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The Initial Stage of Early Carboniferous Rifting in the Southern Urals: First The results of U–Pb Dating of Zircons from Granitoids of the Neplyuevka Complex

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Abstract—Zircons from the Early Carboniferous granitoids of the Neplyuevka pluton of the Southern Urals have been dated (SIMS). Two age groups are distinguished among the studied zircons: group 1 from 334 to 342 Ma and group 2 from 354 to 356 Ma. The older ages probably correspond to the time of zircon crystallization from the melt, while the younger ones resulted from a partial loss of radiogenic lead by zircons during the cooling of the pluton or from the thermal impact of the Early Carboniferous or even the Early Permian intrusions. The formation of the Neplyuevka complex at the very beginning of the Carboniferous marks the most important stage in the geodynamic evolution of the Southern Urals, a rapid transition from island arc margmatism, which continued during the Devonian, to rift-related magmatism, which ended only in the Middle Visean.

Keywords: Southern Urals, granitoids, isotope age, zircons, Early Carboniferous, rifting

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INTRODUCTION

The Neplyuevka granitoid pluton is a key object for understanding the evolution of Early Carboniferous magmatism of the Southern Urals. Its constituent rocks are the least metamorphosed relative to the other Early Carboniferous intrusions. It is represented by rocks from gabbro to leucogranites, for which Rb–Sr isotope ages were determined (Popov et al., 2003). For the Neplyuevka pluton, a model of formation as a strike-slip magmatic duplex was developed (Tevelev, Al.V. and Tevelev, Ark.V., 1996; Tevelev et al., 2006).

The general geological situation. It is generally accepted that the Southern Urals consist of several megazones (Fig. 1): (1) *the Pre-Uralian foredeep megazone* formed of the Middle–Late Carboniferous-Permian flysch and molasse; (2) *the West Uralian megazone* of external folding composed of Paleozoic strata of the paleocontinent margin; (3) *the Bashkir megazone* represented by Precambrian, primarily Riphean complexes; (4) *the Magnitogorsk megazone* where Paleozoic complexes of the Paleo-Uralian ocean, island arcs, and rift systems occur under complicated relationships; (5) *the East Uralian megazone* is usually considered as a paleo-microcontinent with a Precambrian metamorphic basement with numerous intrusive bodies as a distinctive feature; and (6) *the Transuralian megazone* is a complex collage of various structural elements that were formed at various geodynamic settings (Puchkov, 2000; 2010; et al.). In the modern structure of the Southern Urals, four eastern megazones are separated by narrow suture zones with overthrust and strike-slip fault kinematics (Tevelev, 2012).

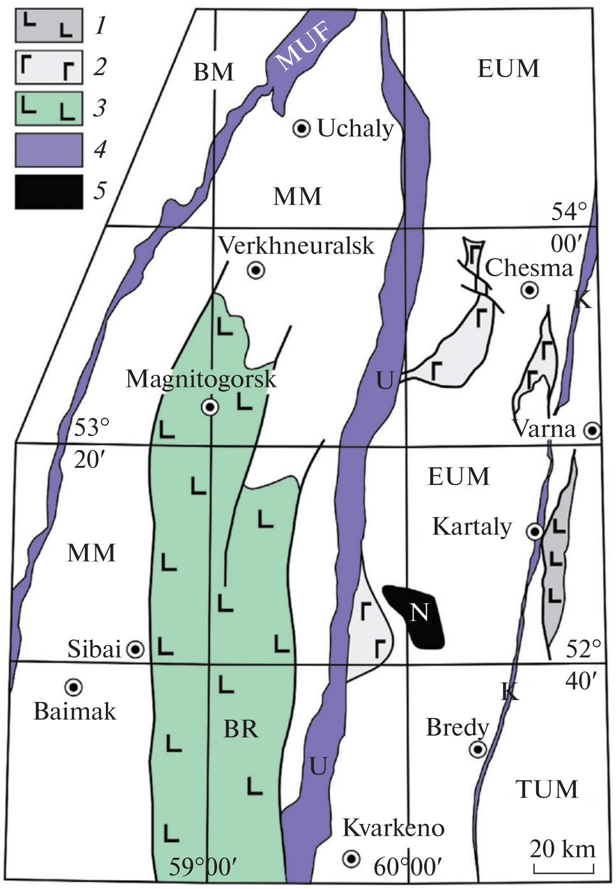


Fig. 1. The structural pattern of the Southern Urals: (*1*) Late Visean-Serpukhov trachybasalts; (*2*) Early Visean contrasting trachybasalt–trachyrhyolite series; (*3*) Late Tournaisian-Early Visean trachybasalt–trachyrhyolite series; (*4*) major suture zones; (*5*) Neplyuevka pluton. The megazones are designated by letters: BM, Bashkirian; MM, Magnitogorsk; EUM, East Uralian; TUM, Transuralian; BR, Bogdanov Paleorift; suture zones: MUF, Main Uralian Fault; U, Uiskaya; K, Kopeiskaya; N, Neplyuevka pluton.

The Neplyuevka pluton is located in the west of the East Uralian megazone of the Southern Urals (Fig. 1), which adjoins the Magnitogorsk megazone from the east. The paleo-island arc complexes of the Magnitogorsk megazone are Ordovician, Silurian, and Devonian volcanic rocks. The latter complexes, comprising two separate zones (the East- and West-Magnitogorsk zones), are the most widely distributed. They are split along almost the entire length by the Central-Magnitogorsk zone, which is an Early Carboniferous paleo-rift system (Pravikova et al., 2004), the so-called Bogdanov paleo-rift. The volcanic activity within the paleo-rift began in its western part in the Late Tournaisian, shifting gradually eastward; in the Early Visean, rifting began within the East Uralian megazone, while in the Late Visean it transited to the Transuralian megazone. The rifting that drifted to the east lasted for approximately 20 Ma (Pravikova and Tevelev, 2003).

