublished database supports the geological interpretations of the drill cores, i.e. that there was widespread Late Proterozoic metamorphism and intrusion within the Izhma, Pechora, and Bolshezemel´skaya Zones. The new results from zircons reported here provide further constraints on the timing of some of the intrusions.

NEW ISOTOPE-AGE STUDIES

Zircons have been separated from intrusions in the Izhma, Pechora and Bolshezemel´skaya Zones for single crystal, Pb-

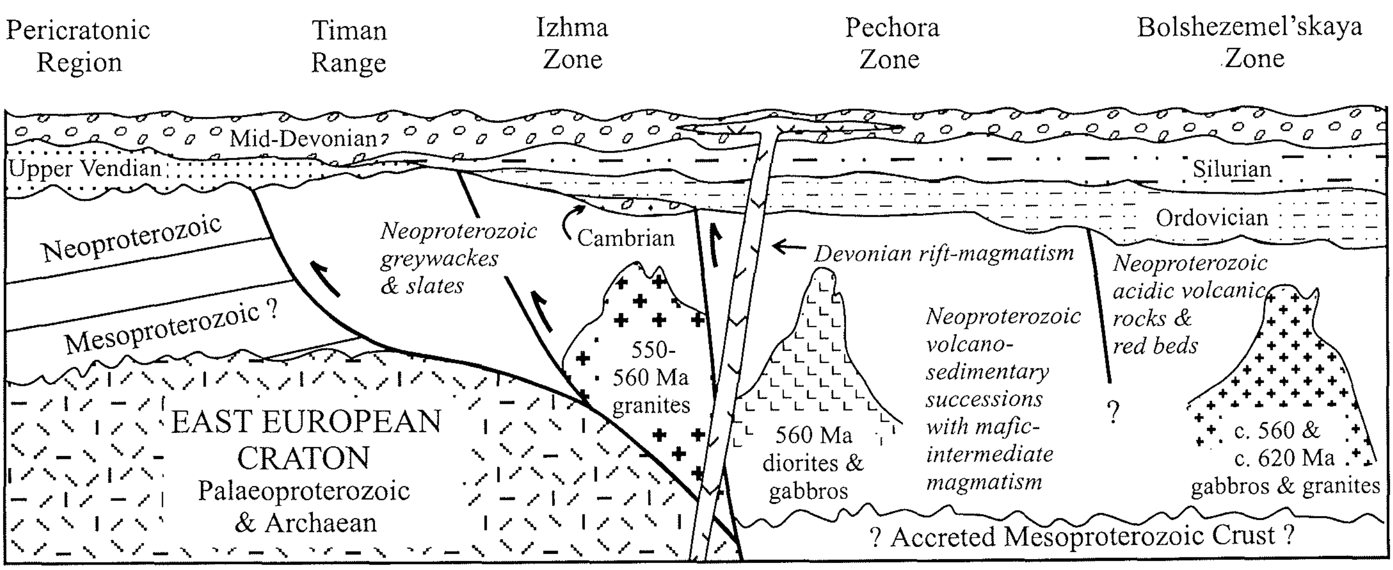

Fig. 3: Diagrammatic profile of the upper crust of the northeastern margin of the continent Balticain the mid-Devonian.

