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GEOLOGY

New Data on the Age of Subalkaline Magmatism at the Eastern Margin of the East European Paleocontinent and Estimation of the Rate of Longitudinal Opening of the Early Paleozoic Rift

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Subalkaline igneous rocks are widespread in the Main Ural Fault Zone as a chain of dikes and minor intrusions that crosscut the Ordovician sequences deposited at the eastern (Uralian) margin of the East European paleocontinent (Fig. 1). In the Polar Urals, the subalkaline rocks belong to the Paipudyn rhyolite complex, the Manitanyrd trachybasalt–trachyrhyolite complex, and the Pozhem rhyolite complex. In the Subpolar and northern Urals, they occur in the Bol'shepatoka and Malinovka trachyrhyolite complexes. The Verkhneserebryanka trachybasalt–trachyte complex, the Vaganovka gabbro–syenite complex, the Kordonokamenka alkali granite complex, and the Belokamenka syenite complex are recognized in the central Urals. Most of these complexes are still poorly characterized in terms of petrography, geochemistry, and reliable isotopic dating. The age of some complexes is based only on random K–Ar determinations of whole-rock samples. These complexes are attributed to tectonomagmatic reactivation in the Ordovician, Carboniferous, and Triassic–Jurassic.

To fill this gap, we studied trachyrhyolite, granite porphyry, and monzodiorite of the Malinovka Complex developed as minor subvolcanic and hypabyssal intrusions of Lower Ordovician volcanosedimentary rocks on the eastern slope of the northern Urals. The Malinovka Complex was first described by Stepanov et al. [1] in the course of verification of aerogammaspectrometric U, Th, and K anomalies in the Malinovka River basin (upper reaches of the Ivdel River). The hypabyssal intrusive rocks (granite and monzodiorite) were mentioned previously in the Main Ural Fault Zone during geological mapping, while the subvolcanic rocks were described as metamorphic schists.

The lenticular (in plan view) bodies of subalkaline rocks of the Malinovka Complex and their metasomatic sericite–carbonate halos make up a belt that is traced along the Salatim Fault from the upper reaches of the Anchug River in the north to the Vagran River basin in the south. In proportions of alkali metals, the rock compositions vary (often within a single body) from ultrapotassic (10–12 wt % K_2O) to sodic and potassic–sodic varieties. In terms of the silica content, they vary from trachyte and pantellerite to trachyrhyolite.

Trachyte and trachyrhyolite are the most abundant rocks of the Malinovka Complex. They occur as a series of lenticular stocks and dikes (up to 3 km long) of light-colored, homogeneous, banded, occasionally brecciated porphyritic, and often vuggy rocks with a very fine-

Fig. 1. Location of subalkaline igneous complexes at the Paleozoic margin of the East European paleocontinent. Compiled using the data of V.N. Puchkov. (*1*) Paleozoic–Mesozoic sedimentary cover of the Russian Platform; (*2*) Permian–Triassic sedimentary rocks of the Ural Foredeep; (*3*) Paleozoic shelf sedimentary rocks of the East European paleocontinent (Belaya River–Yelets Zone); (*4*) Paleozoic volcanic and sedimentary rocks of continental slope of the East European paleocontinent (Sakmara–Lemva Zone); (*5*) pre-Paleozoic rocks (Central Ural Megazone); (*6*) volcanic and intrusive rocks of the Tagil paleoisland-arc system; (*7*) East Ural Megazone (collage of heterogeneous terranes); (*8*) Mesozoic–Cenozoic sedimentary cover of the West Siberian Plate; (*9*) Main Ural Fault; (*10*) Paleozoic subalkaline igneous complexes: (*a*) reliably dated, (*b*) with uncertain isotopic age. Igneous complexes (numerals in boxes): (1) Paipudyn, (2) Manitanyrd, (3) Pozhem, (4) Bol'shepatoka, (5) Malinovka, (6) West Baranchino, (7) Khomutovo and Bilimbaevka.