The Neplyuevka pluton is a typical intrusion of eponymos complex. It occupies 18–20 × 12–14 km in the area of the Neplyuevka, Snezhnyi, Karakul’, and Mogutovskii settlements in the Kartalinsk District of Chelyabinsk region. Four intrusive phases are markedly distinguished in the Neplyuevka pluton with the compositions changing in the homodromic succession: the first phase is gabbro and diorites, the second phase is quartz diorites and granodiorites, the third phase is adamellites, and the fourth phase is leucogranites (Popov et al., 2003). The lower age limit of the Neplyuevka pluton is determined by the active intrusive contacts with the host terrigenous rocks of the Lower Ordovician Rymnik Formation. The upper age limit is characterized by the occurrence of fragments of granitoid rocks in the terrigenous deposits of the Upper Visean Solar Formation (Moseichuk et al., 2003). In addition, Early Permian granites with an age of 278 Ma were recognized in the central part of the Neplyuevka pluton (Popov et al., 2003).

The Rb–Sr isochronous ages of all granitoid rocks in the Neplyuevka pluton range from 346–340 Ma, which corresponds to the Late Tournaisian–Early Visean, the isotope ages of the rocks decrease in conformity with the intrusion phases: the second phase—346 Ma; the third phase—342 and 341 Ma, and a fourth phase—340 Ma (Popov et al., 2003). Thus, according to the Rb–Sr isotope data, the pluton was formed for at least 6 Ma.

MATERIALS AND METHODS

Dating techniques. U–Pb isotope dating of zircons was conducted using a high-resolution secondary-ion microprobe (SHRIMP-II) at the Center of Isotopic Research (CIR) of Karpinsky Russian Geological Research Institute (VSEGEI).

The representative zircons selected manually with the microscope were embedded in epoxy resin (a washer 2.5 cm in diameter) together with grains of the TEMORA and 91 500 International zircon standards and then were ground by approximately half of their thickness and were polished. A current-conducting gold coating was applied on the specimen in a cathodic-vacuum atomization device for 1 min at 20 mA. The zircon grains were then documented using a CamScanMX scanning electron microscope with the CLI/QUA2 system to acquire cathodoluminescence (CL) and BSE images reflecting the internal structure and zoning of the zircons. The working distance was 25–28 mm, the accelerating voltage was 20 kV, the current of the almost-fully focused beam on the Faraday cylinder was 4–6 nA. The probe current was varied to reach the maximum contrast of the CL image and to minimize corrosion on the washer surface as a result of local heating.

The measurements of the U/Pb ratios were taken by a procedure adapted at the CIR (Schuth et al., 2012). The intensity of the primary beam of molecular oxygen was 4 nA, the sampling crater was 20 × 25 μm at a depth of as little as 2 μm. The U–Pb ratios were normalized to 0.0668, which was assigned to the TEMORA standard zircon; this corresponds to an age of this zircon of 416.75 ± 0.24 Ma (Black et al., 2003). The 91500 zircon standard with a uranium content of 81.2 ppm and a $^{206}Pb/^{238}U$ of 1062 Ma (Widenbeck et al., 1995) was employed as a concentration standard. Raster cleanup of the rectangular (50 × 65 μm) mineral segment before determining the age made it possible to minimize surface contamination.

The errors of the single analyses (the ratios and the ages) are provided at the 1σ level; the errors of the determined age values, including the concordant ones, are given at the 2σ level. The correction for nonradiogenic lead was made by the measured ^{204}Pb and the modern isotope composition of lead in the Stacey-Kramers model (Stacey and Kramers, 1975).

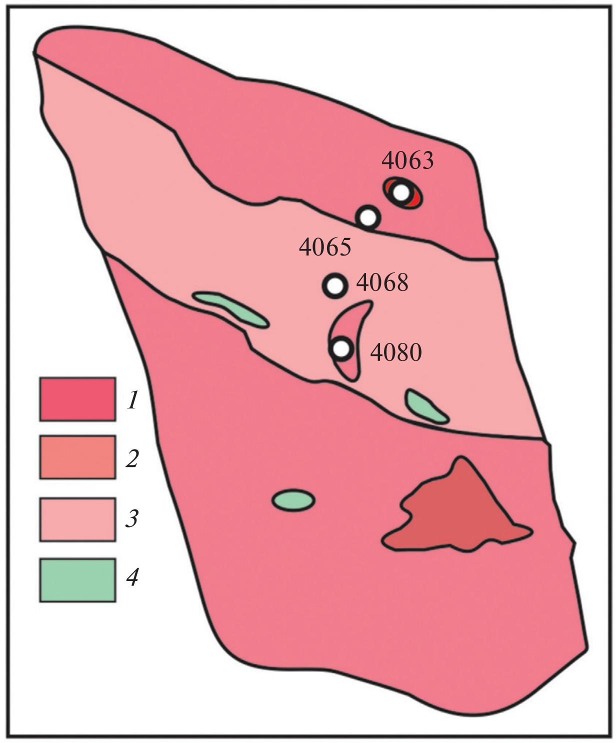


Fig. 2. The sampling procedure in the Neplyuevka pluton. (*1*) leucogranites of the fourth phase; (*2*) adamellites of the third phase; (*3*) granodiorites of the second phase; (*4*) gabbro of the first phase.