No and name of drill core	Interval depth (m)	Tectonic Zone	Lithology	Mineral or whole rock (wr)	Laboratory	Age (Ma)
_Verkhovka-4	585-589	Timan	Phyllite	wr	1	640
823		Timan	Phyllite	wr	1	674
839		Timan	Phyllite	wr	1	615
Timan-6		Timan	Phyllite	wr	1	600
Yarega-3		Timan	Phyllite	wr	1	541
Verchnaya Chut´-12		Timan	Biotite granite		1	530 & 610
Izkos´-Gora-4	830-836	Timan	Syenite		1	600
Izkos´-Gora-4		Timan	Monzonite		1	578
Izkos´-Gora-4	808-811	Timan	Monzonite		2	545 ±16
Izkos´-Gora-1	815-821	Timan	Monzonite		2	575 ±15
Kipievo-1	2730	Izhma	Biotite schist		3	503 ±8
Rassokha-62		Izhma	Biotite schist		2	515 ±18
Nizhn´aya Omra-1	1969	Izhma	Granite	Biotite	1	585
Nizhn´aya Omra-1		Izhma	Granite	Biotite	4	452
Nizhn´aya-227 Omra		Izhma	Two-mica granite	wr	4	364 ±8
Sedujakha-54		Izhma	Granite	Feldspar	4	445
Sedujakha-54		Izhma	Granite	Biotite	1	800 ±30
Yuzhny Dzh´er-1	2241-2244	Izhma	Granite		1	550 ±30
Yuzhny Dzh´er-1	2241-2244	Izhma	Biotite granodiorite		2	486 ±22
Zapadnaya Pokcha-1	2220-2221	Izhma	Granite		2	550 ±5
Zapadnaya Pokcha-1	2181-2183	Izhma	Biotite granite		2	500 ±15
Prilukskaya-1	3049	Izhma	Granite	wr	2	522 ±18
Prilukskaya-1		Izhma	Granite	K-feldspar	2	541 ±19
Prilukskaya-1		Izhma	Granite	K-feldspar	2	501 ±17
Prilukskaya-1		Izhma	Granite	Muscovite	2	690 ±25
Prilukskaya-1		Izhma	Granite	Muscovite	2	511 ±18
Prilukskaya-1		Izhma	Granite	Biotite	2	522 ±18
Prilukskaya-1		Izhma	Granite	Isochron	2	527 ±5
Sredn´aya Mylva-11	2295-2301	Izhma	Granite	Biotite	2	431 ±15
Sredn´aya Mylva-11	2295-2301	Izhma	Granite	Biotite	2	505 ±18
Sredn´aya Mylva-11	2307-2314	Izhma	Granite	Biotite	2	520 ±18
Pal´yu-21	3392-3396	Pechora	Diorite	Biotite	2	425 ±15
Pal´yu-21	3461-3465	Pechora	Diorite	Biotite	2	362 ±18
Severny Savinobor-1	4533-4540	Pechora	Granodiorite	wr	2	555 ±28
Severny Savinobor-1	4533-4540	Pechora	Diorite	Plagioclase	2	500 ±25
Severny Savinobor-1	4533-4540	Pechora	Diorite	Amphibole	2	595 ±30
Severny Savinobor-1	4533-4540	Pechora	Diorite	Biotite	2	565 ±20
Severny Savinobor-1	4579-4586	Pechora	Granodiorite	wr	2	447 ±22
Severny Savinobor-1	4579-4586	Pechora	Diorite	Plagioclase	2	415 ±21
Severny Savinobor-1	4579-4586	Pechora	Diorite	Amphibole	2	476 ±33
Severny Savinobor-1	4579-4586	Pechora	Diorite	Biotite	2	665 ±27
Severny Savinobor-1	4638-4644	Pechora	Granitoid	wr	2	380 ±27
Severny Savinobor-1	4638-4644	Pechora	Diorite	Plagioclase	2	440 ±22
Severny Savinobor-1	4638-4644	Pechora	Diorite	Ampibole	2	590 ±30
Severny Savinobor-1	4638-4644	Pechora	Diorite	Biotite	2	682 ±24
Sredn´aya Shapkina-1	3313-3316	Pechora	Porphyritoid		2	530 ±19
Sredn´aya Shapkina-1	3389-3391	Pechora	Porphyritoid		2	565 ±30
Sredn´aya Shapkina-1	3467-3471	Pechora	Porphyritoid	wr	2	585 ±20
Sredn´aya Shapkina-1	3467-3471	Pechora	Porphyritoid		1	600 ±15
Bagan-1	4409-4409	Bolshezemel´skaya	Schist		1	530 ±15
Bozej-51	4436-4440	Bolshezemel´skaya	Quartz porphyry		1	410 + 12
Bozej-51	4503- 4112	Bolshezemel´skaya	Quartz porphyry		1	440 + 13
Sandivej-1	4094-4096	Bolshezemel´skaya	Rhyolite porphyry		2	473 + 20
Sandivej-1	4107-4112	Bolshezemel´skaya	Rhyolite porphyry		2	496 + 25
Sandivej-4	4219-4224	Bolshezemel´skaya	Rhyolite porphyry		2	515 + 26

Tab. 1: Unpublished K-Ar isotope ages from drill cores of the Timan-Pechora region (prior to 1995, compiled by L. Beliakova). We are unable to assess the accuracy of these results without access to the analytical data (decay constants, composition, etc.). Older data has probably not been calculated using the currently accepted decay constants of Dalrymple (1979), which would generally result in 4-5 % older ages for these samples.
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Intrusion No.	Drill Hole I.D.	Sample Depth (m)	Sample No. (No. Grains)1	Rock type	Age (2σ) Magmatic[2]	Inherited
Izhma Zone						
1	South Charkayu-10	2952	18 (5)	granitic	553 ± 6	>1013 ± 9
3	Mala Pera-11	3318	22 (5)	granitic	551 ± 8	
5	East Charkayu-1	3219	27 (3)	granitic	557 ± 15	2708 ± 26
6	Palyu-21	3360	30 (4)	dioritic	560 ± 15	
Pechora Zone						
2	Mytnyi Materik-2	3097	19 (5)	granodioritic	378 ± 15	>964 ± 19
8	Novaya-1	4320	62 (3)	dioritic	565 ± 8	
Bolshezemel'skaya Zone						
4	East Kharyaga-26	4450	26 (5)	granitic	567 ± 36	1269 ± 11 >1447 ± 66 >905 ± 64
7	Veyak-2	4395	31 (4)	granite	618 ± 6	

Tab 2: Summary of Pb-evaporation data. Notes: 1 total number of grains analysed; 2 refer to Analytical Data (Tab. 3) for total number of grains included in the final weighted average age.

evaporation (Kober method) analyses. The zircons proved in general to be remarkably homogeneous, providing only minor (but important) evidence of inheritance. Largely unsuccessful attempts were also made to separate zircons from acidic volcanic rocks in the Bolshezemel´skaya Zone; the yields were low and the zircons generally too small for Pb-evaporation analyses. (Note that in GEE et al. 1998, Intrusion No. 4 Kharyaga-26 was wrongly referred to as a rhyolite.) Our results are summarised in Table 2.

