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THE PETROLOGY OF THE LATE-KINEMATIC GRANITES IN SOUTH-EAST KARELIA

(7 Figs., 5 Tabs.)

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Abstract: The results of combined Pb-Pb systematics and petrology of some late-kinematic Precambrian granites in the Vodlozero area, S. E. Karelia are discussed.

The granites, which yield a U-Pb zircon isochron of 2680–2700 Ma, intrude a granitoid and gneiss complex of an inter-greenstone belt area. The plutons range in size from 20 to 250 km^2.

The granites are of near minimum-melt composition, for P_{H_2O} of O to 10 kbar, are K-and Rb-rich, and show low concentrations of Y and Sr.

The initial Pb isotopic ratios of the late-kinematic Kubovo intrusion have been measured. Lead-isotopic data on acid-leached feldspars from the Kubovo granites and the host gneisses suggest that Archaean tonalitic gneisses of the Vodlozero area were the possible source of the granitic material. The model of partial melting of the Vodlozero amphibolite and gneisses based on the distribution of some rare earth elements has been checked using the methods of Hanson (1978). The best-fit model of 7 % partial melting of the gneisses is in agreement with real composition of the late-kinematic Kubovo pluton. The geochemical modelling results are consistent with the data on Pb-Pb systematics suggesting that the Vodlozero gneisses were a source of the Kubovo granites.

Key words: petrology, late-kinematic Precambrian granites, Pb-isotopic study, South-East Karelia.

Introduction and regional geological features

Late-kinematic granites occur in the central part of the Vodlozero region (S. E. Karelia, Baltic Shield), which represent an inter-greenstone belt area (Fig. 1) The granites intrude synkinematic Upper Archaean granitoids (mainly of sodic composition) with inclusions of older tonalites (3. 2 Ga), gneisses (3. 5 Ga) and amphibolites (Levchenkov et al., 1987). An increased local abundance of microcline granites is one of the features of Vodlozero area as compared to other regions (for example Central Karelia). Aeromagnetic data indicate that the granitic bodies partly represent the relics of thin plates, as also evidenced by field work in the east part of the region which demonstrate the presence of low-angle overthrusts and associated leucogranites. A magmatic origin of granites can be demonstrated on the north contact of the Kubovo intrusion where granitic apophyses cut the deformed and migmatized gneisses and amphibolites.

The Kubovo and Ochtomozero plutons give U-Pb zircon isochron date of Ma 2680 ± 40 Ma and 2703 ± 40 Ma respectively. The latest thermal event in this area according to K-Ar (Bt, Amph) and U-Pb (Ap) data took place 2500 ± 10 Ma ago (Levchenkov et al., 1987).

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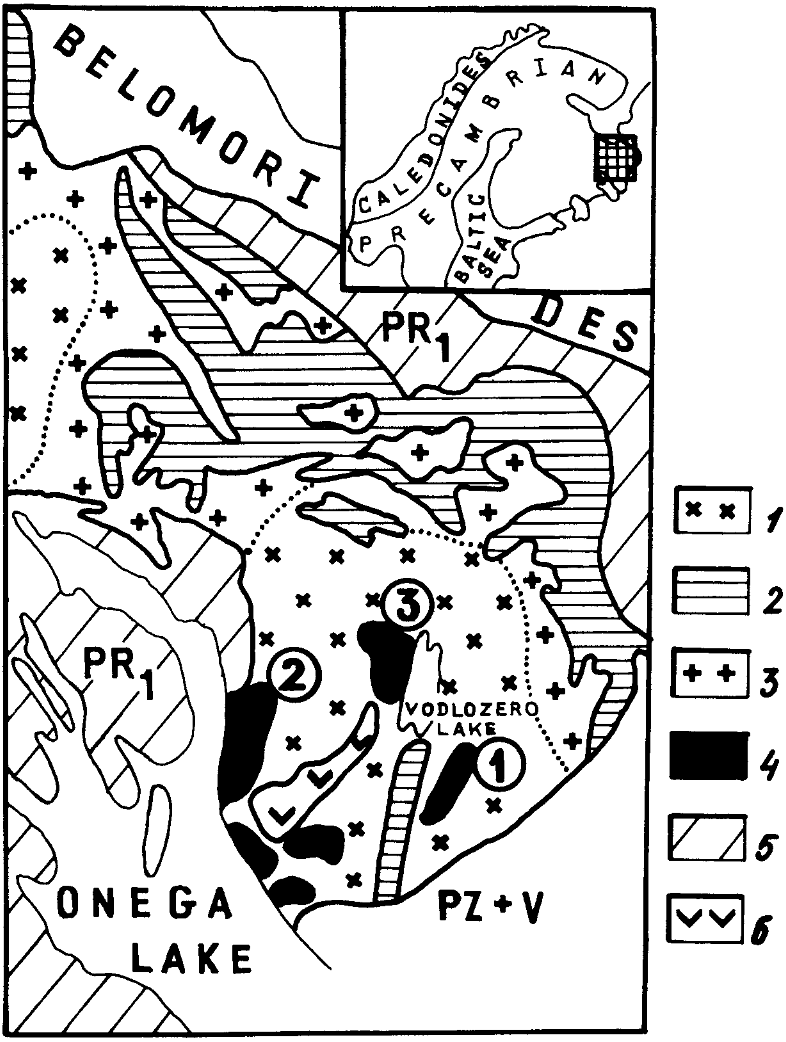