RESULTS AND DISCUSSION

To refine the formation time of the Neplyuevka pluton, we conducted comprehensive studies of the zircon crystals from granodiorites (sample 4068) of the second intrusive phase and adamellites (samples 4080 and 4065) of the third intrusive phase (Fig. 2). All samples were selected strictly from the same sites and rocks that had been the source of previous sampling for Rb–Sr dating. The morphology and the internal structure of the zircon grains were studied using cathodoluminescence images.

Sample 4068. The zircons from the granodiorites of the second phase of the Neplyuevka complex are translucent, pale yellowish idiomorphic bipyramidal-prysmatic crystals with different elongation coefficients (K_{elong} = 2–5); they have a length of 220–350 μm and contain small black inclusions. In the cathodoluminescent images (Fig. 3a), the zircons have moderate luminescence with well-defined moderately contrasting rough and fine oscillatory zoning, which often turns to patchy zoning in the central parts of the grains.

We analyzed 15 individual zircon grains from the granodiorites (15 local analyses) (Fig. 3b, Table 1). For all the analyses, the age was determined in the range from 341 to 360 Ma with an average concordant age of 350 ± 3 Ma (2σ, MSWD = 0.42).

Sample 4080. The zircons from the adamellites of the third phase of the Neplyuevka complex are translucent pale yellow idiomorphic bipyramidal-prysmatic crystals with different elongation coefficients (K_{elong} = 2–4.5); they have a length of 170–360 μm and contain many translucent and black inclusions (Fig. 4a). The grains are often broken by a system of radial cracks that propagate from the center to the rim of a crystal.

The central part of such grains most often has a metamict structure, which is exhibited by abundant sandy-brown traces of ferruginization in translucent light; these areas are darker in back-scattered electron image compared to the undisturbed parts of the zircon. In the cathodoluminescent images the zircons have weak and moderate luminescence with moderately contrasting rough and fine oscillatory zoning, which is often combined with patchy zoning. The metamict areas in the zircon do not fluoresce under cathode light (they are black).

We analyzed 12 individual zircon grains from the adamellites (16 local analyses). The age was determined in the range from 249 to 361 Ma. Four grains (five analyses) have Permian (264 ± 5, 280 ± 6, 289 ± 6, 292 ± 6 Ma) and Early Triassic (249 ± 5 Ma) age (Figs. 4b, 4c; Table 2). For eight zircons (11 analyses) with a rather wide range of individual $^{206}Pb/^{238}U$ age values (326–361 Ma), the average concordant age is 344 ± 4 Ma (2σ, MSWD = 0.30).

Sample 4065. The zircons from the adamellites of the third phase of the Neplyuevka complex are translucent pale yellow idiomorphic bipyramidal–prismatic grains (K_{elong} = 2–5) sized 200–600 μm and

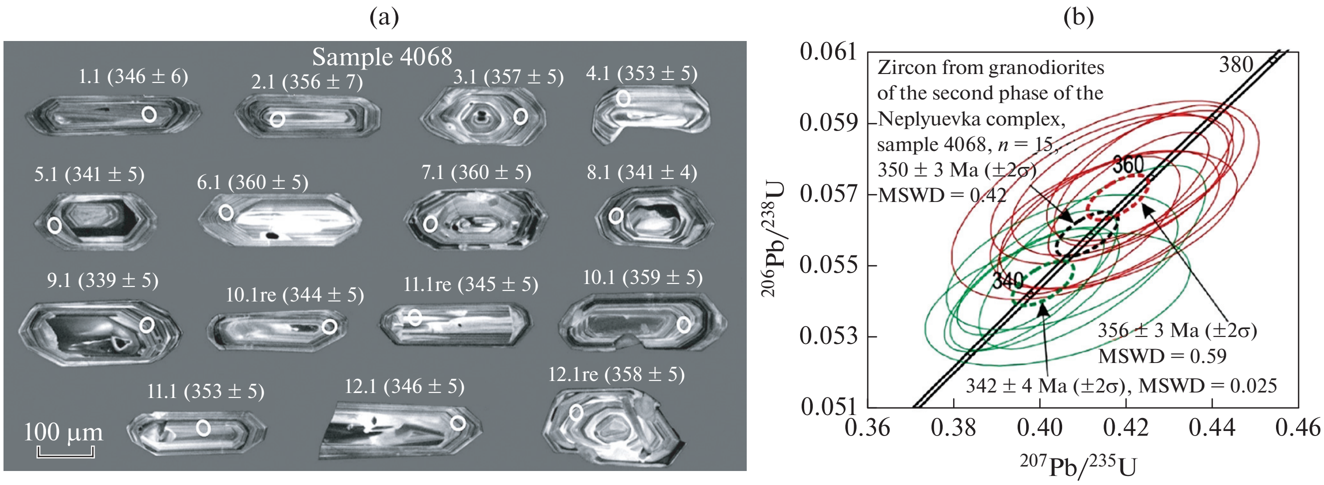


Fig. 3. (a) Cathodoluminescent images of single zircon crystals (sample 4068) dated by the SIMS method (SHRIMP-II); ellipses on the crystals demonstrate the sizes and the location of respective sites of ionic sampling; (b) U–Pb concordia diagram for the analyzed zircons from the granodiorites (sample 4068); error ellipses: at 2σ level.

contain many translucent and black inclusions with an irregular and elongated shape and sized 1–100 μm (Fig. 4a). In the cathodoluminescent images (Fig. 5a), two types of grains are identified: (1) without nuclei, with moderately contrasting rough and fine oscillatory zoning and (2) with amebiform stained nuclei that combine patchy and oscillatory zoning. The nuclei were separated from the overgrowing rim by curved borders. The structure of such grains is usually disturbed, nuclei most often have a metamict structure with numerous radial and traverse cracks and abundant sandy-brown traces of ferruginization.