Methodology

In this study, the single zircon Pb-evaporation technique proposed by KOBER (1986, 1987) and described by many authors (e.g. HELLMAN et al. 1997 and references therein) has been applied. Zircons were separated by standard methods at the Urals Mapping Geological Expedition's laboratory in Russia. Zircons were then hand picked and analysed at the Laboratory for Isotope Geology, Swedish Museum of Natural History using a Finnigan MAT 261 mass spectrometer. Each zircon to be analysed was placed into a "canoe-shaped" rhenium filament as part of a double filament assemblage with the slit of the "canoe" facing a flat ionization filament. Thereafter the samples were heated stepwise from c. 1450 to 1550 °C, at increments of 10-30 °C per step, evaporating and plating Pb onto the ionization filament and analysing each step. Lead emission from the ionization filament was observed at c. 1350-1400 °C. Data were collected in peak-jumping mode using a secondary ion multiplier with each scan encompassing the sequence ^{206}Pb-^{207}Pb-^{208}Pb-^{206}Pb-^{204}Pb. One to eight blocks of 10 scans each were registered for each heating step. All of the scans were used to produce the mean ratios and associated standard errors for each step. No correction for mass fractionation was applied. Correction to $^{207}Pb/^{206}Pb$ for common lead was made using the measured $^{206}Pb/^{204}Pb$ (if <100,000), assuming STACEY & KRAMERS (1975) Pb of appropriate age; otherwise, no correction was made. The mean age of each grain was generally calculated using all evaporation steps which were concordant within 2σ error limits. Results from grains with similar ages were then combined to form a weighted average age for the rock.

Description of intrusions and results

Brief descriptions of the intrusions in the different zones (Fig. 2) are provided below, followed by a presentation and discussion of the results (Fig. 4 and Tab. 3).

Izhma Zone

From the Izhma Zone drill cores, four intrusions were sampled for age-determination (No. 1, South Charkayu-10; No. 3 ,Mala Pera-11; No. 5, East Charkayu-1; and No. 6, Palyu-21). Two of these (No. 5 and 6) were located close to the contact with the Pechora Zone. Their late- to post-tectonic character (witnessed by contact metamorphism superimposed on cleavage) implies that these granitic rocks may not be restricted to the Izhma Zone; indeed they may have intruded after the fault juxtaposition of the Izhma and Pechora Zones.

In thin section, the textures are generally hypidiomorphic, with plagioclase (oligoclase, 40 %) sometimes idiomorphic and dominating over K-feldspar (microcline, 15-20 %), quartz (30 %) and green biotite (5-10 %). Muscovite is generally subordinate (1-2 %). Apatite and zircons occur as accessory minerals. Primary hornblende may be present near the contact to the Pechora Zone. Retrogression, for example with chloritization of biotite and saussuritization of plagioclase (with secondary sericite and clinozoisite), is minor. In the case of Palyu-21, plagioclase (andesine) reaches 50 % and the rock composition is closer to that of a granodiorite or quartz diorite.

All four samples from the Izhma Zone yielded zircons of similar morphology: pink, euhedral, prismatic, transparent grains, with well developed (110)+(100)+(331)+(111) facets. Igneous growth-zoning is visible and both opaque or transparent inclu-

