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GEOCHEMISTRY

Duration of Formation of Magmatic System of Polyphase Paleozoic Alkaline Complexes of the Central Kola: U–Pb, Rb–Sr, Ar–Ar Data

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The estimation of the duration of multiphase alkaline complex formation is a very complicate problem for the following reasons: first, the effect of younger magmatic phases provokes disturbance of isotopic systems in rocks formed at older stages; second, the recrystallization of accessory mineral phases—the main REE concentrators in alkaline rocks—limits feasibility of Sm–Nd and Rb–Sr isochron timing; third, undersaturation of alkaline magmas in silica promotes the replacement of liquidus zircon with other Zr-bearing phases; and fourth, zircons in some Paleozoic alkaline rocks are characterized by extremely low uranium contents, and this sharply narrows application of the U–Pb method.

The above-mentioned limitations are inherent to the rocks of the Kola alkaline province that comprises 20 plutons of carbonatite-bearing alkaline–ultramafic rocks; swarms of alkali picrite, melanephelinite, kimberlite dikes, and explosion pipes; and the largest plutons in the region (Khibiny and Lovozero). The plutons are composed of intrusive complexes that vary in composition from alkaline ultramafic rocks to peralkaline syenite and carbonatite (Fig. 1). Numerous dikes of alkali lamprophyres occur in their framework and as the youngest magmatic injections within these plutons. Despite the spatial conjugation (plutons are divided only by a narrow bridge of country Precambrian rocks) and compositional similarity, the Khibiny pluton consists of ring and conic intrusions, whereas the Lovozero pluton is made up of sheetlike intrusive bodies. The multiphase Kurga intrusion composed of ultramafic rocks and alkali syenite adjoins the northeastern part of the Lovozero pluton. The Rb–Sr isochron age of this intrusion is 404 ± 10 Ma [1]. Thus, a vigorous magmatic system existed in central Kola region in the Paleozoic. According to the timing of the Khibiny and Lovozero plutons [2, 3], the maximum of igneous activity fell on 368 ± 10 Ma. The igneous activity was predated by mantle metasomatism recorded in spinel lherzolite nodules from the explosion pipe on Mt. Namuaiv in the Khibiny (427 ± 6 Ma) [4].

We made an attempt to estimate the duration of development of the entire magmatic system from the moment of caldera subsidence (filling of the early ring faults in the basement with first portions of alkaline melt) until the final events expressed in the formation of the explosion pipes that crosscut all alkaline complexes and the late pegmatoid veins in basement rocks exposed near the contact of alkaline plutons. With allowance for the aforementioned methodical problems, we applied a complex of isotopic methods including the Rb–Sr isochron dating, determination of the $^{40}Ar/^{39}Ar$ age of amphibole and phlogopite, and U–Th–Pb dating of zircon grains. The measurements were performed following the techniques described in [5, 6]. The age uncertainties are quoted at the ±2σ level unless otherwise specified.

Age of the beginning of caldera formation. The formation of the Lovozero caldera was predated by a series of near-latitudinal faults in the northeastern area of the future magmatic structure. The alkaline ultramafic melts were emplaced along these faults, and the