Fig. 1. The distribution of the late-kinematic intrusions in Vodlozero area.
1 – granitoids and metamorphic rocks (AR_1 + AR_2); 2 – greenstone belt (AR_2); 3 – granitoids (AR_2) 4– late-kinematic intrusions. In circles: 1 – Kubovo, 2 – Tuborechensky, 3 – Ochtomozero plutons; 5 – Proterozoic formation; 6 – basic-ultrabasic intrusion (Burakovka pluton).

Petrography and major and selected trace element chemistry

The granites comprise quartz, plagioclase (An $_{19-29}$), perthitic microcline, biotite and accessory zircon, apatite, sphene, epidote. Apatite is associated with biotite aggregates.

Major and some trace element analyses of the three plutons are given in Tab. 1. The normative compositions of the samples are plotted in the Q-Ab-Or diagrams in Fig. 2. A.

Table 1
The content of major (%) and trace-element (ppm) abundances of late-kinematic granites from the Vodlozero area

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	71.62	77.06	72.46	71.65	73.49	71.60	72.90	73.70	71.90	71.20	70.70
TiO_2	0.25	0.09	0.19	0.26	0.20	0.34	0.17	0.17	0.17	0.19	0.43
Al_2O_3	14.63	11.82	13.55	13.45	13.78	14.80	13.80	13.00	14.10	15.00	14.85
Fe_2O_3	0.70	0.75	1.17	1.09	0.66	0.70	0.77	0.73	0.44	0.84	1.21
FeO	1.23	0.57	0.77	1.55	1.29	1.42	0.78	0.91	1.29	0.90	1.49
MgO	0.71	0.50	0.72	0.57	0.69	0.68	0.59	0.44	0.55	0.41	0.77
CaO	1.37	1.00	2.01	1.26	1.86	2.50	1.54	2.31	1.43	1.65	1.98
Na_2O	3.92	3.04	3.84	3.10	4.00	3.53	3.30	3.50	3.45	3.60	3.60
K_2O	5.15	4.18	3.81	5.23	4.25	3.85	4.75	4.45	4.75	5.00	4.10
Rb	214	180	128	256	187	162	212	265	179	210	169
Sr	134	80	164	93	109	231	123	76	139	159	208
Y	9	5	6	32	5	14	23	24	17	17	22
Zr	196	108	295	244	162	188	136	112	138	112	323

The plutons: 1–5 – Kubovo, 6 – Tuborechensky; 7–11 – Ochtomozero.

points fall in the granitic field. The points are situated in Fig. 3 mainly within three fields: granite, subalkalic granite and leucogranite. The granites are K- and Rb-rich and have low concentrations of Y and Sr.