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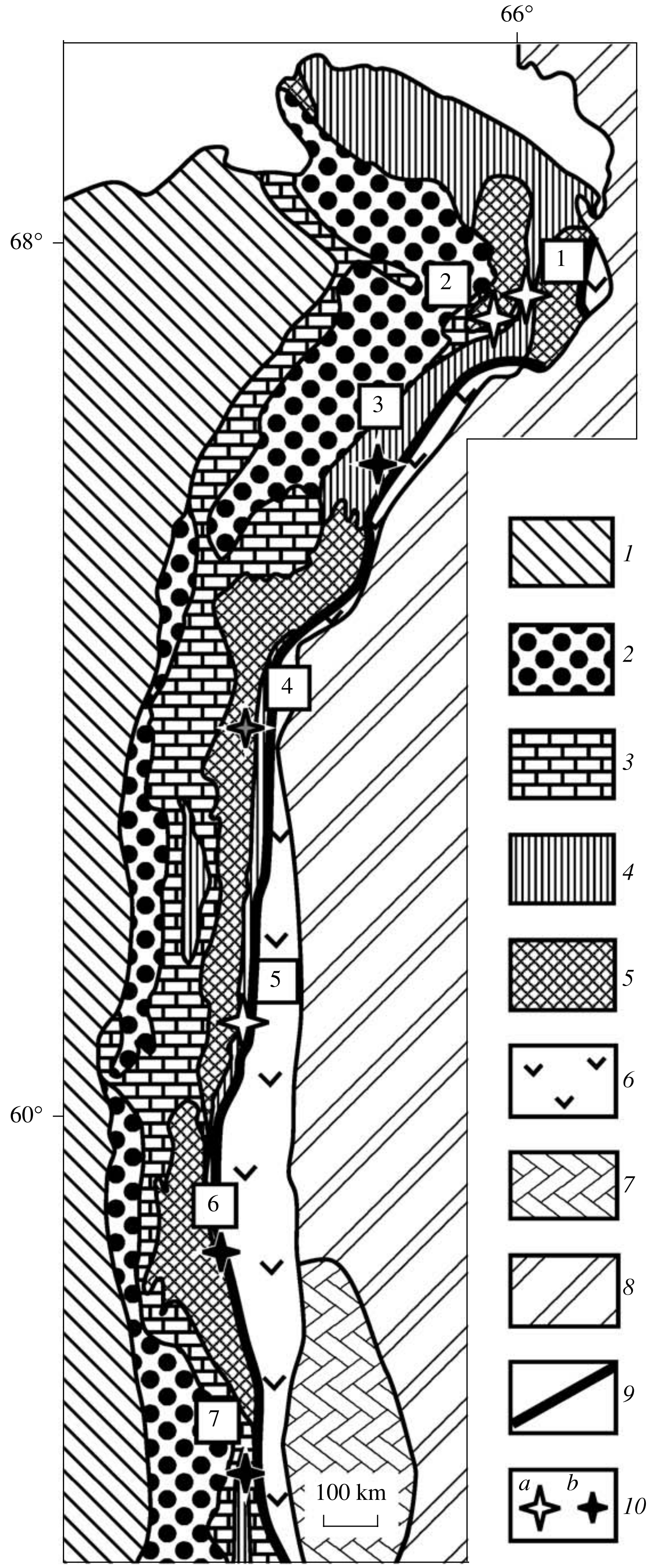
66°
68°
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1
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a
b
10

Table 1. Representative analyses of rocks from the Malinovka Complex (major oxides are given in wt %; trace elements, in ppm)