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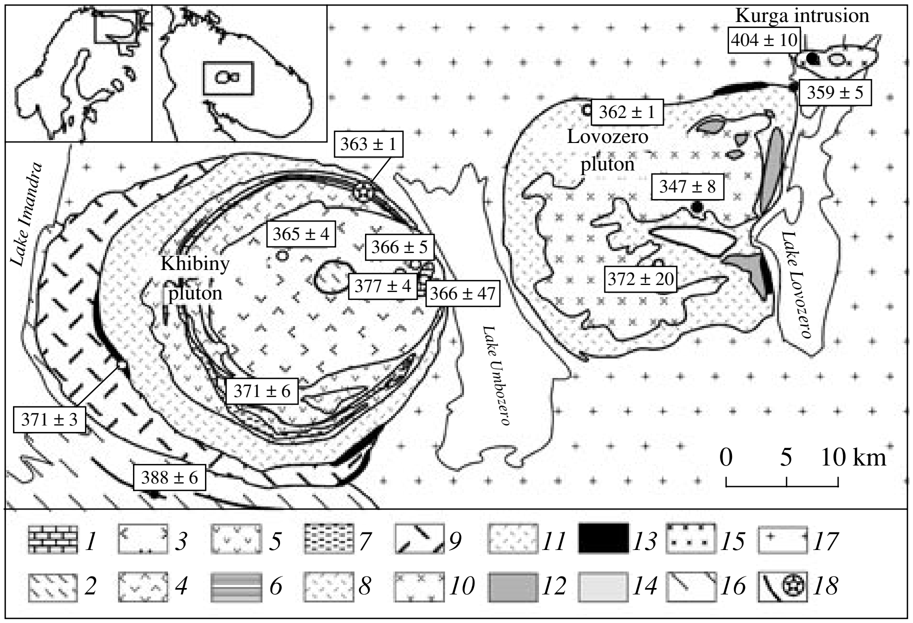

Fig. 1. Geological sketch map of the Khibiny–Lovozero–Kurga magmatic system. Estimates of isotopic ages, Ma, are shown in rectangles. The Khibiny pluton: (*1*) carbonatite; (*2*) pulaskite; (*3*) foyaite; (*4*) inequigranular nepheline syenite; (*5*) rischorrite, juvite, and massive urtite; (*6*) apatite–nepheline rock; (*7*) ijolite and melteigite, (*8*) trachytoid khibinite; (*9*) massive khibinite. The Lovozero pluton: (*10*) eudialyte lujavrite; (*11*) lujavrite, foyaite, and urtite of fractionated complex; (*12*) volcanic rocks of the Lovozero Formation, (*13*) alkaline ultramafic rocks. The Kurga intrusion: (*14*) nepheline syenite, (*15*) peridotite. Country rocks: (*16*) Neoproterozoic basalt and dolerite; (*17*) Archean granodiorite, tonalite, and trondhjemite; (*18*) dikes and explosion pipes. Filled circles designate original data; open circles, the data published in [2, 3, 9, 10].

Kurga intrusion was formed 404 ± 10 Ma ago. Volcanic rocks comagmatic to the Kurga plutonic rocks were erupted at the same time. The volcanic rocks make up the oldest phase in the Kontozero caldera and occur as roof pendants in the northeastern Lovozero pluton. Due to the thermal effect of intrusions, the Rb–Sr isochron dating of these rocks yielded an unsatisfactory result. The regressive line based on 5 points corresponds to 446 ± 56 Ma (I_{Sr} = 0.70301 ± 0.00009, MSWD = 0.64) [7]. The probability of retention of an isotopic signature in the oldest intrusive phases of the Khibiny pluton is minimal. Therefore, we chose for the $^{40}Ar/^{39}Ar$ dating an alkali lamprophyre dike localized in ring structures of the framing at a distance of 5 km from the contact of pluton. The obtained plateau age of 388 ± 6 Ma (Fig. 2) corresponds to the minimal age of the Khibiny caldera and to the onset of its filling with the alkaline ultramafic melt, i.e., the first phase in the Khibiny Complex development.

Age of completion of igneous activity. The youngest explosion pipes and auxiliary melanephelinite dikes that cut all alkaline complexes of the Khibiny pluton were chosen for dating. The $^{40}Ar/^{39}Ar$ age of phlogopite from a sample of olivine melanephelinite from the explosion pipe is 363.4 ± 5 Ma. This estimate was confirmed by a Rb–Sr isochron that yielded 362 ± 11 Ma (n =11, I_{Sr} = 0.70380 ± 0.00005, MSWD = 0.54) [8]. This age is consistent with the datings of the Lovozero Complex (362 ± 1 Ma) [2] and marks the termination of igneous activity in the Khibiny and Lovozero plutons.