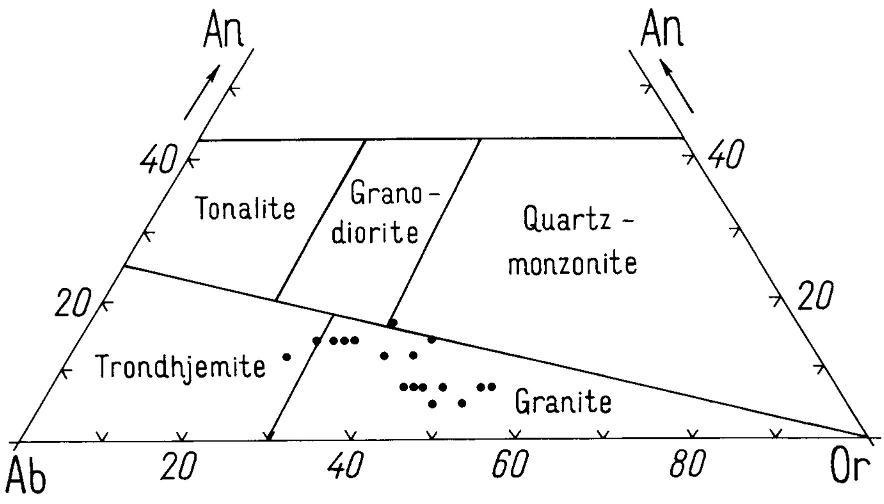

Fig. 2. Normative composition of the late-kinematic granites in a Ab-An-Or plot. Fields shown are those of O'Connor (1965).

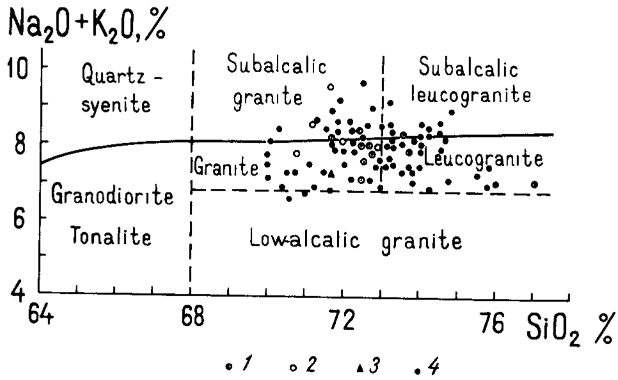

Fig. 3. $Na_2O + K_2O$ vs SiO_2 variation of late-kinematic granites.
Fields shown are those of "Classification..." (1981). 1 – Kubovo; 2 – Ochtomozero; 3 – Tuborechensky plutons; 4 – other granites intrusions of Vodlozero area.

Pb-Pb systematics of feldspars

Lead isotopic compositions of acid-leached feldspar are useful to estimate the initial Pb isotopic ratios of granitoid rocks because the μ-values ($^{238}U/^{204}Pb$) and K-values (Th/U) of feldspars are typically very low (Oversby, 1975; Zartman-Wasserburg, 1969; Ludwig–Silver, 1970). In this work the Pb isotopic composition of 8 HNO_3 – leached feldspars from the Kubovo granites has been studied. The analytical results are represented in

Table 2
Pb-Pb data for feldspars from the Kubovo granites and Vodlozero gneisses

Ne.	Samples	Isotopic ratios			The models parameters by C-K model			Ts
		206 Pb / 204 Pb	207 Pb / 204 Pb	208 Pb / 204 Pb	T_2	M_1	K_1	
		Kubovo granites						
1	19 Pl	14.251	15.005	34 728	2.55	10 68	4.93	2.81
2	20 Pl	14.013	14.907	34.215	2.64	10.61	4.58	2.89
3	53 Pl	13 988	14.915	33.695	2.69	10 89	3.82	3.05
4	61 Pl	14.027	14.918	33.844	2.64	10.69	3 98	2.92
5	19 Mi	14.167	14.978	34.500	2.59	10.73	4.75	2 88
6	20 Mi	14.147	15.003	34 612	2.65	11 21	4.96	3 10
7	53 Mi	14.067	14.935	33.811	2.63	10.70	3.88	2.90
8	61 Mi	13.814	14 848	33.586	2.70	11.04	3.91	3.30
		Vodlozero gneisses						
9	18 r Pl light fraction	13.824	14 861	33 680	2 75	11 30	4 00	3 00
10	18 r Pl	13 803	14.860	33.676	2 79	11 34	4.08	3.07
11	31-1 Pl	13.728	14.832	33 644	2.83	11.48	4.15	3.16
12	18k Pl	13 641	14 798	33.511	2 87	11 66	4.07	3 27
13	18k Pl heavy fraction	13.634	14.798	33.544	2.88	11 68	4.08	3.30

