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GEOLOGY

Geochronological Limits of Subalkaline Magmatism in the Ket-Kap–Yuna Igneous Province, Aldan Shield

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Abstract—Comparative U–Pb (zircon- and sphene-based, for the first time) and K–Ar (biotite-, amphibole, and whole rock-based) dating of monzonitoids and subalkaline granitoids of the Ket-Kap and Uchur volcanic-plutonic complexes (Ket-Kap–Yuna Igneous Province is one of the areas of tectonic-magmatic activation of the Aldan Shield), respectively, has been made.

The new data, which are chiefly acquired by us for the first time, are close to each other and fall within the relatively narrow time interval of the mid-Early Cretaceous.

The U–Pb sphene-based isochron datings indicate the formation time of the subalkali complexes at the Barremian–Aptian boundary. The values of SHRIMP age for zircons from the Uchur Complex subalkali diorites vary from 124.4 to 120.1 Ma; variations in U–Pb dates for monzonitoids of the Ket-Kap Complex fall in the narrower interval of 125.8–123.6 Ma. The extraordinary cases of highly polymodal distribution of SHRIMP-derived zircon-based dates are explained by the presence of detrital zircon crystals probably belonging to the protolith; this is interpreted by evidence for participation of the ancient continental crustal material in the formation of the source for the KKYuIP subalkali magmas. The range of the new K–Ar datings based on the whole rock composition of subalkali rocks and on the results of monomineral determinations is wider; however, it corresponds to the Early Cretaceous as well. This is significantly in contrast with the data given in the literature and geological survey reports.

It was found for the first time that the duration of the subalkali magmatism manifestation in the KKYuIP is only several Ma and, according to the precise U–Pb dating, falls within the Aptian age of the Early Cretaceous epoch; this is sharply in contrast to the previously derived dates that referred to Early Jurassic–Cretaceous age of the magmatism. This time interval probably marks the main stage (relative quiet phase under strong compression) in the evolution of the setting of mutual sliding between the Siberian Craton and Amurian megablock, according to geodynamical reconstructions by A.I. Khanchuk and his colleagues.

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In the Uchur–Maya interfluve (Fig. 1), Mesozoic multiphase volcanic–plutonic central-type construction form a prolonged (more than 300 km), arc-shaped magmatogenic structure, which includes the Ket-Kap–Yuna (KKYuIP) and Tomptokan igneous provinces [1, 3, etc.].

The Ket-Kap–Yuna Province has been studied in recent years by geological survey and petrological methods. However, the issues of its isotope periodization are still under discussion, despite the debates for the last decade. Until recently, based on K–Ar dating of whole rocks, rarely, of monomineral fractions (for example, [2, 4, 5]), it was believed that KKYuIP igneous complexes were formed for the Jurassic–Early Cretaceous. For better insight into the tectonic and magmatic evolution of the KKYuIP, nowadays we need to elaborate a specified scheme of its isotope periodization, which will be based on modern dating methods; additionally, this is of a certain applied value with respect to industrial gold-bearing regions of the Uchur complex.

We keep to the two-cycle five-stage evolutionary scheme for the magmatism of the Ket-Kap–Yuna Province [6, 9]. It was suggested to subdivide Mesozoic igneous rocks into four complexes: trachyandesite–diorite–granodioritic (Uchur), tephrite–phonolite–alkalitrachytic with syenites (Bokur), foid–alkalitrachyte–syenitic (Dar'inskii), and monzonite–syenitic (Ket-Kap). Their geological and petrological–geochemical characteristics were given in [7–10].