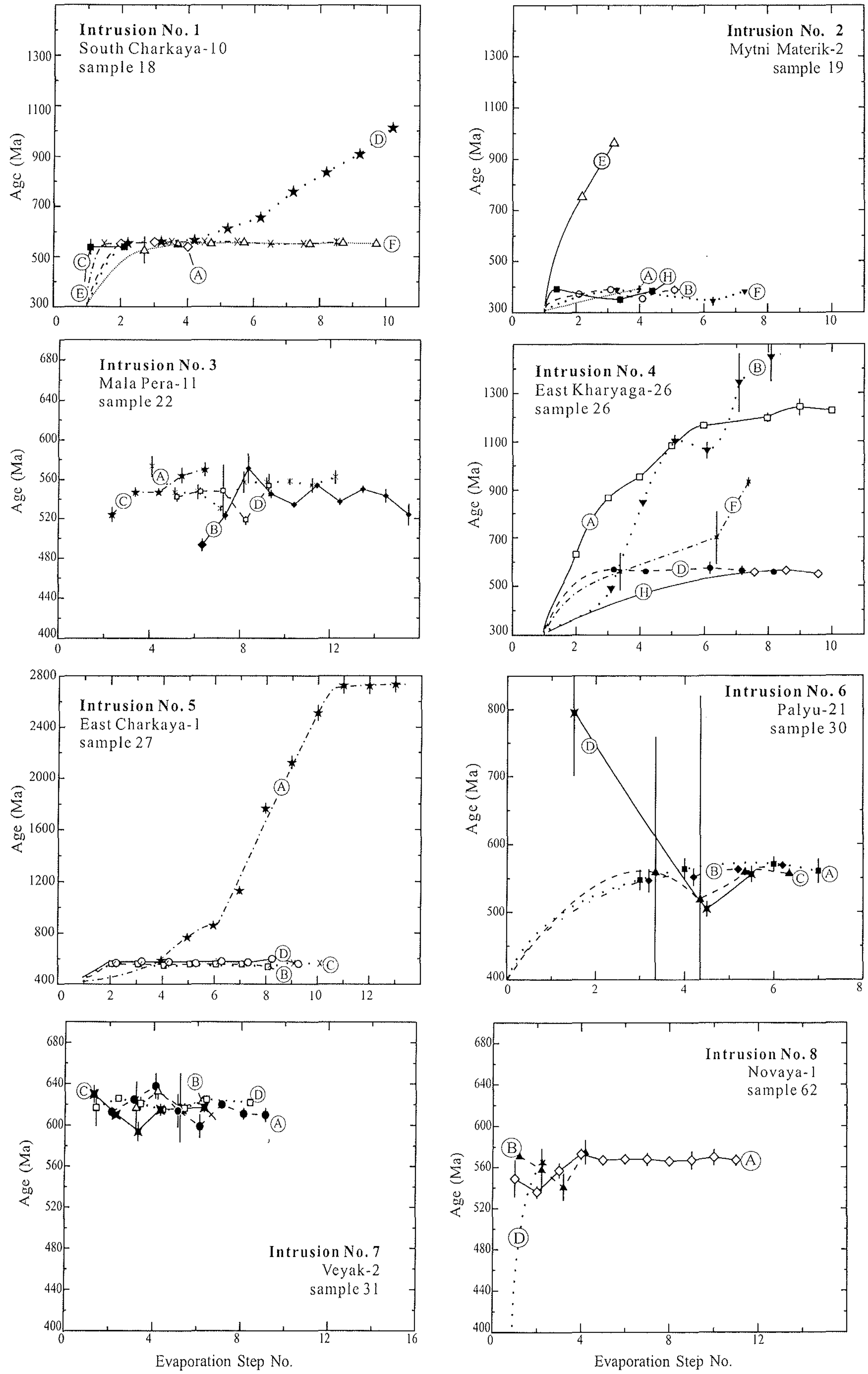

Fig. 4: Lead evaporation-step profiles for all samples. Different grains indicated by circled letters, while different evaporation steps for each grain are denoted with similar symbols.