Tab. 2. Isotopic composition has been measured by a single-collector 90^0 – solid source mass-spectrometer. The external reproducibility is estimaled as ± 0.05 % per amu^{-1}. The data are corrected for mass-fractionation based on measurements of isotopic standards NBS-SRM 981 and SRM 982. The analytical blank is 5 ± 2 ng Pb. All data are plotted in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagrams (Fig. 4). On the plot in Fig. 4a, all the

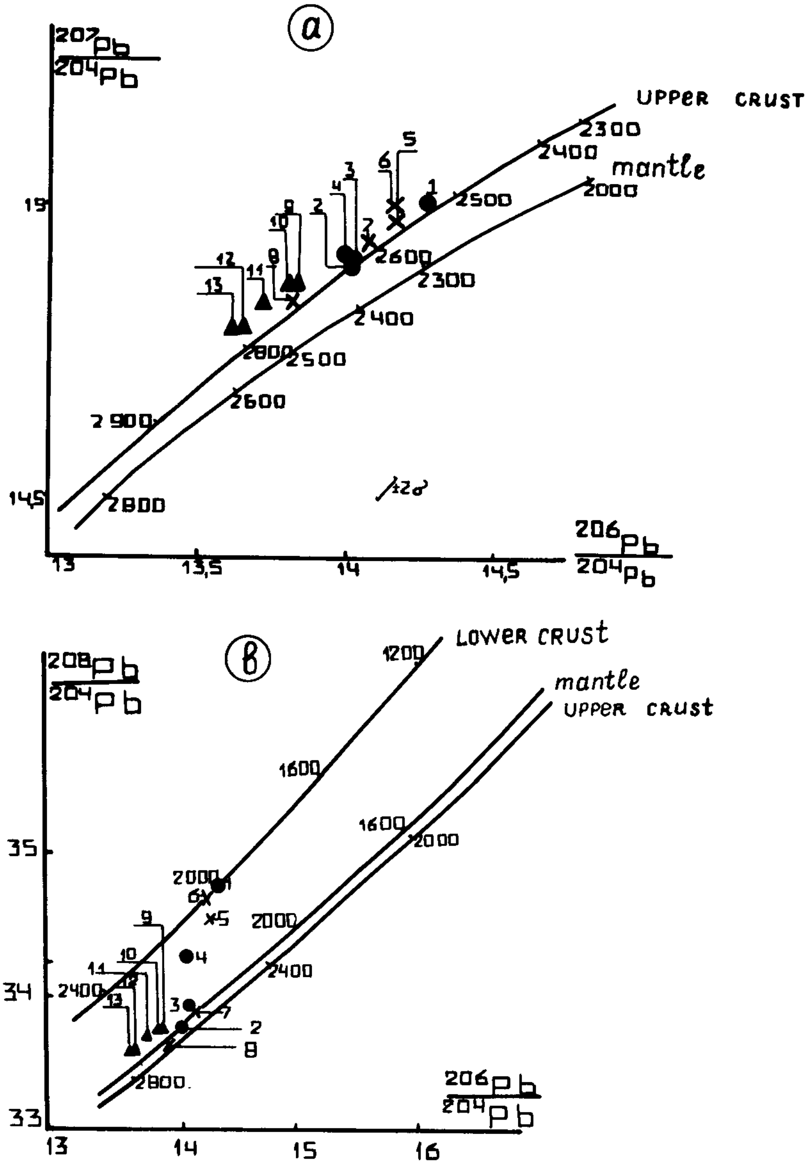

Fig. 4. Pb-isotopic ratios of HNO_3-leached feldspars on a – $^{207}Pb/^{204}Pb$ – $^{206}Pb/^{204}Pb$; b – $^{208}Pb/^{204}Pb$ – $^{206}Pb/^{204}Pb$ plot. 1–8 – Kubovo granite; 9–13 – Vodlozero gneiss.