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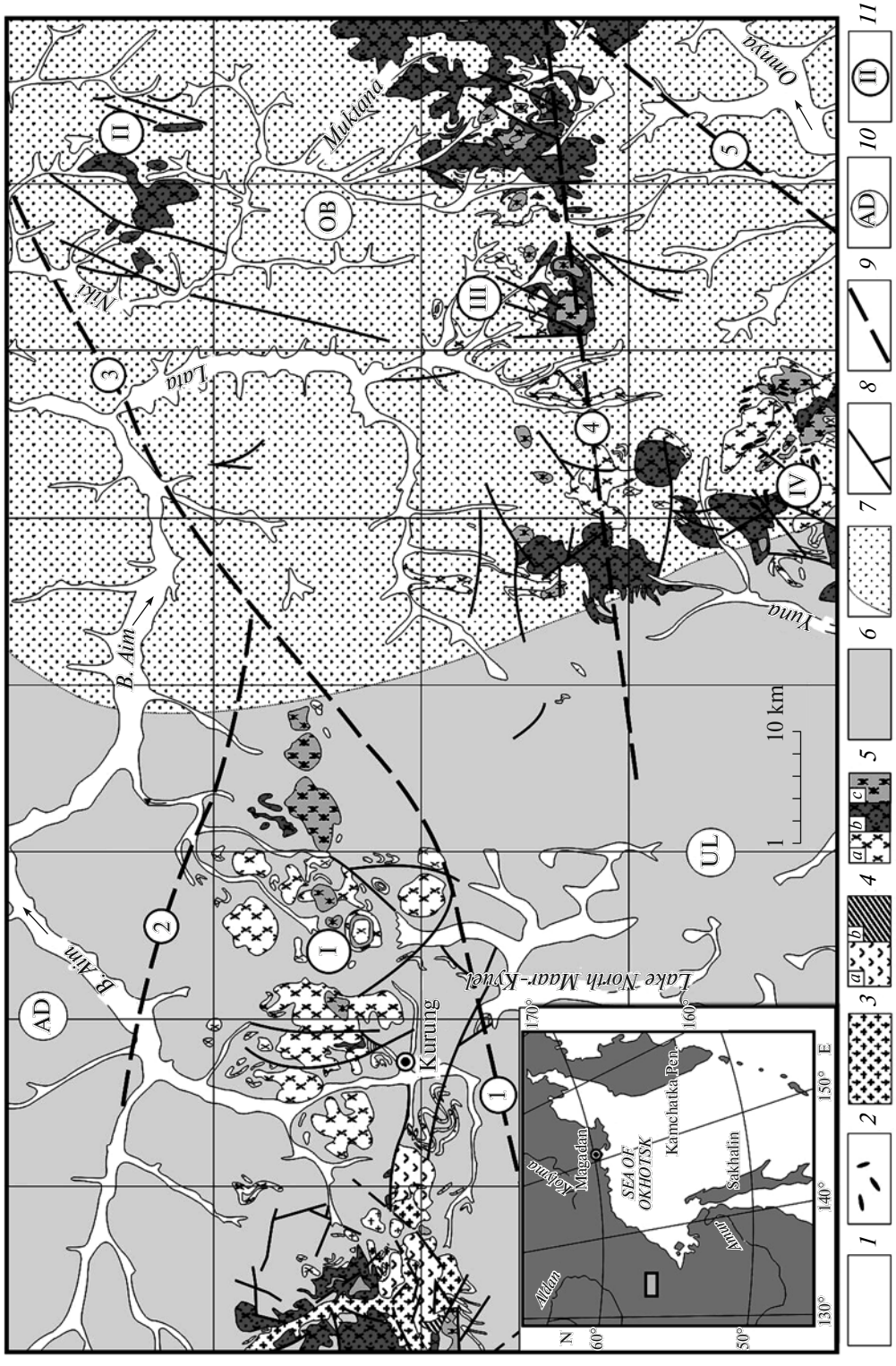


Fig. 1. Geological–structural scheme of the Ket-Kap–Yuna igneous province (based on geological survey and prospecting data, with additions and modifications). *1*, Quaternary deposits; *2*, Cretaceous Dar'inskii hypoabyssal complex: dykes and thin sills (conventional); *3*, Early Cretaceous Ket-Kap volcanic-plutonic complex; *4*, Jurassic–Early Cretaceous Bokur volcanic–plutonic complex: (*a*) volcanic rocks, (*b*) intrusions and subvolcanic bodies; *5*, Jurassic(?)–Cretaceous Uchur volcanic-plutonic complex: (*a*) first phase, (*b*) second phase, (*c*) third and fourth undifferentiated phases; *6*, Proterozoic–Paleozoic units of the platform cover, chiefly sedimentary ones; *7*, Early Archean metamorphogenic and magmatogenic units of the Siberian Craton basement and the approximate boundary of their outcrops; *8*, main faults; *9*, basement faults, supposed on the basis of geophysical and indirect geological data: 1, South Ket-Kap; 2, Middle Ket-Kap; 3, Ket-Kap; 4, Konder-Bukinda; 5, Uchur-Ingili; *10*, main structural elements: AD, Aldan Trough; UL, Ulkan Trough; OB, Omnya-Batomga Swell (*9* and *10* are after [1] with additions); *11*, Mesozoic magmatogenic swells: I, Ket-Kap; II, Odolinskii; III, Yuna-Dan'skoe; IV, Usmun-Dar'inskoe. The inset shows the geographic position of the study area.