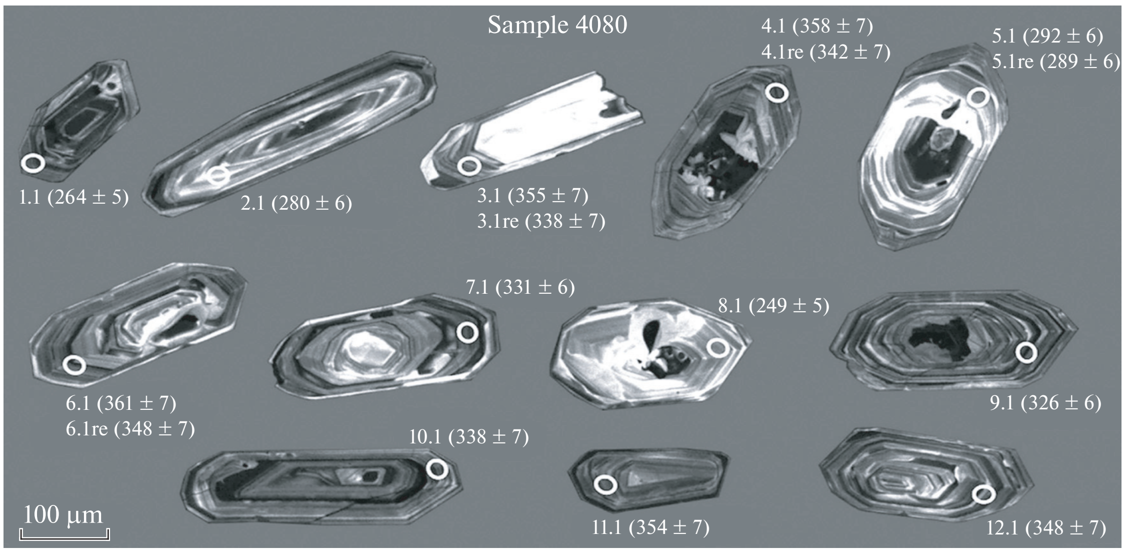
We analyzed 12 individual zircon grains from adamellites (12 local analyses). Their age was deter-

Table 1. The results of U–Pb isotope studies of the zircon grains from the granodiorites of the second phase of the Neplyuevka complex (sample 4068, the Neplyuevka pluton)

Analysis no.	$^{206}Pb_c$, %	Content, ppm			$^{232}Th/^{238}U$	Isotope ratios, ± % (1σ)						Rho	Age, Ma, ± 1σ				D, %
		U	Th	$^{206}Pb^*$		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$			$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$		
4068-9.1	0.22	374	275	17.4	0.76	0.0542	±2.8	0.404	±3.1	0.0540	±1.4	0.4	339	±5	379	±63	12
4068-8.1	0.00	644	467	30.0	0.75	0.0529	±1.3	0.396	±1.9	0.0543	±1.3	0.7	341	±4	326	±30	–4
4068-5.1	0.00	461	391	21.5	0.88	0.0532	±1.5	0.399	±2.0	0.0543	±1.3	0.7	341	±5	339	±34	–1
4068-10.1re	0.00	596	498	28.0	0.86	0.0529	±1.4	0.399	±1.9	0.0548	±1.3	0.7	344	±5	324	±31	–6
4068-12.1	0.16	306	187	14.5	0.63	0.0533	±2.3	0.405	±2.7	0.0551	±1.4	0.5	346	±5	341	±52	–1
4068-1.1	0.04	452	353	21.4	0.81	0.0541	±1.8	0.412	±2.6	0.0552	±1.9	0.7	346	±6	376	±40	9
4068-11.1re	0.00	396	243	19.1	0.63	0.0532	±1.6	0.411	±2.1	0.0561	±1.4	0.6	352	±5	336	±37	–5
4068-11.1	0.07	279	238	13.5	0.88	0.0537	±2.1	0.416	±2.5	0.0563	±1.4	0.6	353	±5	357	±47	1
4068-4.1	0.14	265	208	12.8	0.81	0.0538	±2.4	0.417	±2.8	0.0562	±1.4	0.5	353	±5	363	±54	3
4068-2.1	0.28	236	243	11.5	1.06	0.0530	±2.9	0.415	±3.5	0.0568	±2.0	0.6	356	±7	329	±66	–7
4068-3.1	0.00	723	518	35.3	0.74	0.0536	±1.2	0.420	±1.8	0.0569	±1.3	0.7	357	±5	354	±27	–1
4068-12.1re	0.00	234	229	11.5	1.02	0.0528	±2.3	0.416	±2.7	0.0571	±1.5	0.5	358	±5	321	±51	–10
4068-10.1	0.17	395	245	19.4	0.64	0.0531	±2.0	0.419	±2.5	0.0572	±1.4	0.6	359	±5	333	±46	–7
4068-6.1	0.08	426	328	21.1	0.80	0.0535	±1.7	0.424	±2.2	0.0575	±1.3	0.6	360	±5	352	±39	–2
4068-7.1	0.00	433	218	21.4	0.52	0.0535	±1.5	0.424	±2.0	0.0575	±1.4	0.7	360	±5	349	±34	–3

Errors in standard calibration are 0.33% (sample 4068), 0.48% (sample 4080), 0.48% (sample 4065); $^{206}Pb_c$ and $^{206}Pb^*$ is the content of common and radiogenic Pb, respectively; isotope ratios and age data are corrected by measured ^{204}Pb; D is discordancy: D = 100[age($^{207}Pb/^{206}Pb$/age ($^{206}Pb/^{238}U$) – 1]; Rho is the correlation coefficient between the errors of determining isotope ratios $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$.