points lie along a straight line. Feldspars are known to be the acceptors of lead, so they can change their Pb-isotopic pattern due to the capture of lead released from the donor-minerals zircon, apatite and sphene, whose Pb-Pb systems become open in specific P-T and fluid regimes during overprinting (Ludwig – Silver, 1977; Vidal et al., 1980; Neymark – Ovchinnikova, 1987). In our case $^{207}Pb/^{204}$ Pb and $^{206}Pb/^{204}$ Pb ratios of different samples of feldspars form a linear trend with the slope which may have a geochronological sense, corresponding to the time interval between the formation (2.7 Ga) and the last lead redistribution (2.5 Ga) in the Kubovo granites. The Pb-Pb age calculated on two-point (acid-soluble and residual Pb) isochrons from each sample yields a value near 2700 Ma. In the light of this result we can predict the absence of Pb-mobility at ages younger than 2500 Ma.

In the $^{207}Pb/^{204}Pb - ^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb - ^{206}Pb/^{204}Pb$ plots, all points are situated well above the model growth curve of the upper crust (Zartman – Doe, 1981). The high initial $^{87}Sr/^{86}Sr$ ratios of two plagioclases (0.74471 ± 3 and 0.744210 ± 10 and apatite (0.76631 ± 3) also suggest that the granites represent a reworking of continental crustal sources.

A possible source for the Kubovo granites has been calculated model μ_I values ($^{238}U/^{204}Pb$) of about 10.8 and K_I value (Th/U) of about 4.3 after Stacey – Kramers (1975) (Tab. 2). Such high values of μ_I and K_I reported by many authors (Fischer – Stacey, 1986; Doe – Delevaux, 1980) are generally thought to be indicative of a long crustal residence – time for the protolith to similar granites.

Range of the calculated model ages reflects the disturbance of the lead-isotope systems of feldspars with a capture of radiogenic lead during metamorphic event 2.5 Ga. (Tab. 2).

In both plots in Fig. 4 the Pb isotopic ratios of feldspars from granites and the host gneisses form a single linear array.

It should be bear in mind that Pb isotopic ratios of the plagioclases from the Vodlozero gneisses are in indicative of average Pb composition of these rocks 2860 Ga ago; many mineral phases: metamorphic zircons, amphiboles and plagioclases have been formed at that time. However, it is only U-Pb systematics of zircon cores that preserved a memory of ancient age of the basement rocks (Levchenkov et al., 1987).

Linear array of the points on Pb-Pb diagram (Fig. 4 a, b) suggests that Pb isotopic composition of the plagioclases from the gneisses has been altered due to the 2.5 Ga hydrothermal event. The obtained data are fairly consistent with the fact that average isotopic lead composition of felsic varieties of the gneisses had been similar 2700 Ma ago during the granite source to that of the above mentioned plagioclases. So, both the Pb-Pb systematics of the feldspars and values μ_I and K_I for the gneisses and granites (Tab. 2) suggest that the tonalitic gneisses of the Vodlozero present a possible source of the granitic material.

The petrology of the late-kinematic granites.

This assumption was tested using geochemical modelling (Hanson, 1978; Allegre – Minster, 1978). The model of partial melting of gneisses and amphibolites was calculated. The content of main and trace elements in the rocks are given in Tabs. 3, 4.

The gneiss 45 consists of quarz, plagioclase, biotite and hornblende; zircon and apatite – accessory minerals. The essential minerals of the amphibolite – 45b are hornblende and plagioclase; biotite and quartz occur in small quantities; among the accessory minerals apatite is abundant. All mineral assemblages and mineral compositions (Lobach-Zhuchenko et al., 1989) are typical of low pressure amphibolite facies.