Plating[1]	T(°C)	T[2]	Lead Ratios[3] $^{206}Pb/^{204}Pb$	±2 σ %	$^{207}Pb/^{206}Pb$	±2 σ %	Age[4] (Ma)	±1 σ
Intrusion No. 1, South Charkayu-10, sample 18								
A-2, 30	1420	8	8018	46	0.05866	1.3	554.5	28
A-3, 30	1420	8	24000	67	0.05868	0.7	555.1	16
A-4, 10	1420	7	15598	78	0.05825	0.9	539.3	20
C-1, 20	1400	13	4048	64	0.05826	3.2	539.6	68
C-2, 30	1540	14	22662	125	0.05836	1.5	543.2	33
D-2, 50	1420	9	20389	36	0.05861	0.6	552.5	13*
D-3, 10	1420	4	21884	44	0.05866	0.6	554.7	13*
D-4, 20	1430	5	36115	120	0.05914	0.7	572.3	16*
D-5, 60	1450	5	35038	54	0.06025	0.5	612.7	12*
D-6, 40	1450	5	25086	81	0.06149	0.7	656.5	15*
D-7, 30	1450	5	32849	172	0.06458	0.8	760.6	17*
D-8, 30	1450	6	25916	59	0.06693	0.8	835.8	16*
D-9, 20	1450	7	20662	94	0.06934	0.8	908.9	16*
D-10, 40	1480	7	21673	42	0.07295	0.4	1012.6	8*
E-2, 30	1420	9	1728	14	0.05855	1.2	550.6	26
E-3, 30	1430	6	3031	17	0.05878	1.2	559.0	26
E-4, 30	1430	7	5703	14	0.05884	0.7	561.2	16
E-5, 30	1450	7	8702	34	0.05861	0.6	552.6	14
E-6, 30	1470	5	16621	266	0.05854	2.2	550.2	48
E-7, 30	1500	5	25246	49	0.05862	0.7	552.9	14
E-8, 20	1500	3	31004	320	0.05833	1.7	542.1	37
F-2, 10	1430	7	11300	846	0.05704	10.3	493.2	212*
F-3, 30	1460	8	49408	42	0.05861	0.4	552.5	8
F-4, 30	1460	3.5	46629	54	0.05878	0.4	559.0	10
F-5, 20	1460	3	100000	35	0.05878	0.4	558.8	8
F-7, 20	1500	3	72792	60	0.05848	0.4	547.7	8
F-8, 20	1500	3	100000	40	0.05877	0.6	558.7	12
F-9, 20	1550	2	293000	30	0.05854	0.3	550.0	6
Intrusion No. 2, Mytnyi Materik-2, sample 19								
A-6, 10	1470	17	35399	306	0.05450	2.1	391.9	46
B-2, 20	1450	10	100000	300	0.05426	0.9	381.7	20
B-3, 10	1450	12	56811	72	0.05399	0.6	370.7	13
B-4, 10	1480	10	100000	300	0.05385	1.0	364.6	22
B-5, 10	1520	15	28637	168	0.05441	2.5	388.0	54
E-2, 80	1450	10	36609	182	0.06438	0.9	754.1	19*
E-3, 30	1450	8	36914	180	0.07122	0.9	963.8	19
F-3, 10	1430	10	8644	44	0.05442	1.5	388.5	32
F-6, 10	1440	15	100000	300	0.05390	2.6	367.0	58
F-7, 10	1500	15	6900	122	0.05422	2.6	380.1	58
G-2, 40	1430	10	5200	48	0.05731	1.5	503.5	33*
G-3, 40	1460	9	6776	46	0.05666	1.2	478.5	26*
G-4, 10	1460	7	8635	15	0.05566	1.4	438.9	30*
H-1, 30	1450	7	4173	32	0.05448	1.3	391.1	28
H-3, 20	1500	8	15709	129	0.05350	2.1	349.9	46
H-4, 20	1520	11	24557	270	0.05490	2.1	408.3	46
Intrusion No. 3, Mala Pera-11, sample 22								
A-4, 10	1430	11	1203	20	0.05916	2.3	572.8	50
A-5, 30	1450	12	1030	16	0.05775	2.1	520.3	46
A-6, 40	1450	9	786	17	0.05856	2.9	550.7	62
A-7, 30	1480	7	655	4	0.05803	0.9	531.0	20
A-8, 30	1480	4	1046	9	0.05876	1.6	558.1	35
A-9, 30	1480	6.5	1303	6	0.05867	1.1	555.0	24
A-10, 20	1480	6.5	2383	12	0.05894	0.9	565.0	19
A-11, 40	1520	6	3731	16	0.05874	0.6	557.4	12
A-12, 30	1520	7.5	7951	20	0.05885	1.1	561.7	23
B-6, 30	1450	10	1113	27	0.05764	3.2	515.9	69
B-7, 40	1480	10	1177	6	0.05770	0.8	518.2	17
B-8, 10	1480	7	1261	13	0.05911	2.0	571.0	43
B-9, 50	1500	10	1469	7	0.05907	0.7	569.7	16
B-10, 20	1530	5	1388	7	0.05824	0.9	538.7	20
B-11, 20	1530	5	2075	9	0.05879	0.7	559.2	14
B-12, 20	1530	5	2153	9	0.05837	0.7	543.6	14
B-13, 30	1540	5	4039	13	0.05853	0.8	549.8	18
B-14, 20	1540	7	2675	25	0.05834	1.4	542.6	30
B-15, 10	1550	7	873	9	0.05856	1.9	550.7	42
C-2, 10	1420	5	1130	11	0.05784	1.6	523.5	34
C-3, 30	1430	7	1521	9	0.05875	1.1	557.7	24
C-4, 30	1460	9	2143	7	0.05854	0.5	550.0	11
C-5, 30	1460	7	2825	20	0.05892	1.0	564.0	21
C-6, 10	1460	6	2219	18	0.05907	1.2	569.7	26
D-5, 20	1430	15	666	12	0.05774	2.3	519.7	51
D-6, 40	1450	7	550	12	0.05928	2.8	577.3	60
D-7, 20	1450	7	569	24	0.05873	5.5	557.1	116
D-8,10	1450	14	725	17	0.05768	3.1	517.7	67
D-9,30	1450	16	954	14	0.05991	2.2	600.3	48
Intrusion No. 4, East Kharyaga-26, sample 26								
A-2, 30	1440	6	909	8	0.06077	1.3	631.0	29*
A-3, 30	1450	5	8112	21	0.06784	1.0	863.8	20*
A-4, 20	1470	6	12883	32	0.07082	0.5	952.4	10*
A-5, 30	1470	5	7471	42	0.07549	0.7	1081.6	14*
A-6, 40	1470	6	15358	56	0.07875	0.8	1166.0	15*
A-8, 20	1480	6	14949	29	0.08009	1.1	1199.1	22
A-9, 10	1500	5	100000	300	0.08264	1.4	1260.8	28
A-10, 10	1530	10	100000	300	0.08259	0.6	1259.5	11
B-3, 20	1450	5	2785	48	0.05689	3.4	487.2	73*
B-4, 30	1520	6	16178	83	0.06725	0.9	845.7	19*
B-5, 10	1480	17	6923	77	0.07624	1.6	1101.3	32*
B-6, 10	1520	9	1502	1404	0.07480	90.0	1063.1	1190*
B-7, 20	1550	10	22791	205	0.08618	3.6	1342.2	68*
B-8, 10	1550	16	16109	101	0.09100	3.6	1446.6	66
D-3, 20	1440	7	7117	40	0.05905	1.2	568.9	27
D-4, 40	1500	6	6534	45	0.05884	1.1	561.2	24
D-5, 10	1500	4	20986	182	0.06124	5.3	647.7	109
D-6, 10	1500	7	10016	150	0.05921	2.9	574.8	62
D-7, 40	1500	7	25764	410	0.05890	2.3	563.4	48
D-8, 30	1520	11	27929	88	0.05874	0.7	557.5	15
F-5, 10	1460	6	14731	113	0.05882	1.4	560.3	30*
F-6, 20	1500	12	100000	300	0.06010	1.5	607.3	33*
F-7, 10	1540	10	12898	324	0.06922	3.2	905.4	64
H-4, 10	1500	7	100000	300	0.06089	3.3	635.3	70
H-6, 10	1500	7	100000	300	0.05939	2.9	581.3	62
H-7, 10	1520	8	13851	682	0.05871	6.2	556.2	130
H-8, 10	1520	11	100000	300	0.06028	5.0	613.7	105
H-9, 20	1560	9	100000	300	0.05930	1.0	578.1	21
J-4, 10	1530	8	6158	71	0.06300	2.4	708.1	50*
J-6, 10	1590	8	100000	300	0.07227	1.4	993.7	29
Intrusion No. 5, East Charkayu-1, sample 27								
A-4, 20	1430	8	100000	303	0.05964	1.4	590.7	29*
A-5, 40	1450	11	52505	149	0.06479	1.2	767.6	26*
A-6, 20	1450	10	44002	118	0.06766	0.9	858.2	20*
A-7, 60	1460	18	72013	136	0.07735	0.9	1130.2	18*
A-8, 10	1460	12	38064	262	0.10801	2.7	1766.1	49*
A-9, 30	1500	14	15241	566	0.13144	2.8	2117.3	49*
A-10, 60	1520	14	53392	162	0.16546	0.9	2512.3	15*
A-11, 30	1520	7	11410	1330	0.18736	3.8	2719.1	62
A-12, 10	1520	8	18880	78	0.18609	0.8	2707.9	13
A-13, 20	1550	15	12424	874	0.18912	85.6	2734.5	977
B-2, 60	1420	8	39516	60	0.05876	0.6	558.1	14
B-3, 20	1420	6	151559	150	0.05884	0.5	561.2	12
B-4, 20	1420	4.5	60521	56	0.05855	0.4	550.6	8
B-5, 20	1420	4	71894	88	0.05873	0.5	557.3	10
B-6, 20	1440	6.5	94564	40	0.05870	37.1	555.9	653
B-7, 20	1440	3	170393	60	0.05877	0.4	558.7	10
B-8, 20	1450	3	73048	85	0.05813	0.6	534.6	13