Age of late magmatic processes. The veins of microcline–albite pegmatoids with ilmenite and large zircon grains are hosted in the Precambrian gneiss 100 m away from the northeastern contact of the Lovozero pluton (Mt. Vavnbed). These rocks are the most favorable for dating. Zircon in pegmatoids occurs as perfectly faceted crystals up to 2 cm in size. The cathodoluminescence study has shown their complicate structure: the

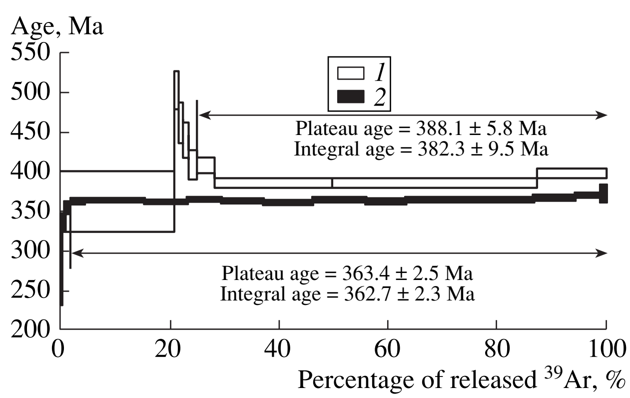

Fig. 2. Results of $^{40}Ar/^{39}Ar$ study with stepwise heating of (*1*) amphibole monomineral fraction from ring dike 99-1 in the southern framework of the Khibiny pluton and (*2*) phlogopite from olivine melanephelinite in the Khibiny pluton. The uncertainty of the age in this figure corresponds to an interval of ±1σ.

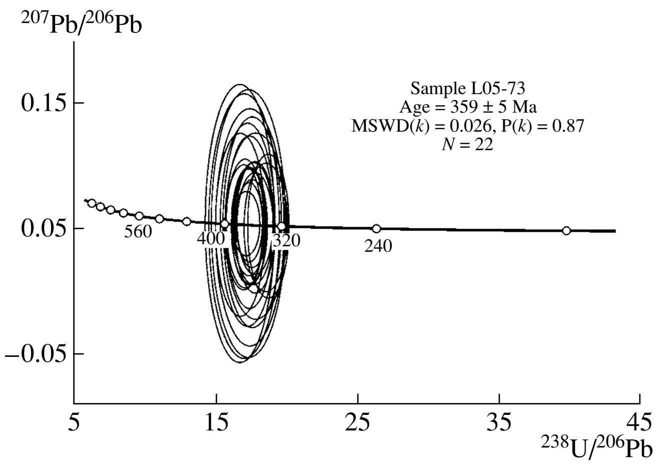

Fig. 3. Diagram with concordia for zircon from the microcline–albite vein on the northeastern slope of Mt. Vavnbed in the Lovozero pluton.

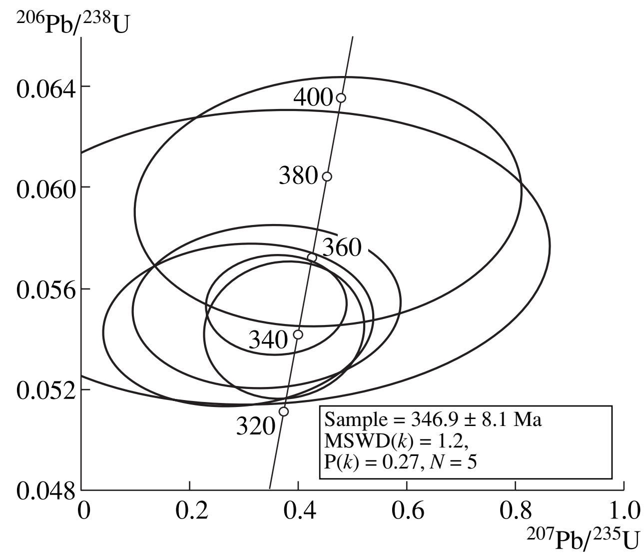

Fig. 4. Diagram with concordia for zircon from zircon-bearing alkali syenite, core of borehole 903, depth is 978 m in the central part of the Lovozero pluton.

inner zones are composed of an aggregate of acicular crystals, while the outer zones are homogeneous and reveal distinct growth zones. The SHRIMP II U–Pb dating was performed at the Center of Isotopic Research, All-Russia Geological Research Institute (22 measurements in four grains). The darkest sectors of grains relatively enriched in U were chosen for the analysis. The results are presented in Fig. 3 and in Table 1. The analyzed points are characterized by low U contents (20–50 ppm) and Th/U = 19–46, which is typical of zircon crystallized from an alkaline medium. The data points make up a concordant cluster. The discordance varies from –26 to 28%. The concordant age for 22 points is 359 ± 5 Ma.