Table 1. Brief geological characteristics and results of K–Ar age determination for the representative rock samples of the KKYuIP

No.	Phase of magmatism	Number of sample and the analyzed material	Rock	Potassium, % ±σ	$^{40}Ar_{rad}$, (ng/t) ±σ	Age (Ma), ±2σ	Period, epoch, age
			Uchur Complex				
1	First	PN-238-8642, whole rock	subalkaline quartz diorite	1.84 ± 0.02	18.86 ± 0.06	142.0 ± 3.0	K_1, berriasian
2		PN-157-1711, biotite	"	6.94 ± 0.17	57.6 ± 1.1	118.4 ± 4.6	K_1, aptian
3		PN-70.2-8130, biotite	"	7.02 ±0.17	57.7 ± 1.0	117.3 ± 3.6	K_1, aptian
4	Second	PN-9260-6, whole rock	subalkaline granodiorite	1.92 ± 0.02	17.36 ± 0.06	126 ± 2.5	K_1, barremian
5	Third	PN-142-8126, whole rock	subalkaline quartz diorite	2.08 ± 0.03	16.17 ± 0.05	109 ± 3	K_1, albian
6		PN-174-8199, amphibole	ferrogabbro	0.74 ± 0.04	6.63 ± 0.11	127.5 ± 4.8	K_1, barremian
7	Fourth	PN-238-8618, whole rock	subalkaline granodiorite	1.72 ± 0.02	15.90 ± 0.05	129 ± 3	K_1, barremian
			Ket-Kap Complex				
8	First	PN-111.594\2, whole rock	subalkaline essexite-shonkinite	2.97 ± 0.03	27.26 ± 0.09	128 ± 2.5	K_1, barremian
9		PN-111.594\2, biotite	"	7.12 ± 0.17	53.8 ± 0.8	108.1 ± 3.2	K_1, albian
10		PN-137-1580, whole rock	monzonite	4.13 ± 0.05	39.90 ± 0.13	134 ± 3	K_1, valanginian
11		PN-137-1580, biotite	"	7.51 ± 0.18	62.5 ± 1.0	118.7 ± 3.6	K_1, aptian
12	Third	PN-137-1575, biotite	syenite-quartz monzodiorite	7.39 ± 0.18	59.7 ± 0.9	115.3 ± 3.6	K_1, aptian
13		PN-160-1741A, biotite	"	7.43 ± 0.18	62.9 ± 1.0	120.6 ± 3.6	K_1, aptian
14		PN-131.588-598D, whole rock	monzodiorite	3.94 ± 0.04	34.06 ± 0.11	121 ± 2.5	K_1, aptian
15		PN-134-1528, biotite	"	7.25 ± 0.17	57.9 ± 0.9	114.1 ± 3.5	K_1, aptian
16	Fourth	PN-131.574, whole rock	granosyenite	5.14 ± 0.06	38.08 ± 0.12	104 ± 2.5	K_1, albian
17		PN-138-1607B, amphibole	"	1.80 ± 0.04	15.69 ± 0.20	124.2 ± 3.7	K_1, aptian

Note. Determination of K–Ar age for whole rock samples was made at the Laboratory for Isotope Geochemistry and Geochronology (Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences) on a MI-1201 IG mass spectrometer by the method of isotope solution with ^{38}Ar applied as a tracer; potassium was determined by flame spectrophotometry, analysts M.M. Arakelyants and V.A. Lebedev. The K–Ar dating of monomineral samples was made in the Laboratory of Stable Isotopes (Analytic Center of the Far East Geological Institute, Far East Branch, Russian Academy of Sciences), analyst S.Yu. Budnitskii. The radiogenic argon concentration was measured by the original CF-GC-IRMS method developed in the laboratory [13]. The potassium content was determined by atomic emission spectroscopy with induction-bound plasma on an iCAP 6500Duo spectrometer (manufactured by Thermo Scientific Corporation, United States), analysts G.A. Gorbach, E.A. Tkalina, and N.V. Khurkalo. Designations of age intervals of the phytostratigraphic scale are given in accordance with [12].