B-9, 30	1490	3	59195	60	0.05879	0.6	559.3	13
B-10, 40	1530	3	184370	53	0.05875	0.6	557.7	12
C-2, 20	1400	7	24047	60	0.05864	0.6	553.6	13
C-3, 20	1420	7	43599	80	0.05865	0.5	554.0	10
C-4, 20	1430	8	35656	45	0.05870	0.4	556.0	9
C-5, 30	1430	8	34293	42	0.05879	0.5	559.3	11
C-6, 20	1450	5	24843	62	0.05860	0.5	552.2	11
C-7, 20	1450	9	35878	32	0.05879	0.5	559.5	11
C-8, 40	1500	8.5	60151	73	0.05853	0.6	549.5	13
D-2, 30	1400	6	1379	45	0.05896	4.2	565.6	90
D-3, 20	1420	7	2200	14	0.05914	1.0	572.3	21
D-4, 10	1430	5	2349	29	0.05935	1.6	580.0	34
D-5, 30	1430	9	2474	81	0.05851	4.2	549.0	88
D-6, 20	1430	8	5486	18	0.05891	0.7	563.6	15
D-7, 20	1450	8	10146	41	0.05894	0.6	564.9	12
D-8, 10	1470	8	4913	9	0.05958	0.9	588.3	19
D-9, 20	1520	11	5490	32	0.05876	1.1	558.0	23
Intrusion No. 6, Palyu-21, sample 30								
A-3, 20	1500	14	5596	64	0.05656	2.5	474.4	54
A-4, 20	1520	13	40400	273	0.05875	1.1	557.9	23
A-6, 20	1560	10	26901	209	0.05894	1.4	564.8	30
A-7, 30	1580	13	10880	108	0.05745	2.9	508.9	62
B-3, 20	1500	9	15454	510	0.05862	4.4	553.0	93
B-4, 20	1520	14.5	76033	122	0.05905	0.8	569.1	18
B-5, 30	1530	14	21046	107	0.05900	1.0	567.2	22
B-6, 50	1540	16	62246	286	0.05906	1.1	569.4	24
C-3, 20	1500	8	7100	42	0.05891	1.3	563.6	27
C-4, 40	1520	7	5429	101	0.05818	3.3	536.5	70
C-5, 30	1540	7	10380	44	0.05878	1.0	559.0	21
C-6, 30	1540	7	5584	56	0.05870	1.5	556.0	32
D-1, 20	1480	7	128	5	0.06155	6.7	658.4	138
D-4, 20	1520	10	5450	72	0.05743	2.3	508.2	50
D-5, 20	1540	8	6854	44	0.05870	1.8	556.1	38
Intrusion No. 7, Veyak-2, sample 31								
A-2, 30	1410	7	16761	60	0.06025	0.8	612.5	18
A-3, 20	1410	8	23992	112	0.06058	0.8	624.5	17
A-4, 20	1410	5	21122	169	0.06095	1.3	637.5	27
A-5, 20	1420	6	12163	59	0.06002	1.3	604.4	27
A-6, 20	1430	6	13403	36	0.05987	1.0	598.7	21
A-7, 30	1440	9	40000	308	0.06044	1.2	619.3	26
A-8, 20	1470	5	20581	44	0.06019	0.9	610.3	19
A-9, 20	1520	5	41362	88	0.06015	0.8	609.1	16
B-3, 20	1450	11	100000	60	0.06119	1.9	646.0	40
B-4, 20	1450	12	15615	170	0.06081	1.5	632.4	32
B-5, 20	1460	14	19233	84	0.06063	1.4	626.1	30
B-6, 50	1480	17	20667	91	0.06054	1.6	622.9	34
C-1, 10	1400	9	3042	12	0.06072	0.9	629.3	19
C-2, 20	1400	4	19225	53	0.06016	0.7	609.3	15
C-3, 20	1460	6	4075	46	0.05972	2.0	593.6	43
C-4, 40	1480	5	9586	33	0.06034	0.8	615.8	17
C-5, 30	1480	5	19776	46	0.06030	0.7	614.4	15
C-6, 30	1500	7	16668	45	0.06035	0.6	616.1	13
D-1, 20	1410	5	3526	24	0.06036	1.4	616.4	31
D-2, 40	1450	4	9667	37	0.06063	0.7	626.0	15
D-3, 30	1480	3	7073	24	0.06046	0.6	620.1	13
D-4, 20	1480	3	8322	24	0.06029	0.5	614.2	10
D-5, 20	1480	3	8857	33	0.06033	0.7	615.5	15
D-6, 20	1480	3.5	13479	30	0.06058	0.4	624.5	9
D-7, 20	1500	2	12250	19	0.06049	0.5	621.1	10
Intrusion No. 8, Novaya-1, sample 62								
A-1, 30	1400	5	1853	29	0.05850	2.7	548.7	58
A-2, 20	1400	5	2475	33	0.05814	1.9	535.1	42
A-3, 60	1400	7	2123	22	0.05872	1.5	556.8	32
A-4, 40	1430	5	2738	12	0.05915	0.8	572.5	17
A-5, 30	1440	5	2332	11	0.05899	51.3	566.7	842
A-6, 30	1440	5	2342	7	0.05901	0.5	567.6	11
A-7, 40	1440	6	2239	10	0.05902	0.8	567.8	18
A-8, 30	1480	3	2339	14	0.05896	0.8	565.5	16
A-9, 30	1480	3	2051	8	0.05899	1.0	566.7	22
A-10, 30	1480	3	2210	14	0.05908	1.1	569.9	24
A-11, 30	1480	3	3061	17	0.05897	0.9	566.1	19
B-1, 30	1410	5	34625	105	0.05910	1.2	570.7	25
B-2, 10	1420	6	100000	60	0.05873	1.9	557.2	41
B-3, 20	1430	7	33663	109	0.05828	1.3	540.4	28
B-4, 20	1430	7.5	100000	60	0.05920	1.1	574.3	24
D-2, 40	1500	5	13163	35	0.05890	0.5	563.5	11
E-1, 30	1450	4	3436	35	0.05870	1.6	556.0	35
E-2, 10	1450	5	3743	23	0.05935	2.9	580.0	61