Component	1	2	3	4
SiO_2	62.6	63.38	73.83	70.49
TiO_2	1	0.18	0.34	0.19
Al_2O_3	10.35	17.27	8.22	14.32
Fe_2O_3	7.05	1.63	2.73	0.48
FeO	1.58	0.72	1.08	0.63
MnO	0.21	0.02	0.04	0.02
MgO	4.41	0.15	2.28	0.05
CaO	2.98	0.94	2.44	0.23
Na_2O	6.57	3.04	4.87	0.26
K_2O	2.34	4.84	1.79	11.81
P_2O_5	0.47	0.11	0.11	0.03
L.O.I.	0.21	0.96	1.25	0.51
Total	99.93	99.79	99.47	99.42
Ni	10.14	26.10	–	250.90
Li	17.31	7.66	5.74	5.24
Be	3.86	3.48	7.21	2.32
Sc	12.37	6.31	0.73	1.58
V	3.28	12.31	3.81	10.22
Co	2.91	2.77	1.01	27.26
Ga	31.40	25.88	37.17	25.21
Rb	23.56	207.36	36.08	100.48
Sr	270.60	22.15	14.67	45.65
Y	62.35	37.48	184.06	175.41
Zr	563.99	160.66	364.82	756.71
Nb	114.29	27.02	133.84	175.90
Mo	0.93	1.65	4.45	1.99
Cs	1.34	4.40	0.29	0.41
Ba	1228.06	1066.79	500.15	3044.78
La	57.36	23.00	85.28	152.88
Ce	133.92	56.46	193.97	198.11
Pr	16.00	5.90	21.77	25.94
Nd	65.77	23.40	81.78	105.64
Sm	13.60	5.69	20.92	24.91
Eu	5.47	0.49	2.78	5.01
Gd	12.50	5.65	22.40	26.56
Tb	1.86	0.97	4.15	4.83
Dy	10.87	6.02	27.36	30.93
Ho	2.21	1.28	6.03	6.42
Er	5.66	3.53	15.78	16.52
Tm	0.77	0.57	2.25	2.34
Yb	4.93	3.93	13.66	14.41
Lu	0.72	0.67	1.83	2.21
Hf	12.00	5.80	12.32	25.59
Ta	4.93	2.10	7.80	4.90
W	4.73	2.75	2.34	2.53
Th	6.25	15.56	14.31	13.99
U	1.73	2.27	4.83	3.59
Cr	132.60	756.50	248.17	297.11

Note: (1, 2) Monzodiorite (samples 1005, 8089); (3) granite (sample 5019), (4) trachyrhyolite (sample 02119).

grained, granoblastic, allotriomorphic-granular, trachytic, spherulitic, cryptocrystalline, or micropoikilitic groundmass. Phenocrysts are composed of microcline, microcline-perthite, and albite; albite, quartz, microcline, muscovite, and chlorite make up the groundmass, which also contains stilpnomelane, phlogopite, and glaucophane–riebeckite amphibole. In alkali metal contents, the rocks vary from subalkaline to alkaline species (comendite, pantellerite, and trachyte). In terms of their proportions, sodic, potassic–sodic, and potassic varieties are distinguished. Trachyte and trachyrhyolite are often subjected to sericite–quartz metasomatic alteration with formation of carbonate–feldspar–sericite–quartz, sericite–quartz, and sericite metasomatic rocks that contain stockworks of sulfide–quartz and sulfide–carbonate–quartz veinlets. The fine gold occurs in these veinlets in addition to pyrite, galena, molybdenite, and chalcopyrite [1].

In the Ivdel River basin, trachyrhyolites are associated with granite dikes, while granites crop out as small stocks in the Vagran River valley. These are fine-grained porphyritic and equigranular rocks consisting of albite, microcline, quartz, and phlogopite in various proportions.

Monzonite and monzodiorite occur as small stocks in the basins of the Kriv Vagran and Sos'va rivers. These are medium-grained porphyritic and equigranular rocks composed of idiomorphic zonal albite–oligoclase crystals (40–45%), microcline (25–30%), green hornblende (20%), and phlogopite (10–15%). Apatite, titanite, and magnetite are accessory minerals. One can see stilpnomelane and the primary hornblende glaucophane–crossite amphibole rims [2].