Table 3

The content of main and trace (ppm) element abundances in rocks used in the model calculations

Element	gneiss 45-LZ	amphibolite 45b-LZ	granite 19-SS
SiO_2	62.32	53.88	71.65
TiO_2	0.47	0.70	0.26
Al_2O_3	15.84	15.29	13.45
Fe_2O_3	2.04	2.11	1.09
FeO	3.30	6.29	1.55
MnO	0.13	0.16	0.09
MgO	3.15	5.56	1.57
CaO	5.66	8.32	1.26
Na_2O	4.00	3.84	3.10
K_2O	1.06	1.02	5.23
P_2O_5	0.14	0.13	0.11
H_2O^-	0.63	1.20	0.25
Y	24	32	14
Zr	109	244	244

Table 4

The content of trace elements (ppm) in rocks and model melts

RE	gneiss 45	amphibolite 45b	Model compositions				granite 19
			F = 7 % (from 45)	F = 20 % (from 45b)	F = 10 % (from 45b)	F = 5 % (from 45b)	
Rb	35	25	211	100–102	75–97	93–86	256
Sr	431	324	117	104–113	95–103	99–106	93
Ce	34.0	37.4	136	58–65	71–78	82–94	140
Nd	16.1	20.8	89	23–35	27–32	28–37	57
Sm	3.29	4.64	7.9	3.0–5.3	4.3–4.9	4.8–7.3	9.8
Eu	0.94	0.80	0.64	0.46–0.51	0.52–0.54	0.49–0.54	0.50
Yb	0.89	1.73	0.30	1.5–2.5	2.2–3.3	1.82–2.9	1.1

The equations:

$$C_e/C_8 = \frac{1}{D_o + F_1(1-P)} \quad \text{– for gneisses and}$$

$$C_e/C_o = \frac{1}{D_{RS} - F(1-D_{RS})} \quad \text{– for amphibolites were used}$$

(Allegre – Minster, 1978; Hanson, 1978). Incongruent melting of biotite (Platen, 1965) produced effect of K in the melt. The maximum possible quantity of the melt was determined by the normative content of K-feldspar in the source.

The computations have made for F = 20 and 7 % for the gneiss source; 20, 10, 5 % – for the amphibolite source (Tab. 4). For each F ten variants of melting of the amphibolite were

Table 5

Distribution coefficients of trace elements

	K-feldspar	plagioclase	biotite	zircon	apatite	magnetite	garnet	hornblende
Rb	0.366[1]	0.09[3]	1 92[2]	–	–	–	0.009[3]	0.014[1]
Sr	3.87[1]	4 4[1]	0 24[3]	–	–	–	0.02[3]	0.022[1]
Ce	0.044[1]	0.27[1]	0 32[3]	2 64[1]	34 7[1]	0.61[3]	0.62[3]	1.52[1]
Nd	0 025[1]	0.21[1]	0.04[3]	2.20[1]	57.1[1]	0 88[3]	0.63[3]	4.26[1]
Sm	0 018[1]	0 13[1]	0.26[3]	3 14[1]	62.8[1]	0 93[3]	2 2[3]	7.77[1]
Eu	1.13[1]	2 15[1]	0.24[3]	3 14[1]	30.4[1]	0.58[3]	0 7[3]	5 14[1]
Yb	0.012[1]	0.049[1]	0 44[3]	270[1]	23 9[1]	0.4[3]	43[3]	8.38[1]

1 – Arth – Hanson, 1976; 2 – Villemont et al., 1981, 3 – Henderson, 1982.

calculated in accord once with compositional variations in the restite. These are defined by possible variation of $f = \dfrac{\Sigma FeO}{\Sigma FeO + MgO}$ of Hb, Di, Hyp and Bt in garnet absent paragenesis of the granulite and amphibolite facies. The value of the distribution coefficients of trace elements are given in Tab. 5.

Comparison of the calculations and element abundance in the Kubovo granite 19 (Tab. 4) shows a good fit (Fig. 5) with the model composition of 7 % partial melting of Vodlozero gneiss 45 with mineral assemblage: Bt, Gr (2 %), Pl, Qu.