(a)



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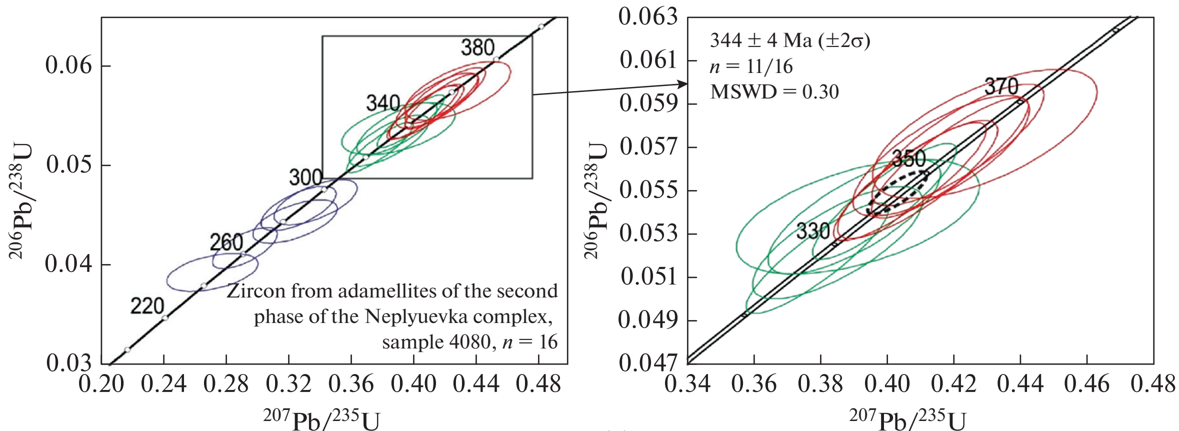

(c)

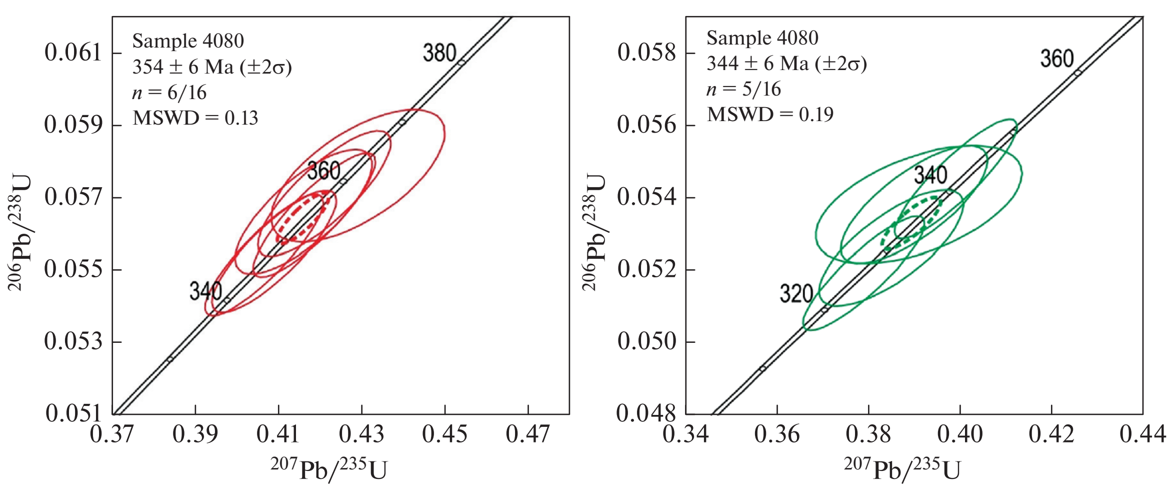

Fig. 4. (a) Cathodoluminescence images of individual zircons from the granodiorites (sample 4080) dated by the SIMS method (SHRIMP II); ellipses on the crystals demonstrate the sizes and the location of respective sites of ionic sampling; (b) U–Pb concordia diagram for the analyzed zircons from the adamellites (sample 4080); error ellipses: at 2σ level.