Metasomatic sericite–carbonate rocks are observed as narrow halos that extend along the Salatim Fault for more than 50 km. Sericite and carbonate replace metavolcanic rocks and metapelites of the Ordovician Khomas'inka Formation. The degree of metasomatic alteration varies from the appearance of sporadic grains of the newly formed minerals to the complete replacement and formation of metasomatic rock consisting of ankerite and muscovite with a sporadic admixture of chlorite, albite, and quartz. Zones of disseminated and stringer–disseminated magnetite mineralization (a few meters in thickness) are associated with sericite–carbonate metasomatites.

The igneous rocks of the Malinovka Complex bear rather specific geochemical features. The silicic rocks correspond to trachydacite and rhyolite in classification diagrams and reveal wide variations in alkali metal contents from ultrapotassic ($K_2O > 10$ wt %, $Na_2O < 0.2$ wt %) to sodic varieties ($Na_2O > 6$ wt %, $K_2O < 0.5$ wt %) and a series of transitional compositions. The total REE content varies from 50 to 485 ppm (La/Yb = 5.8–11.6). Trachyryolites are enriched in Zr, Y, Nb, Ta, Cr, Ni, and Ba relative to the global averages for granites (Table 1). In these parameters, the rocks are closer to the mantle associations of rift zones than to the crustal palingenetic

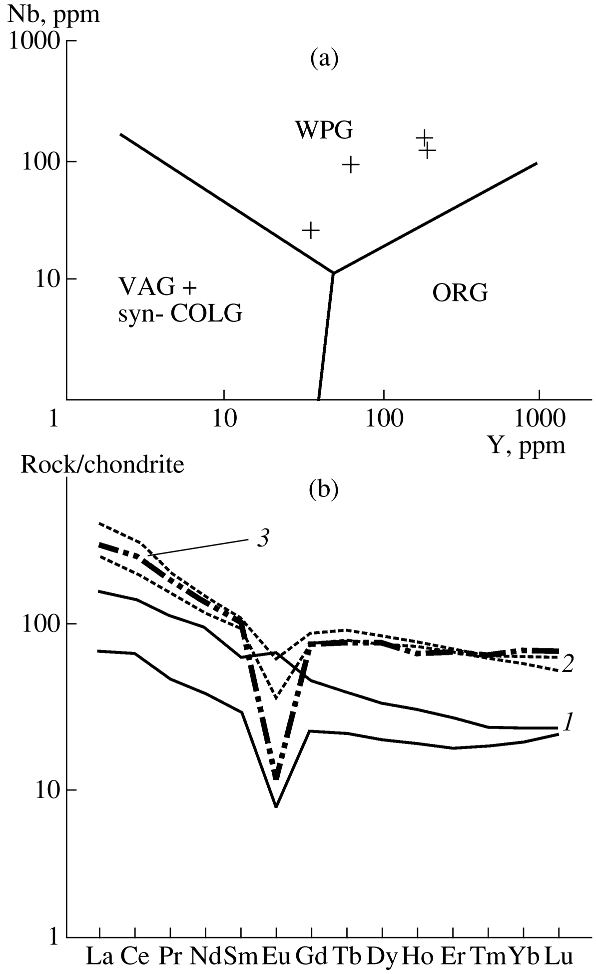

Fig. 2. (a) Compositions of igneous rocks of the Malinovka complex plotted on the Y–Nb discriminant diagram [3]. Fields of granitoids related to different geodynamic settings: (WPG) within-plate; (VAG) island-arc; (syn-COLG) collision; (ORG) ocean-ridge. (b) Chondrite-normalized REE patterns: Malinovka Complex: (*1*) monzonites, (*2*) trachyrhyolites and granites; (*3*) pantellerite from the Ethiopian Rift, after [4].