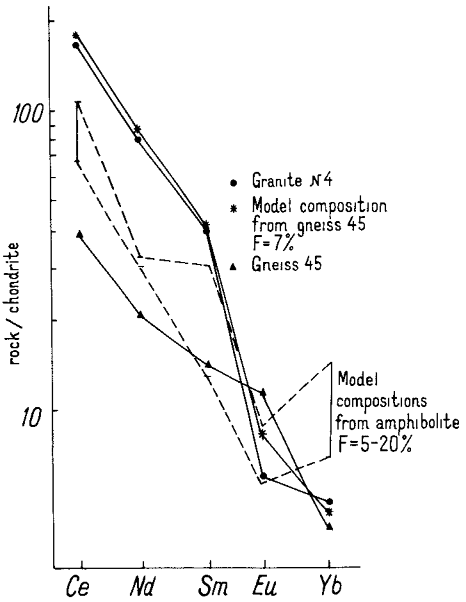

Fig. 5. Comparison of REE distribution in the granite, host gneiss and models compositions.

The speculation on granitoids generated in the crust as result of melting of the older metamorphic rocks is confirmed also indirectly by the calculation of "model age of source-region" (Pb-crustal residence time) on the basis of Pb isotopic data from feldspars (Neymark, 1988).

The sense of this kind of calculations consists on determination of the slope *(R)* for a line connecting the experimental Pb-Pb points with the point reflecting the model Pb-isotopic data for mantle at time corresponding to the age of the geological object (T_2, in our case for granites 2700 Ma).

The model age of the source-region for granite *(Ts)* in other terms, the time of separation from a hypothetical mantle reservoir, assuming a single-stage Pb-isotope evolution in crustal reservoir, can be determined as the following:

$$R = \frac{exp\,\lambda_5 T_s - exp\,\lambda_5 T_2}{137.88\,(exp\,\lambda_8 T_s - exp\,\lambda_8 T_2)}$$

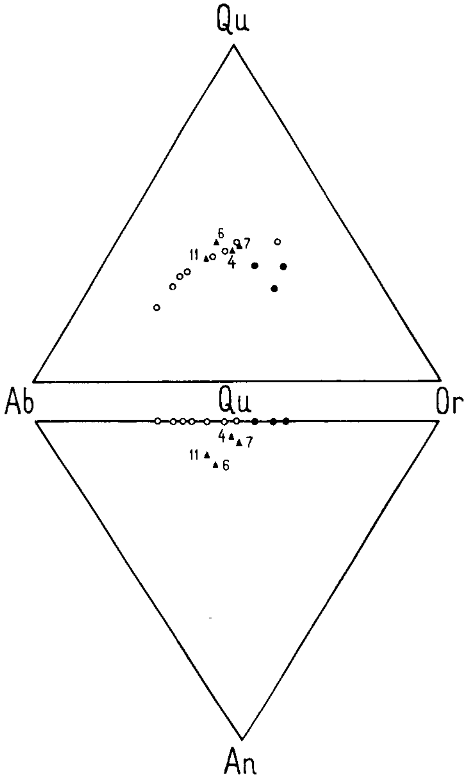

Fig. 6. Normative composition of some late--kinematic Kubovo, Ochtomozero and Tuborechensky plutons. 1. – Normative compositions of the granites; in Ab-Qu-Or (H_2O) and Ab-Qu-An (H_2O) plots; 2 – Kotectic and eutectic points at P_{H_2O} from O to 10 kbar; 3 – the same at P_{H_2O} = O kbar and P from 1 to 10 kbar (after Kravtzova, 1974). The numbers on the plot (in Figs. 6,7) are corresponding to numbers in the text.

The obtained data range from 2.8 to 3.3 Ga (Tab. 2). These values fit well to the data of Ts of the Vodlozero gneisses (3.0–3.3 Ga) (using T_2 = 2.86 Ga in the calculations) and are also close to the U-Pb zircon age (3.5 G.a) for protoliths of gneisses (Levchenkov et al., 1987). A scatter of the calculated *Ts* – values for the granites and gneisses can be explained by variations of lead isotopic ratios in the feldspars resulted from a 2.5 Ga – metamorphic event.