In the present communication, we discuss the results of geochronological studies of rocks belonging to the Uchur and Ket-Kap complexes of the KKYuIP, with the help of the modernized K–Ar method [13], as well as the U–Pb isochron dating based on sphenes and the U–Pb local (SHRIMP-II) zircon-based dating. The data of K–Ar geochronological studies are presented in Table 1; those for SHRIMP analysis, in Table 2 and Fig. 2; and those for U–Pb sphene-based dating, in Table 3 and Fig. 3.

The available K–Ar datings for the KKYuIP generally vary from 188 to 98 Ma [2, 4, 5], which corresponds to the age interval of the Early Jurassic–Late Cretaceous. New results of isotope dating for KKYuIP magmatism have been acquired for the following massifs: Ulakhan, Yurtovyi (Ket-Kap swell), Yuna-Dan'skii, Dyus'-Makit (Yuna-Dan'skii swell), and Usmun-Dar'inskii (swell of the same name) (Fig. 1).

K–Ar datings were derived by us for eight whole rock and nine monomineral samples of intrusive rocks (Table 1). The age interval based on the whole rock composition of subalkaline rocks corresponds to the Early Cretaceous (142.3 ± 3–104.2 ± 2.5 Ma), which significantly differs from the estimates given in the

Table 2. The age of rocks from the KKYuIP igneous complexes based on the results of the U–Pb dating of zircons

No.	Number of sample	Coordinates		Phase of magmatism	Rock	$^{206}Pb/^{238}U$-age (Ma)	±2σ	rms deviation	*p*	*N*
		N	E							
Uchur Complex										
1	PN-239-8572	57°75′05″	133°43′37″	Fourth	subalkaline granodiorite	102	23	1.8	<0.01	7
						2020	13			
						*388	11			1
						***117.8**				1
						***123.0**				1
2	PN-238-8642	57°35′37″	133°43′25″	Third	Subalkaline quartz diorite	**120.1**	5.5	0.01	0.92	2
						259.2	9.3	0.35	0.55	2
						2012	23	2.1	0.14	5
3	PN-142-8126	57°32′27″	133°33′37″	Third	Subalkaline quartz diorite	124.4	1.6	0.03	0.86	11
4	PN-133-1501	57°44′42″	132°20′05″	First	subalkaline quartz dioritic porphyrite	122	1	0.04	0.84	10
Ket-Kap Complex										
5	PN-045-6105	57°22′21″	133°24′55″	Fourth	Alaskite	**125.8**	2.5	0.01	0.91	7
						351	17	0.26	0.61	1
						516	26	0.23	0.63	1
						2063	66	0.42	0.52	1
6	PN-131.588-598Д	57°39′44″	132°13′29″	Third	Monzodiorite	123.6	1.6	0.15	0.70	11

Note. The position of samples in the table corresponds to the age position of igneous rock phases in every complex, from bottom to top is the direction from ancient to young rocks. * is absolute age datings based on particular points, without calculation of statistical characteristics; other values of the absolute age are concordant values of datings. In the samples with polymodal distribution of datings, the values assumed as the age of the rock are in bold type.

publications and geological survey reports. The formation time of the studied complexes, according to the monomineral-based K–Ar estimates, is also Early Cretaceous but with a narrower interval (Barremian–Albian, 127.5–108.1 Ma). Obviously, there is a certain underestimation of K–Ar monomineral datings relative to whole rock ones, as well as most zircon-based estimates (Tables 1, 2).

For the purpose of U–Pb dating of sphenes, we examined eight samples from subalkaline and alkaline rocks. The insignificant quantity of accumulated ^{207}Pb did not allow us to plot the traditionally used chart in $^{206}Pb/^{238}U$–$^{207}Pb/^{235}U$ coordinates; therefore, based on six points, we calculated the isochrone in $^{206}Pb/^{204}Pb$–$^{238}U/^{204}Pb$ coordinates for alkaline and subalkaline rocks on aggregate (Table 3, Fig. 3). The age determined this way is 124.3 ± 2.0 Ma. Sphene-based dating of subalkaline rocks is the same, within the measurement error limits, 125 ± 20 Ma. The high values of rms deviation can be caused by different reasons. At first, the uranium–lead system of sphenes might be disturbed by any superimposed events. In this case we cannot claim an isochron dependence and the resulting plots are erochrones that provide only the approximate age. The second probable reason is the presence of some primary lead in the examined samples and the correction must have been introduced to it after analysis of cogenetic minerals. This is a task for the future. In general, the acquired results can evidence for nearly synchronous formation (the Barremian–Aptian boundary) of the KKYuIP subalkaline and alkaline complexes.