Table 2. The results of U–Pb isotope studies of the zircon grains from the adamellites of the third phase of the Neplyuevka complex (sample 4080, the Neplyuevka pluton)*

Analysis no.	$^{206}Pb_c$, %	Content, ppm			$^{232}Th/^{238}U$	Isotopic ratios, ± % (1σ)						Rho	Age, Ma, ± 1σ				D, %
		U	Th	$^{206}Pb^*$		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$			$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$		
4080-8.1	0.82	349	210	11.9	0.62	0.0502	±3.9	0.272	±4.4	0.0393	±2.0	0.5	249	±5	202	±91	–19
4080-1.1	0.81	917	589	33.2	0.66	0.0508	±2.1	0.293	±2.9	0.0418	±2.0	0.7	264	±5	233	±50	–12
4080-2.1	0.37	313	276	12.0	0.91	0.0531	±2.7	0.325	±3.4	0.0444	±2.0	0.6	280	±6	332	±61	18
4080-5.1re	0.28	325	243	12.8	0.77	0.0519	±2.3	0.327	±3.0	0.0458	±2.0	0.7	289	±6	279	±52	–3
4080-5.1	0.25	378	297	15.1	0.81	0.0529	±2.5	0.338	±3.2	0.0464	±2.0	0.6	292	±6	323	±57	10
4080-9.1	0.13	1036	716	46.3	0.71	0.0529	±1.1	0.379	±2.3	0.0519	±2.0	0.9	326	±6	325	±24	0
4080-7.1	0.45	713	463	32.4	0.67	0.0531	±1.8	0.385	±2.7	0.0526	±2.0	0.7	331	±6	333	±41	1
4080-3.1re	0.12	282	175	13.0	0.64	0.0526	±1.8	0.390	±2.7	0.0538	±2.0	0.7	338	±7	313	±40	–7
4080–10.1	2.89	1145	715	54.5	0.65	0.0526	±3.2	0.391	±3.8	0.0538	±2.0	0.5	338	±7	312	±74	-8
4080-4.1re	0.04	782	562	36.6	0.74	0.0531	±1.0	0.399	±2.2	0.0545	±2.0	0.9	342	±7	331	±24	–3
4080-12.1	0.09	845	752	40.2	0.92	0.0532	±1.1	0.407	±2.3	0.0554	±2.0	0.9	348	±7	339	±25	–2
4080-6.1re	0.15	604	334	28.8	0.57	0.0534	±1.3	0.409	±2.4	0.0555	±2.0	0.8	348	±7	348	±29	0
4080-11.1	0.05	702	425	34.1	0.63	0.0538	±1.2	0.419	±2.3	0.0565	±2.0	0.9	354	±7	361	±26	2
4080-3.1	0.14	374	237	18.2	0.65	0.0532	±1.7	0.416	±2.6	0.0566	±2.0	0.8	355	±7	339	±39	–5
4080-4.1	0.03	731	465	35.8	0.66	0.0535	±1.4	0.421	±2.5	0.0571	±2.0	0.8	358	±7	352	±32	–2
4080-6.1	0.36	719	429	35.7	0.62	0.0540	±2.4	0.429	±3.2	0.0576	±2.1	0.6	361	±7	373	±55	3

* Refer to notes to Table 1.

mined in the range of 254–368 Ma. Excluding one highly metamict grain with an age of 254 ± 5 Ma, the concordant age was estimated at 356 ± 4 Ma (2σ, MSWD = 0.25) from 11 analyses (342—368 Ma) (Fig. 5b; Table 3).

Sample 4063. The zircons from the leucogranites of the fourth phase of the Neplyuevka complex are dark gray, almost black, in the cathodoluminescent images. They are short-prismatic crystals with weak oscillatory zoning. The concordant age by eight individual grains was 308.6 ± 7.6 Ma (2σ, MSWD = 0.67), which corresponds to the end of the Moscovian. This fact has not yet found an explanation under the accepted ideas. Several crystals sharply differ from the others, they are light in color in the images, have long-prismatic habitus and exhibit clear oscillatory zoning. They are Archean captured zircons.

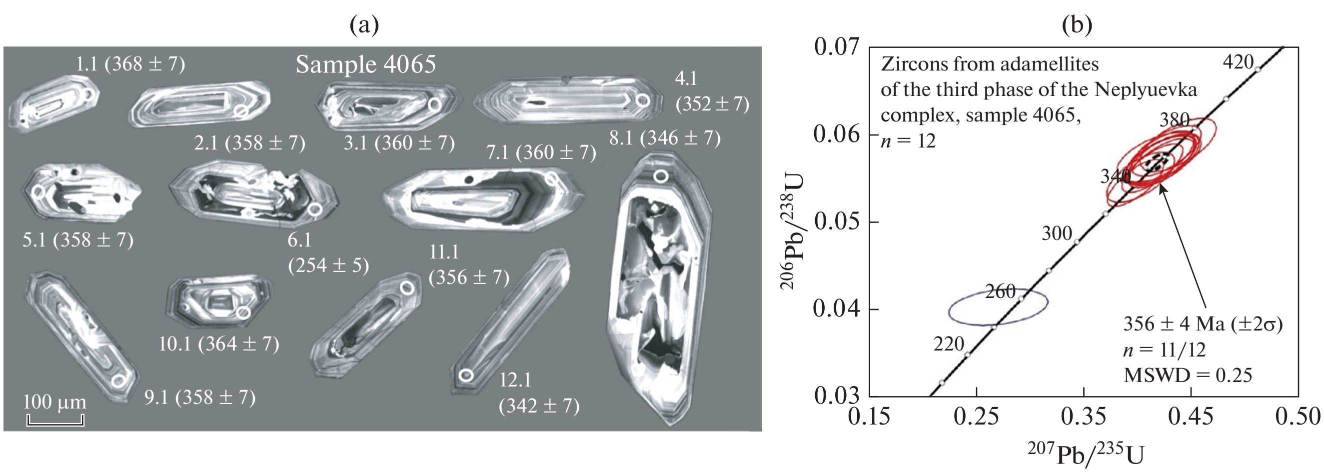

Fig. 5. (a) Cathodoluminescence images of single zircon crystals from the adamellites (sample 4065) dated by the SIMS method (SHRIMP-II); ellipses on the crystals demonstrate the sizes and the location of respective sites of ionic sampling; (b) U–Pb concordia diagram for the analyzed zircons from the adamellites (sample 4065); error ellipses: at 2σ level.