The distinction between the granitic compositions of individual plutons is connected with the composition differences of the initial melts which in turn reflect the variation in the extent of melting and/or the different sources. The observed variations in each pluton reflect the evolution of granitic magmas during their emplacement. The variation show trends both in their normative composition (Fig. 6) and Rb and Sr contents (Fig. 7).

On Q-Ab-An-Or (H_2O) (Kravtzova, 1974) plots the compositions trend towards eutectic points at given P_{H_2O}. The trend extends from points 6 and 11 to 7 and 4 (Tab. 1) according to the An – content (from 12 to 5 %). Samples 6 and 11 correspond to higher P and T than 7 and 4 which are closer to the eutectic point (Fig. 6). The difference in temperatures of the crystallization of the melts of these groups are supported by the zircon data. On the basis of the morphological features of zircons from granites (Ovchinnikova et al., 1989) in Pupin's method (1980) the temperatures of the crystallization of the melts varies from 900–800 °C (sample 6, Tuborechensky pluton) to 750–600 °C (sample 4, Kubovo pluton). The contents of Rb increase and Sr- decrease in the series from higher to lower T (Fig. 7).

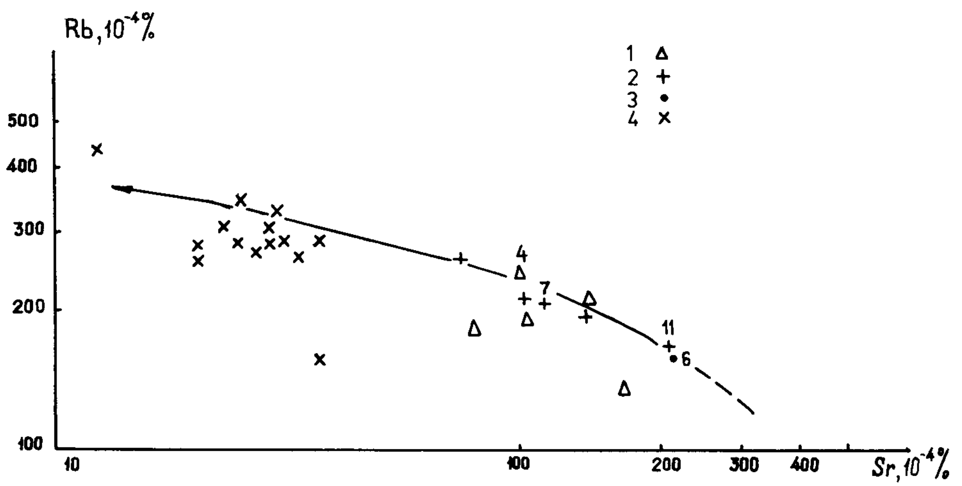

Fig. 7. Rb_{ppm} vs Sr_{ppm} variations of the late-kinematic granites.

Intrusions: 1 – Kubovo, 2 – Ochtomozero, 3 – Tuborechensky; 4 – leucogranites.

If initial melt was entirely homogeneous then fractionation of plagioclase is responsible for the variations.

In the case of heterogeneous initial composition (mixture of eutectic melt and minerals of the source) the variations reflect the degree of cleaning of the eutectic melt from the restite minerals. The trend of the ratio Rb/Sr supports the first assumption.

It is possible on the basis of geological data to propose that the evolution of granite compositions took place during the formation of granitic melt and its later movement along low-angle detachments. The crustal thickening was probably responsible for filter pressing of so small quantity of the melt from the host gneiss.

Conclusions

The partial melting of older (3.5 Ga) tonalitic gneisses of the Vodlozero area can be considered as the genetic model of Upper Archaean late-kinematic plutons in the Vodlozero area. The model is based on Pb-Pb data of the feldspars from the granite and host gneiss and on trace-element modelling in Hanson's method (1978).

The mineralogical and chemical variations of the individual granitic plutons are likely to have been produced by the fractionation of the plagioclase at temperature and pressure changing during magmatic emplacement.

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