Utilizing the SHRIMP-II ion microprobe (Center for Isotopic Research, Karpinskii All-Russia Geologic Institute), we derived in most cases dates that statistically belonged to the whole. In two cases (samples PN-239-8572 and PN-238-8642, Table 2), substantial variations in the weighted average values with an rms deviation of 1.8 and 2.1 and probability (*P*) <0.01 and 0.14, respectively, were identified for zircon groups. The variations in the subconcordant U–Pb individual dates for these zircons exceeded 20 Ma. We explain such cases of highly polymodal distribution of dates by the presence of xenogenic inherited zircon crystals most likely from a protolith material (Table 2, Fig. 2). The formation age of the studied rock in such

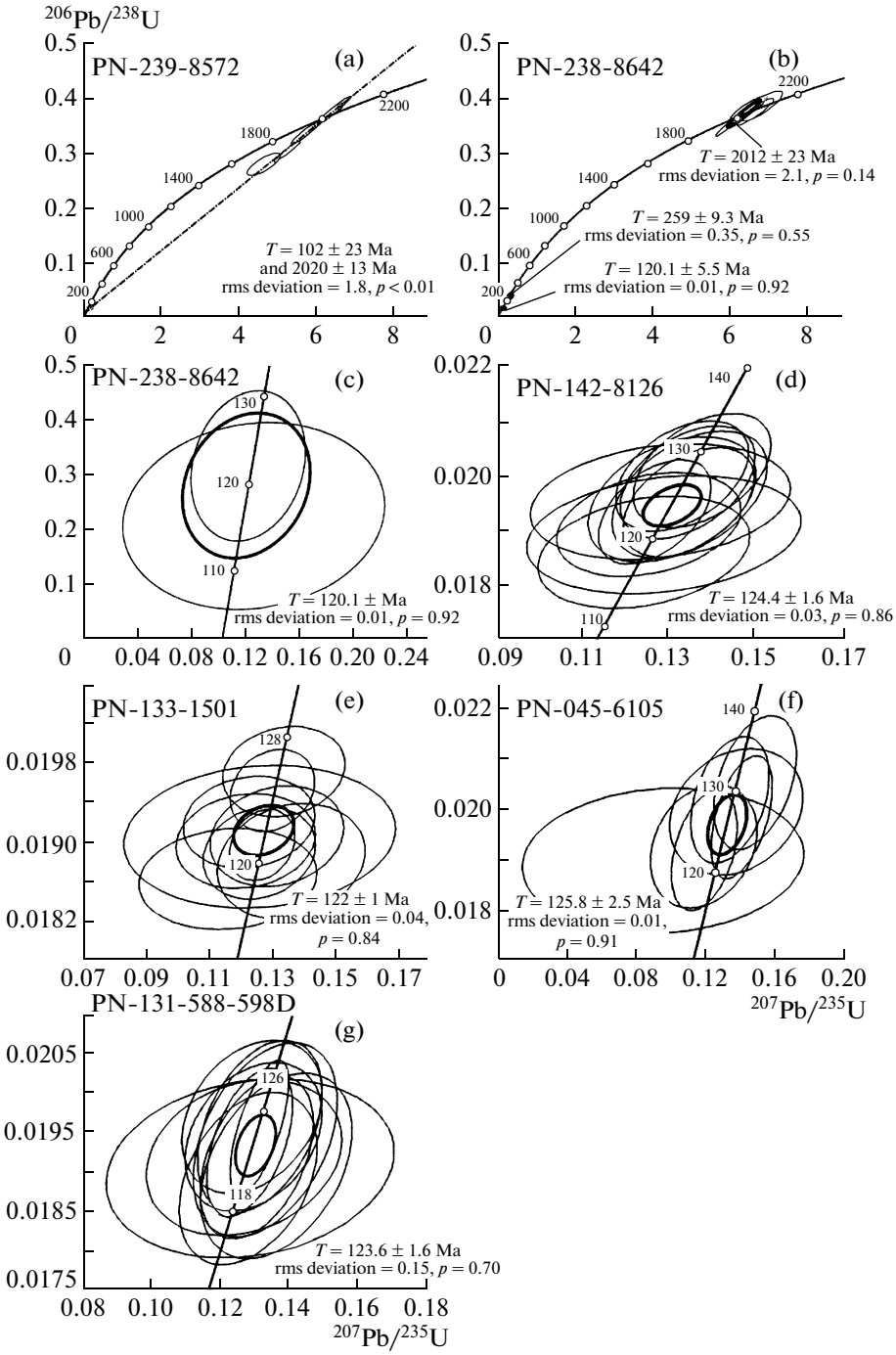


Fig. 2. The results of SHRIMP dating of zircons from the KKYuIP igneous rocks. Wetherill plots for all the analyses: (a–e) Uchur Complex; (f–g) Ket-Kap Complex. The size of ellipses is within the 2σ value. Weighted average results are shown in the thick-lined ellipse, and thin ellipses show the data of individual determinations.

cases was determined as that approaching the age of the youngest zircon crystals (Table 2, in bold type). The dates for xenogenic zircons (from 2 Ga to 200 Ma) conform to the known stages of magmatism and metamorphism within the Aldan Shield.

The derived values of the U–Pb (SHRIMP) age of the Uchur Complex vary from 124.4 to 120.1 Ma; variations in U–Pb dates for monzonitoids of the Ket-Kap Complex fall in a narrower interval of 125.8–123.6 Ma (Table 2). The maximal values of datings conformed well to the sphene-based isochron age (Fig. 3).

Comparison of the U–Pb (SHRIMP) and whole rock K–Ar age estimates for the same sample (Tables 1, 2) has

Table 3. U–Pb isotope data for sphenes from the KKYuIP subalkali and alkali igneous rocks

No.	Sample, complex, rock	Weighing, mg	Pb	U	$^{206}Pb/^{204}Pb^*$	$^{238}U/^{204}Pb^*$	*Rho*
			ppm				
1	PN-111-594/2, Ket-Kap, subalkaline essexite–shonkinite	3.16	11.06	159.8	54 ± 0.24	1880.5 ± 9.97	0.89
2	PN-142-8126, Uchur, subalkaline quartz diorite	2.20	3.25	67.36	109.4 ± 1.83	4682 ± 93.6	0.99