Tab 3: Pb-Pb analytical data.

Notes: [1] Grain–evaporation step, number of scans; [2] time in minutes; [3] $^{206}Pb/^{204}Pb$ = measured ratio (2σ%) and $^{207}Pb/^{206}Pb$ = ratio corrected for common Pb (2σ%); [4] asterix indicates analyses omitted from calculation of final weighted average ages (1σ absolute).

sions are common. Zircon aspect ratios (length : width) and sizes are also similar (2:1 to 5:1; 100 to 200 μm in length). Inherited grains do not occur as cores with overgrowths, but as discrete grains.

All these samples yielded single zircon, Pb-evaporation ages of 550-560 Ma (Tab. 3, Fig. 4), implying a late Vendian age of intrusion (Tucker & McKerrow 1995). This age is compatible with the late- to post-tectonic character of the intrusions and the evidence from the Mala Pera-11 drill core (No. 3, 551 ±8 Ma) of unconformably overlying Middle Cambrian shales. Previous mineral (biotite, muscovite, K-feldspar) ages from these Izhma Zone granites have provided a wide range of Cambrian and Vendian ages; the results presented here introduce a new precision to the age data. Evidence of inheritance is present in three of the samples. These data do not provide a basis for inferring the character of the lower crystalline source (perhaps Archaean for East Charkayu), but imply that a closer analysis by ion microprobe should yield significant information on provenance.

Pechora Zone

Two intrusions from the Pechora Zone were sampled. One (No. 8, Novaya-1) is a quartz diorite, a characteristic component of the mafic to intermediate igneous suites from this zone. The second (No. 2, Mytnyi Materik-2) is a highly altered granodiorite (hybrid?); surprisingly the latter yielded an unambiguous Devonian age.

The Novaya-1 sample (No. 8) is dominated by idiomorphic plagioclase (70 %) with andesine to oligoclase zoning, subordinate quartz (15–20 %), biotite (5-15 %), and hornblende (2 %). Accessory minerals include sphene, zircon, garnet, and magnetite. Sericite, clinozoisite, and chlorite are present as alteration products. Zircon grains are pink, transparent, euhedral, and prismatic, with well developed (110)+(100)+(111) +(331) facets. Igneous growth-zoning is also visible. Grain fractures are common and opaque inclusions rare. Due to a low zircon yield, only four crystals were analysed for ages. One grain burnt out, and the three remaining grains yielded plateau with a well defined, weighted average age of 565 ±8 Ma.