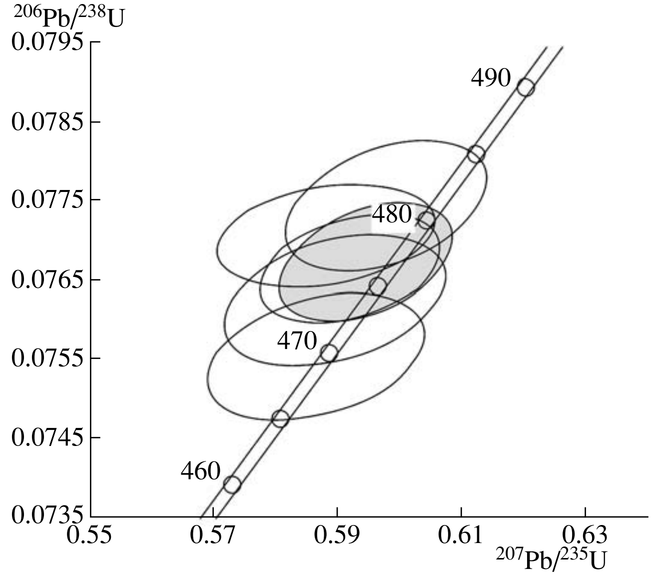

Fig. 3. U–Pb (SHRIMP II) data on zircons from trachyrhyolites of the Malinovka Complex. The size of ellipses corresponds to analytical uncertainties at $\pm 1\sigma$. $t = 476 \pm 2.7$ Ma; MSWD = 2.1.

granites. In the Y–Nb discriminant diagram (Fig. 2a), the compositions of igneous rocks of the Malinovka Complex fall into the field of within-plate granitoids. The total REE content and chondrite-normalized REE pattern are also close to those of the rocks pertaining to the continental rift series (Fig. 2b). The K/Rb ratio of trachyrhyolite is >700, and the $^{87}Sr/^{86}Sr$ ratio of monzodiorite is 0.70415 ± 0.00020. These data testify to the absence of substantial crustal contamination.

We should mention the appreciable geochemical and petrographic similarity of subvolcanic rocks of the Malinovka Complex of the northern Urals with trachyrhyolite and trachydacite of the Bilimbaevo–Ufalei belt in the central Urals [5] and rhyolite and trachyrhyolite complexes of the Polar and Subpolar Urals [6–8]. Minor intrusions and dikes of similar rocks are also known from other districts of the central and northern Urals where they make up a belt (more than 1500 km long) confined to the Main Ural Fault Zone. This belt of subalkaline and alkaline rocks apparently marks the Early Paleozoic rift zone that trends parallel to the eastern margin of the East European paleocontinent.

The K–Ar age of comendites of the Malinovka Complex was estimated at 231 Ma, whereas the quartz–sericite metasomatite formed after rhyolites in the Ivdel River basin have a K–Ar age of 338 ± 14 Ma [1]. Taking into account the wide scatter of K–Ar dates, the nonuniform and often high rate of rock foliation, and almost overall development of metamorphic minerals, the euhedral zircon crystals of magmatic habit were separated from the comendite sample previously dated at 231 Ma by the K–Ar method. The U–Pb SHRIMP II age of five zircon grains (Center for Isotopic Studies, All-Russia Research Institute of Geology) was estimated at 476.2 ± 2.7 Ma (Early Ordovician, Arenigian Age) (Table 2, Fig. 3). This value should be regarded as the most reliable timing of igneous rocks of the Malinovka Complex. According to the Rb–Sr method (feldspar, amphibole, biotite, titanite, and apatite fractions and whole-rock sample), monzonite of the Malinovka Complex from the stock in the Kriv Vagran River valley has an age of 367 ± 15 Ma. This dating practically coincides with the Sm–Nd isochron age of glaucophane schist metamorphism (370 ± 35 Ma) in the Main Ural Fault Zone [9] and should be regarded as a synmetamorphic estimate.

Slightly older U–Pb ages of single zircon grains from subalkaline igneous rocks of the Manitanyrd Complex (482 ± 11 Ma) and Paipudyn Complex (485–492 Ma) of the Polar Urals were obtained previously [8].

