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SHORT COMMUNICATIONS

Formation Time of the Ni-Bearing Norite–Cortlandite Association of East Asia

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The Ni-bearing hornblende peridotite (cortlandite)–norite association was first distinguished by Zimin [1] in North Korea. Previously found sulfide-bearing mafic–ultramafic intrusions in the folded framing of the Aldan shield and Bureya crystalline massif were also ascribed to this association. Similar Ni-bearing massifs were later described as troctolite–cortlandite association by Shcheka and co-authors in Kamchatka and Primorie [2]. According to our data [3], mafic–ultramafic rocks hosting Cu–Ni deposits of the Hongqiling ore district in the Jilin province, northeastern China, are also ascribed to this association. In spite of such a wide occurrence in the eastern Asian margin, no reliable age data have been available for this association until recently. Based on geologic evidence, Zimin suggested that these Ni-bearing intrusions in the Far East have a Late Proterozoic age. This viewpoint is generally inconsistent with the widely scattered K–Ar data on norite–cortlandite associations of Kamchatka and China (385–80 Ma) obtained afterwards [2]. Geologists of Kamchatka presently accept a Cretaceous age for the Ni-bearing intrusions of the Sredinny Range [4, 5]. Significant progress in deciphering the age of norite–cortlandite associations was achieved in China. Aihua [6] and Zhang [7] reported consistent U–Pb and $^{40}Ar/^{39}Ar$ ages (216 and 220 Ma, respectively) for Ni-bearing intrusions of the Hongqiling ore district, suggesting their relation with the Indo-Sinian Orogeny.

To obtain reliable age data on the Ni-bearing intrusions of Kamchatka and to support their correlation with similar complexes of northeastern China, we dated them with $^{40}Ar/^{39}Ar$ and U–Pb methods. For this purpose we selected the Kuvalorog Intrusion (Fig. 1), the largest (~25 km^2) massif of this association in the southeastern part of the Sredinny Range [2, 8], which was studied most exhaustively. The massif has the shape of a lopolith and is dominated (90%) by gabbroids (hornblende norites, gabbros, hornblendites, and garnet leucodiorites), with cortlandite, hornblende orthopyroxenites (perknites), and melanocratic hornblende norites (10%) confined to its western margin. The major minerals of these rocks are hypersthene, magmatic hornblende, and the accessories are ilmenite, with these minerals indicating crystallization from tholeiite water-saturated parent melts at low oxygen fugacity.

Ar–Ar dating was performed on hornblende and biotite taken from the core of the Borehole s-5 at the western outercontact of the Kuvalorog Massif (Medvezhii stream). The analyses were conducted at the Analytical Center of the United Institute of Geology, Geophysics, and Mineralogy of the Siberian Branch of RAS, Novosibirsk. The following technique was used. Minerals were wrapped in aluminum foil and welded in a quartz ampoule together with aliquots of corresponding monitors (MCA-11 and LP-6). The samples were irradiated under Cd-shielding in the scientific BBP-K Nuclear Reactor at the Tomsk Polytechnical Institute. The neutron flux gradient was less than 0.5% relative to the sample size. Step heating was carried out in a quartz reactor with external heating. The blank on ^{40}Ar (10 min at 1200°C) was no greater than 5×10^{-10} cm^3 *STP*. The released Ar was purified using Ti and ZrAl SAES