Table 3. The results of U–Pb isotope studies of the zircon grains from the adamellites of the third phase of the Neplyuevka complex (sample 4065, the Neplyuevka pluton)*

Analysis no.	$^{206}Pb_c$, %	Content, ppm			$^{232}Th/^{238}U$	Isotopic ratios, ± % (1σ)						Rho	Age, Ma, ± 1σ				D, %
		U	Th	^{206}Pb*		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$			$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$		
4065-6.1	1.88	608	384	21.4	0.65	0.0486	±6.7	0.270	±7.0	0.0402	±2.1	0.3	254	±5	130	±160	–49
4065-12.1	0.06	551	509	25.8	0.95	0.0531	±1.8	0.398	±2.7	0.0544	±2.0	0.7	342	±7	331	±41	–3
4065-8.1	0.22	513	327	24.4	0.66	0.0530	±2.4	0.403	±3.2	0.0551	±2.1	0.6	346	±7	328	±54	–5
4065-4.1	0.07	518	512	24.9	1.02	0.0536	±1.9	0.414	±2.8	0.0561	±2.0	0.7	352	±7	355	±42	1
4065-11.1	0.20	508	345	24.8	0.70	0.0540	±2.2	0.422	±3.0	0.0567	±2.0	0.7	356	±7	372	±49	5
4065-9.1	0.17	434	254	21.3	0.60	0.0535	±2.4	0.421	±3.2	0.0570	±2.0	0.6	358	±7	351	±54	–2
4065-2.1	0.11	315	174	15.5	0.57	0.0538	±2.5	0.424	±3.2	0.0571	±2.1	0.6	358	±7	364	±56	2
4065-5.1	0.19	392	357	19.3	0.94	0.0536	±2.5	0.422	±3.2	0.0571	±2.0	0.6	358	±7	352	±56	–2
4065-7.1	0.10	343	200	16.9	0.60	0.0532	±2.4	0.421	±3.1	0.0574	±2.1	0.7	360	±7	338	±53	–6
4065-3.1	0.39	371	241	18.4	0.67	0.0531	±3.2	0.420	±3.8	0.0574	±2.0	0.5	360	±7	332	±73	-8
4065-10.1	0.15	455	467	22.7	1.06	0.0533	±2.3	0.427	±3.1	0.0581	±2.0	0.7	364	±7	340	±52	–7
4065-1.1	0.19	366	255	18.5	0.72	0.0540	±2.6	0.438	±3.3	0.0588	±2.1	0.6	368	±7	370	±58	1

* Refer to notes to Table 1.

The concordant ages of 350 ± 3 (for sample 4068) and 344 ± 4 Ma (for sample 4080) could be easily interpreted as the formation time of the granodiorites of the second phase and the adamellites of the third phase from the Neplyuevka complex; however, a set of data available for today suggests a slightly different look on the results.

For these samples (samples 4068, 4080, and 4065), the Rb–Sr isochronous ages of 346, 342, and 340 Ma, respectively, determined by the rocks and minerals were published previously (Popov et al., 2003). These ages are similar to the ages of younger zircons (group 1) of three samples. Their concordant age is 342 ± 4 Ma (sample 4068) and 334 ± 6 Ma (sample 4080), and the age of the two youngest zircon grains from sample 4065 is 342 ± 7 Ma (Fig. 5b).

However, we can also distinguish a group of older grains (*group 2*) in each of the three samples. Their average concordant ages are almost the same: 356 ± 3 (sample 4068), 354 ± 6 (sample 4080), and 356 ± 4 Ma (4065). As an explanation for the existence of two age groups of zircons, it can be assumed that older ages correspond to the time of crystallization of zircon from the melt, while younger dates are the result of a partial loss of radiogenic Pb by zircon during the cooling of the pluton and/or (?) thermal impact of the Early Carboniferous (325–349 Ma) mafic intrusions distributed throughout the Urals. In the South Urals, this is the Khudolaz complex (Salikhov et al., 2014), the North-Kassel' and the Zamatokhin intrusions (Salikhov and Mitrophanov, 1994), the Kamensk pluton (Ferstater, 2013), and the Musyur complex in the Polar Urals (Sobolev et al., 2020). At this stage of mafic magmatism, the Rb–Sr system could restart in the minerals of granitoids and the U–Pb isotope system could be partly disturbed in the zircons. The greatest loss of radiogenic Pb could occur in the disturbed (metamict) segments of the grains, which explains the quite broad range of the age data for the zircons from the rocks. In our opinion, the comparison of the Rb–Sr data and the ages of the younger group of the zircons indirectly confirms this assumption.

Another variant of interpreting the presence of older zircons in the granitoids is to consider them to be xenogenic. In particular, T.A. Osipova et al. (2018) described zircons with manifested rhythmic zoning, which were extracted from the Early Permian granites of the same Neplyuevka pluton and have an age of 278 Ma by the Rb–Sr isochron (Popov et al., 2003). Their U–Pb (SRIMP) age is 360 ± 2 Ma, i.e., it corresponds to the Devonian–Carboniferous boundary; two of six analyzed zircon grains have an Early Carboniferous age of 353 and 355 Ma. The authors of the above work showed (by the Lu-Hf isotope data) that these zircons are metamorphic but not magmatic. In addition, a surprising fact that was noted by these researchers is that no Early Permian zircons were found in the Early Permian granites at all. However, among the zircon crystals we studied, several exemples were older than 360 Ma, i.e., it is not unlikely that they form a common set with the grains discovered by T.A. Osipova and her colleagues (2018).