Table 2. U–Pb (SHRIMP II) data on zircons from trachyrhyolites of the Malinovka Complex

Crystal, crater	$^{206}Pb_c$, %	U	Th	$^{232}Th/^{238}U$	(1) $^{207}Pb^*/^{206}Pb^*$ (±%)	(1) $^{207}Pb^*/^{235}U$ (±%)	(1) $^{206}Pb^*/^{238}U$ (±%)	*Rho*	(1) $^{206}Pb/^{238}U$-age, Ma (±%)	(1) $^{207}Pb/^{206}Pb$-age, Ma (±%)	*D*, %
		ppm									
02119.1.1	0.16	602	380	0.65	0.0560 (1.6)	0.598 (1.8)	0.0775 (0.7)	0.44	481 (3.5)	452 (36)	–6
02119.2.1	0.66	1328	1570	1.22	0.0553 (1.9)	0.588 (2.0)	0.0771 (0.6)	0.32	479 (3.0)	424 (42)	–11
02119.3.1	–	627	419	0.69	0.0563 (1.8)	0.587 (2.0)	0.0756 (0.7)	0.39	470 (3.4)	464 (40)	–1
02119.4.1	0.24	602	298	0.51	0.0560 (1.9)	0.590 (2.0)	0.0763 (2.0)	0.37	474 (3.4)	452 (42)	–5
02119.5.1	0.01	777	622	0.83	0.0562 (1.4)	0.595 (1.5)	0.0768 (0.6)	0.43	477 (3.0)	460 (31)	–4

Note: Uncertainties are given at the ±1σ level; (Pb_c, Pb*) common and radiogenic lead, respectively. Errors of calibration relative to standards are equal to 0.43%. (1) Correction using ^{204}Pb; (*D*) discordance 100{1 – [age ($^{206}Pb^*/^{238}U$/age ($^{207}Pb^*/^{206}Pb$)]}; (*Rho*) correlation coefficient $^{207}Pb^*/^{235}U$–$^{206}Pb^*/^{238}U$. Hand-picked zircon grains were implanted into the pellet with epoxy resin along with zircon standards TEMORA and 91500. Further, zircon crystals were ground and polished approximately to half-thickness. Optic images (transmitted and reflected light) and cathodoluminescence images were used. The intensity of the initial beam of molecular (negatively charged) oxygen ions was 4 nA, and the spot (crater) diameter was 20–30 μm. The experimental results were processed with the SQUID program, and the diagrams with concordia were plotted using the ISOPLOT/EX program.

These estimates correspond to the Tremadocian Age (Early Ordovician) and the terminal Late Cambrian.

Thus, the isotopic geochronological data on igneous rocks in the Main Ural Fault Zone available to date are consistent with the age of basal units of the Paleozoic structural stage at the eastern margin of the East European continent. In the Polar and Subpolar Urals, the Paleozoic sequence begins with the Upper Cambrian–Tremadocian coarse-clastic rocks of the Manitanyrd Group and the Pogurei, Obeiz, and Tel'pos formations [10, 11]. In the northern and central Urals, the sequence begins with conglomerates of the Arenigian–Llandellian Khapkhar Formation and Promyslovka Group [12].

As follows from the data discussed above, the Early Paleozoic rifting accompanied by deposition of coarse-clastic sequences and subalkaline igneous rocks started in the Polar Urals in the Late Cambrian–Tremadocian. In the northern and central Urals, this process began in the Early–Middle Ordovician. Thus, the rate of longitudinal opening of the rift system (its southward propagation) may approximately be estimated at 10 cm/yr, because the Paipudyn Complex occurs at a distance of 1200 km from the Malinovka Complex and their age difference is 12 Ma. The obtained estimate is in good agreement with the published estimates of the opening rate of such rift systems as Kewenawan (10.0–12.5 cm/yr), Red Sea (10–16 cm/yr), and Urengoi–Koltogor (4.25–4.50 cm/yr), as well as the Late Triassic (4.8–6.0 cm/yr) and Late Jurassic (4.7–5.0 cm/yr) grabens in the east of the North American Craton that preceded the opening of the North Atlantic [13–15].

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