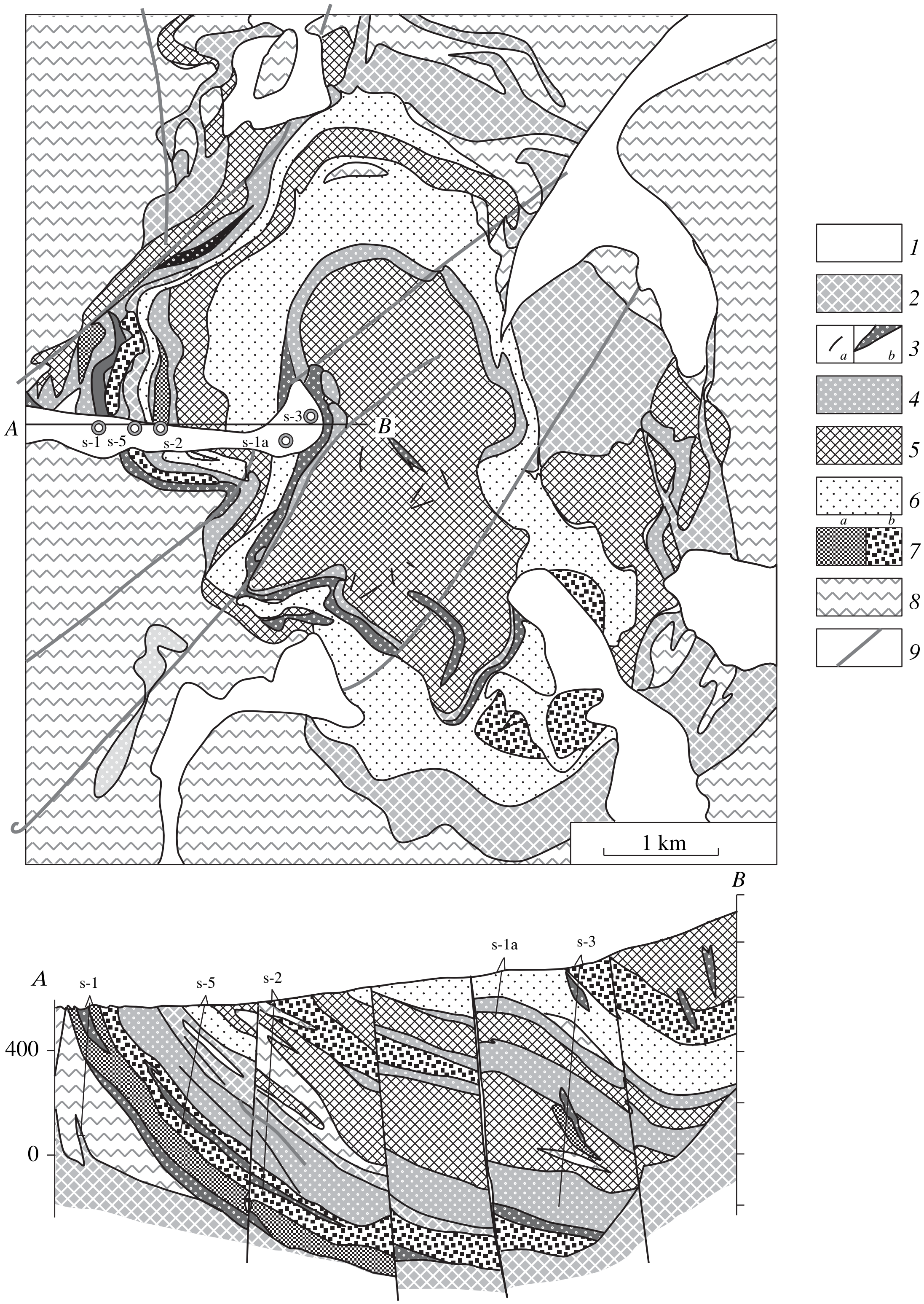

Fig. 1. Geological scheme and cross section (along line *AB*) for the Kuvalorog norite–cortlandite massif [5]. (*1*) Loose deposits, (*2*) granitoids, (*3*) dikes, (*a*) and layers (*b*) of cortlandites, (*4*) hornblende norites, gabbronorites, and pyroxenites; (*5*) banded hornblende gabbro and hornblendites; (*6*) leuconorites and gabbrodiorites; (*7*) massive (*a*) and disseminated (*b*) sulfide ores; (*8*) host rocks, (*9*) faults; (s-1, s-5 and others) are numbers of boreholes.