The Mytnyi Materik sample (No. 2) contains long prismatic plagioclase crystals, with subordinate quartz, K-feldspar, and minor chlorite and accessory apatite, zircon, and magnetite. The prismatic morphology of the zircon population coincides with aspect ratios of 2:1 to 5:1. These euhedral grains are light-pink to colourless, transparent, and fractured. Five zircon grains were analysed, four of which yielded consistent Middle to Late Devonian (weighted average 378 ±15 Ma) ages and some evidence of inheritance from a Grenvillian or older source.

Bolshezemel´skaya Zone

Two intrusions from the Bolshezemel´skaya Zone were investigated (No. 4, East Kharyaga-26; No. 7, Veyak-2). Granites underlie Ordovician strata in the East Kharyaga-26 drill hole and are similar to those in the Izhma Zone, being hypidiomorphic, plagioclase-dominated (45 %) intrusions, with quartz (30 %), K-feldspar (20 %), and subordinate biotite / muscovite (5 %). Accessory minerals include apatite, zircon, and magnetite. Alteration is extensive with saussuritization of plagioclase, chloritization of biotite, and some calcite. The zircon population from this sample is generally euhedral, pink, transparent, and has well developed (110)+(100)+(331) +(111) facets. Aspect ratios of these zircon grains are relatively consistent (2:1 to 3:1) and the grains are generally free of inclusions. Subhedral morphologies accompanied by slight corrosion are likely to represent inherited grains. This sample (East Kharyaga, No. 4) displays more inheritance than is seen in the intrusions of the Izhma Zone, but two grains yielded consistent late Vendian plateau ages (weighted average 567 ±36 Ma). This inheritance provides evidence of a Grenvillian or older source in the lower part of the Bolshezemel´skaya Zone.

The Veyak-2 sample (No. 7) is more complex than the Kharyaga-26 granite: The drill core displays a variety of intrusive relationships into amphibole-bearing, diabase-gabbro with local hybridisation. Zircons were separated from a plagioclase (50 %)- and quartz (40 %)-dominated rock, with subordinate epidote (10 %) and accessory green hornblende, apatite, and magnetite. The zircon population comprises euhedral, prismatic grains, which are pink, transparent, and have well developed (110)+(100)+(111)+(331) facets. Inclusions are rare, but some grains are characterised by up to 50 % turbid domains. Despite the apparent hybrid character of the intrusion, four zircons from the sample yielded consistent ages (Tab. 2, Fig. 4) with a weighted average of 618 ±6 Ma. This age is probably also Vendian, but significantly older than the late Vendian intrusions from elsewhere in the basement of the Pechora Zone.

Previous attempts to date the acidic volcanic rocks in the Bolshezemel´skaya Zone by the K/Ar method (Tab. 1) have only yielded Early Palaeozoic ages, significantly younger than the Veyak and Kharyaga intrusions. It can be concluded that the Bolshezemel´skaya volcanic rocks must be Vendian or older in age, and new analyses are necessary in order to accurately determine their ages.

DISCUSSION AND CONCLUSIONS

The new age data presented here constrain the tectonothermal evolution of the basement beneath the Pechora basin. Previous isotopic-age investigations, mainly by the K/Ar method (Tab. 1), have yielded evidence of Vendian to Cambrian greenschist facies metamorphism. However, without knowledge of the influence of the detrital component from the metasediments, the significance of these data has been in doubt. Previous K/Ar work also generated a wide range of ages (Vendian to Ordovician) for the granitic intrusions, many of which are incompatible with the their location beneath a major Lower Ordovician (locally Middle Cambrian) unconformity. The late- and post-tectonic granite ages of c. 550-560 Ma reported here are remarkably consistent, emphasising the importance of late Vendian plutonism and supporting the geological evidence of Vendian-age orogeny.

The evidence of inheritance in the zircon populations is insufficient to allow confident assessment of the character of the deeper basement beneath the different zones. Nevertheless, it provides an incentive for future work, with the possibility for defining the northeasterly extent of the Baltica craton (Archaean and Palaeoproterozoic crust) beneath the Izhma Zone, and perhaps other zones. A thorough analysis of inheritance from the basement granites and volcanic rocks beneath the Bolshezemel´skaya arch, where there is some evidence of Mesoproterozoic source rocks, would be of particular interest.

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ANNEX

We define Baltica as the name given to an independent continent that is inferred to have existed in the Early-Mid Palaeozoic. This continent is defined by the area covered by Cambrian, Ordovician, and Silurian platform sediments containing characteristic faunal assemblages (in particular, in the Early

Ordovician) that differ from those of other contemporaneous continents. The Precambrian basement of Baltica is composed of crystalline rocks of the East European Craton, largely of Palaeoproterozoic and older age, but in western areas (present coordinates) of Mesoproterozoic age and, in some areas (particularly eastern) of Neoproterozoic age. The southern parts of Baltica were rifted off the continent in the Late Palaeozoic and their present location is not well defined. Continent Baltica can be usefully distinguished from the Baltica plate, the latter including both continental and surrounding oceanic crust in the Early Palaeozoic. Continent Baltica originated in the Late Neoproterozoic with the break-up of a megacontinent, (Rodinia); the exact time of formation of oceanic crust surrounding continent Baltica remains to be defined. Baltica, in the Vendian, was a continent with a rifting (or rifted) and extending passive margin on the northwestern side (Baltoscandian margin) and active margins to the east and probably also to the southwest (central European zone).

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