3	PN-131-588.598Д, Ket-Kap, monzodiorite	3.34	3.92	40.1	39.5 ± 0.45	1096 ± 20.1	0.66
4	PN-045-6100, Dar'inskii, spreustein syenite–porphyry	2.83	1.79	16.6	37.6 ± 0.33	1009 ± 14.1	0.93
5	PN-M62-038, Dar'inskii, apo-nepheline syenite–pegmatite	3.05	н.о.	н.о.	19.9 ± 0.016	99.7 ± 0.36	0.39
6	PN-M62-430, Dar'inskii, nepheline syenite-derived pegmatite	2.36	32.02	217.6	29.8 ± 0.057	585 ± 1.5	0.76

Note. Pb extraction from sphenes was made by the method described in [15]. Contents of elements were determined by the isotope dilution method. The Pb and U isotope compositions were measured at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, on a Finnigan MAT-261 mass spectrometer, analyst N.G. Rizvanova. All the errors are within the limits of 2σ. The calculations of isotope ratios and ages for minerals were made utilizing the software described in [14]. * is the isotope ratio corrected to fractionation (0.13%) to a mass unit and laboratory contamination (0.05 ng for Pb and 0.01 ng for U). *Rho* is the value of the correlation coefficient between $^{206}Pb/^{204}Pb$ and $^{238}U/^{204}Pb$.

revealed an extraordinary peculiarity: in some cases the K–Ar values exceeded the U–Pb values. Such a phenomenon can be explained either by the presence of surplus radiogenic argon or by potassium removal from the rock. Since the examined rocks are not altered, the first suggestion is preferable. Additionally, a certain part of the discussed KKYuIP rocks may be of rheomorphic genesis due to intrusion of alkaline-basite melts and their powerful thermal effect on the crystalline basement rocks, and this is why an older age resulted from K–Ar analysis. The sharp noncoincidence of some dates from reports and publications (T_3–J_1) for the early phase of the Uchur Complex with the dates derived by us (K_1) can be explained by another reason: the whole rock samples might have been contaminated with the material of xenolites (crystalline schists, amphibolites), which were highly typical for the first phase diorites. In general, our datings derived by different methods are close to each other and refer to the Early Cretaceous; their variations often do not exceed the errors of the methods used.