A body of alkali syenite penetrated by Borehole 903 at a depth >900 m in the central part of the Lovozero pluton was the next object of dating. The abundance of small grains of accessory zircon promoted the U–Pb dating. Five of eight measurements in three grains yielded a concordant age of 347 ± 8 Ma (Fig. 4, Table 2).

Duration of the formation of system and succession of the formation of massifs. The new results obtained and the published isotopic dates [2, 3, 9, 10] indicate multistage evolution of the Khibiny–Lovozero volcanoplutonic system. The emplacement of magma at the oldest stage was accompanied by the formation of the autonomous Kurga intrusion. The subsequent events occurred in both the Khibiny and Lovozero plutons and covered a short time span. The sequence of events was as follows.

Premagmatic stage

427 ± 6 Ma ago. Mantle metasomatism that predated the vigorous Paleozoic magmatism [4].

Early magmatic stage

404 ± 6 Ma ago. Faulting in the Neoarchean tonalites, trondhjemites, and granodiorites; emplacement of the Kurga intrusion and eruption of ultramafic and subalkaline volcanics (Lovozero Formation) in the northeastern area of the future Lovozero ring structure.

Major magmatic stage

388 ± 6 Ma ago. Development of ring faults and initial subsidence of the Khibiny caldera at the contact of the Neoarchean complex of tonalites, trondhjemites, and granodiorites and the Paleoproterozoic Pechenga–Imandra–Varzuga Rift Belt; injection of the first portions of melanephelinitic magma as ring dikes of the framework.

388–371 Ma ago. Emplacement of alkaline ultramafic melts in the northern Khibiny caldera and in the northeastern Lovozero caldera; formation of the bodies of olivine pyroxenite, melilitolite, and olivine melteigite.

371–362 Ma ago. Formation of the main Khibiny and Lovozero plutonic complexes of peralkaline syenite.

367–366 Ma ago. Intrusion of carbonatitic stock and formation of stocklike pulaskite body in the eastern Khibiny pluton.

363–362 Ma ago. Formation of the late dike complex of the Khibiny and Lovozero. Emplacement of dikes and explosion pipes of alkali picrite, olivine melanephelinite, nephelinite, and phonolite.

Late magmatic stage

359 ± 5 Ma ago. Formation of the late microcline–albite pegmatoids with ilmenite and zircon in the framework of the Lovozero pluton.

Table 1. SHRIMP II U–Th–Pb isotopic compositions determined at local points of zircons from microcline–albite veins in the northeastern framework of the Lovozero pluton (sample L05-73)