Could only the Early Carboniferous zircons of the second phase intrude into the Early Permian granites of the Neplyuevka pluton, while the zircons of the first phase could not? This situation is highly unlikely. The Permian zircons are present in the granitoids from the Neplyuevka complex, although almost all of them (samples 4080, 4065) have segments with a metamict structure. This is probably the reason that the U–Pb system was disturbed in such grains during the intrusion of igneous rocks at the main stage of the Uralian collision (Popov et al., 2003).

CONCLUSIONS

These novel data make it possible to interpret the development of the Early Carboniferous magmatism in the Southern Urals in a new way. Its geodynamic interpretation is a matter of scientific dispute. Many researchers consider this magmatism to be subduction-related, but their opinions about the direction of dip of the subduction zone differ sharply. There are grounds for this conclusion, since the geochemical characteristics of Early Carboniferous volcanic rocks feature marks of subduction-related settings, in particular, Ta–Nb minima (Rudakova et al., 2007). K.S. Ivanov (1998) suggested an east-dipping subduction zone, R.G. Yazeva and V.V. Bochkarev (2000) assumed the same and also its outcrop at the surface in Pre-Uralian foredeep. G.A. Mizens (2000) holds that the subduction zone dips west. In the opinion of V.N. Puchkov (2010), the Early Carboniferous magmatism has a rift-related origin and the subduction in the Southern Urals had terminated by the Carboniferous due to slab delamination. V.N. Puchkov (2000) also believes that in the Early Carboniferous, the East Uralian megazone developed as a marginal-continental volcano-plutonic belt above the subduction zone.

This hypothesis is interpreted by D.N. Salikhov and his colleagues (2014) in their own way; in particular, I.R. Rakhimov showed later in his Cand. Sci. Dissertation that the gabbro–diorite–granite series of the Magnitogorsk megazone was formed in the Tournaisian–Early Visean in a pull-apart setting during oblique collision related to rifting in the East Uralian megazone. For the last 20 years, we have also been elaborating the idea about the rifting in the Early Carboniferous within the entire Southern Urals (Pravikova and Tevelev, 2003; Pravikova et al., 2008; Yaroshevskii et al., 2007) and the idea of large shear deformations in the Early Carboniferous (Tevelev et al., 2006).

Almost all mentioned works refer the beginning of the rift-related magmatism to the second half of the Tournaisian, at the onset of the formation of the Berezovskaya contrasting series of volcanites. These ideas were also supported by the results of Rb–Sr dating of the granitoids from the Neplyuevka pluton (346–340 Ma (Popov et al., 2003). In addition, numerous Famennian–Early Tournaisian “transitional” sedimentary complexes are known to occur within the Southern Urals, i.e., there was a significant hiatus between the formation of the island-arc Late Devonian and rift-related Early Carboniferous volcanic complexes (Pravikova et al., 2008). The data we acquired make it possible to shift the time of the onset of rifting to the Devonian–Carboniferous boundary. This boundary is defined as a major geodynamic frontier (Puchkov, 2000; Fershtater, 2013), that is, the collision between the Magnitogorsk island arc and the East European continent and the beginning of the marginal-continental accretion, which completed by the end of the Famennian age.

This situation led to the termination of island-arc magmatism and the onset of rifting. In the meantime, the geochemical characteristics of the granitoids still retained the marks of subduction-related (Tevelev et al., 2006). As well, according to G.B. Fershtater (2013), the age of the zircon from the Devonian trachybasalts of the final phase of island-arc volcanism in the Magnitogorsk Megazone is 356.4 ± 3.3 Ma (already the Early Carboniferous!), which overlaps with the age of the zircons from the Neplyuevka pluton. Unfortunately, G.B. Fershtater, who described many intrusives of a wide age span, did not mention the Neplyuevka pluton in his excellent book. With all of the possible errors in defining and interpreting the geochemical data, the time interval between the island-arc and the rift-related magmatism is very short.

The intense tectonic activity in the Early Tournaisian is also confirmed by the age of the amphibolite facies metamorphism within the Sysert-Il’menogorsk block located to the north (352 ± 40 Ma, amphibolites by the Sm–Nd isochrone, as well as 353 ± 3.4 and 355 ± 5 Ma, the amphibole–biotite gneiss by the U–Pb zircon method (Ronkin et al., 1993, 1997)).

Thus, two age groups were identified among the studied zircons: group 1 from 334 to 342 Ma and group 2 from 354 to 356 Ma. The older age data are likely to correspond to the time of zircon crystallization from the melt, while the younger data resulted from partial loss of radiogenic Pb by zircons during the long-term cooling of the pluton and/or (?) from a thermal impact of the Early Carboniferous or even the Early Permian intrusives.

The formation of the Neplyuevka complex at the very beginning of the Carboniferous marks the most important stage in the geodynamic evolution of the Southern Urals, a rapid transition from island arc magmatism, which continued during the entire Devonian, to rift-related magmatism, which began at the Devonian–Carbonaceous boundary and developed under conditions of left-lateral transtension. The rifting ended only in the Middle Visean.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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