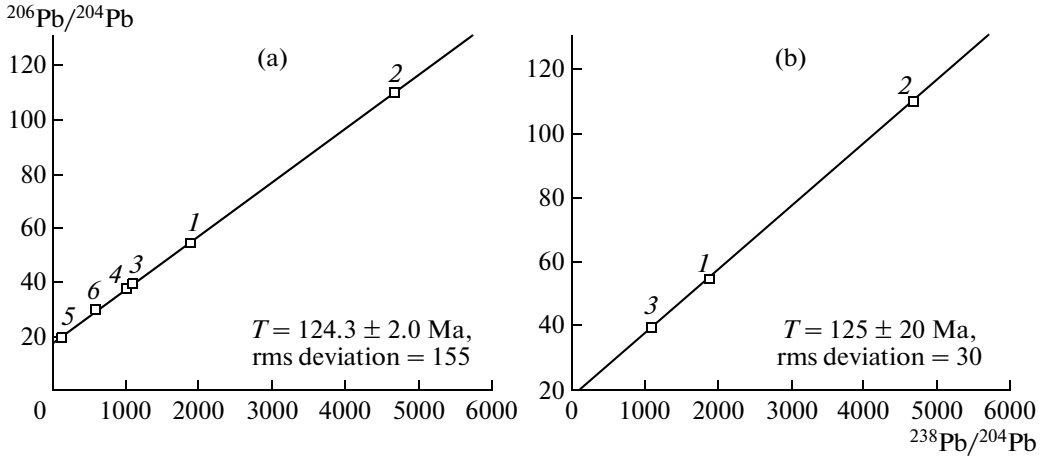


Fig. 3. The results of U–Pb isochron sphene-based dating of the KKYuIP igneous rocks. Isochrons: (a) aggregated for subalkaline and alkaline rocks, (b) for subalkaline rocks. The size of figurative points in plots exceeds the real measurement errors. Numbers of points correspond to the sample numbers from Table 3.

The time gap between intrusion of melts, which were sources for rocks of different phases of the Uchur Complex within the single massif, identified by an ion microprobe (Table 2, samples PN-239-8572 and PN-238-8642, Pavel massif) is minimal and does not exceed 2 Ma. The disturbance in age correlations between the third and fourth phase representatives from the Ket-Kap Complex (sample PN-131.588-598D belongs to the third phase, 123.6 Ma; PN-045-6105, to the fourth phase, 125.8 Ma), analogous to that between the first (PN-133-1501, 122 Ma) and third (PN-142-8126, 124.4 Ma) phases of the Uchur Complex is explained by the fact that the examined rocks belong to different massifs (to the Ulakhan massif at the Ket-Kap swell (Fig. 1) and to Usmun-Dar'inskii at the swell of the same name, respectively, in the former case; to the Ulakhan and Nedostupnyi massifs at the Yuna-Dan'skoe swell, respectively, in the latter case). The formation time intervals for the complex's phases of the same name in different massifs probably do not coincide due to the fact that every massif was formed by an individual igneous source having its own evolution.

The main conclusion from the analysis of new isotope dating is that the duration of manifestation of subalkaline magmatism in the KKYuIP was several Ma long and fell within the Early Cretaceous (the Barremian–Aptian boundary, based on SHRIMP dating of zircons and U–Pb dating of sphenes). This time interval may mark the main stage (relative quiet phase at strong compression) in the evolution of the setting of mutual sliding between the Siberian Craton and the Amurian megablock, according to geodynamical reconstructions [11].

The geochronological studies have proved the formerly stated viewpoint [10] that the Ket-Kap Complex is a petrological analog of the Uchur one, but more alkaline in composition owing to an additional inflow of potassium and related microelements by a deep fluid into source melts. The presence of relic zircons in crystalline phases of monzonitoides and subalkaline dioritoids evidences the participation of the ancient crust material in the formation source of these rocks.

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