Analyzed points	$^{206}Pb_c$, %	U, ppm	Th, ppm	$\frac{^{232}Th}{^{238}U}$	$^{206}Pb^*$, ppm	$\frac{^{238}U}{^{206}Pb^*}$	±, %	$\frac{^{206}Pb}{^{238}U}$ age, Ma		$\frac{^{207}Pb^*}{^{206}Pb^*}$	±, %	$\frac{^{207}Pb}{^{206}Pb}$ age, Ma		*D*, %
3.6	5.99	27	914	35.63	1.45	16.7	6	374	±22	0.055	82	400	±1800	8
4.1	3.55	36	1610	45.77	1.94	16.73	4.3	374	±15	0.054	55	370	±1200	–1
4.5	6.01	23	438	20.06	1.22	17	6	368	±22	0.053	81	310	±1900	–15
2.4	3.92	32	1132	36.53	1.69	16.98	3.2	368	±11	0.052	39	272	±900	–26
2.6	3.13	35	987	29.46	1.8	17.07	3.2	367	±11	0.055	38	424	±840	16
4.2	3.12	34	962	29.16	1.76	17.15	2.3	365	±8	0.055	19	392	±430	7
2.1	5.18	35	823	24.60	1.82	17.25	4.6	363	±16	0.054	61	380	±1400	6
4.6	5.17	49	1886	39.69	2.57	17.3	6.2	362	±22	0.055	79	420	±1800	16
4.3	2.68	36	675	19.28	1.84	17.36	2.8	361	±10	0.056	31	445	±690	23
3.2	2.28	35	962	28.32	1.78	17.37	3	361	±11	0.053	36	310	±820	–14
3.3	2.50	44	1531	36.24	2.22	17.37	2.2	361	±8	0.056	23	459	±500	27
3.4	4.17	40	1013	26.38	2.05	17.37	3	360	±11	0.053	35	341	±800	–5
2.3	5.93	29	1008	35.79	1.53	17.39	3.9	360	±14	0.056	50	430	±1100	20
1.3	4.61	24	832	36.15	1.23	17.4	5.7	360	±20	0.052	74	300	±1700	–16
4.7	3.64	41	1276	32.39	2.07	17.56	2.5	357	±9	0.055	26	430	±570	20
4.4	4.03	29	977	34.60	1.48	17.58	4.8	356	±17	0.056	61	450	±1400	28
1.1	3.49	37	1318	36.56	1.88	17.67	3.2	354	±11	0.055	36	421	±810	19
2.5	4.67	37	709	19.77	1.88	17.77	2.9	352	±10	0.055	30	416	±670	18
3.5	4.10	35	710	20.79	1.78	17.78	3.2	352	±11	0.052	41	300	±930	–15
1.2	4.08	26	759	29.63	1.33	17.82	5	352	±17	0.053	57	320	±1300	–8
3.1	4.32	25	917	37.60	1.22	18.54	3.4	338	±11	0.052	40	296	±920	–13
2.2	5.88	33	966	30.09	1.62	18.71	3.2	335	±10	0.053	44	310	±1000	–7

Note: Here and in Table 2 errors are given for 1σ interval; Pb_c and Pb* are common and radiogenic lead, respectively. 1σ error of standard calibration is 0.29%; correction for Pb_c was introduced by measured ^{204}Pb. *D*, % (discordance): $D = 100 \cdot \{[\text{age}(^{207}Pb/^{206}Pb)]/[\text{age}(^{206}Pb/^{238}U)] - 1\}$.

Table 2. SHRIMP II U–Th–Pb isotopic compositions determined at local points of zircons from zircon-bearing alkali syenite from the central part of the Lovozero pluton (sample 903/978)

Analyzed points	$^{206}Pb_c$, %	U, ppm	Th, ppm	$\frac{^{232}Th}{^{238}U}$	$^{206}Pb^*$, ppm	$\frac{^{206}Pb^*}{^{238}U}$	±, %	$\frac{^{206}Pb}{^{238}U}$ age, Ma		*D*, %
1.1	25.61	1.0	168	169.77	0.06	0.0506	28.4	318	±88	–
1.2	35.83	1.4	80	58.31	0.07	0.0368	57.2	233	±131	–
2.1	2.02	15.3	981	66.25	0.73	0.0545	2.5	342	±8	–237
3.1	5.13	4.0	2659	694.00	0.21	0.0573	4.3	359	±15	–124
4.1	0.78	10.8	887	84.49	0.47	0.0502	2.3	316	±7	84
5.1	2.99	4.0	810	211.50	0.21	0.0593	3.5	371	±13	11
2.2	0.93	15.5	961	63.89	0.73	0.0543	2.1	341	±7	–43
2.3	2.02	15.3	989	66.64	0.74	0.0553	2.4	347	±8	–110

347 ± 8 Ma ago. Late magmatic processes in alkali syenite located in the central part of the Lovozero pluton that mark completion of igneous activity in the Khibiny and Lovozero calderas.

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