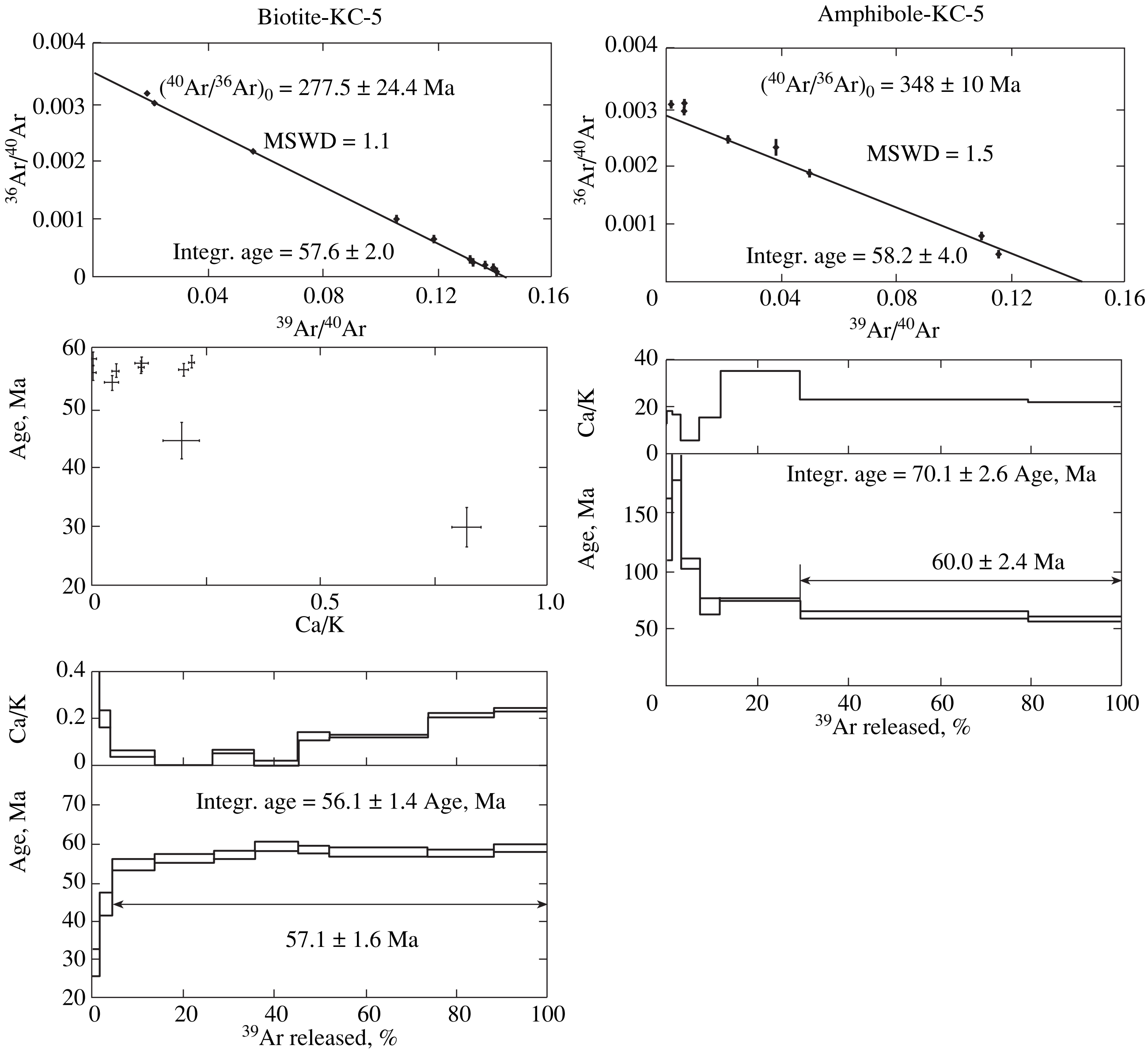

Fig. 2. Results of ^{40}Ar/^{39}Ar dating on biotite (2a) and amphibole (2b) from mafic rocks of the Kuvalorog Massif. Age and Ca/K spectra and isochron diagrams are shown for both minerals. Diagram of age versus Ca/K ratio is shown for biotite.

getters. The Ar isotopic composition was measured on a Noble Gas 5400 Micromass spectrometer.

In the age biotite spectrum (Fig. 2), a stepwise upward progression is followed by an age plateau. In the diagram of the measured age versus the Ca/K ratio, the plateau points define a trend with a Ca/K ratio from 0 to 0.22 at consistent age values. The low-temperature part of the spectrum defines a trend toward younger age values (up to 29 Ma) and relatively high Ca/K (up to 0.8). The presence of two trends suggests two different Ar sources in the sample. The plateau points presumably correspond to primary biotite, while low-temperature points reflect late alteration. The age calculated with an isochron regression (57.6 ± 2.0 Ma) coincides with the plateau age (57.1 ± 1.6 Ma). In the amphibole spectrum (Fig. 2), a stepwise segment with an elevated age value (up to 190 Ma) is followed by a two-step plateau with an average age of 60.0 ± 2.0 Ma. At the same time, the four-step isochron age (58.2 ± 4.0 Ma) is consistent with the biotite age. Based on the pair criterion (coincidence between the ages of two minerals with different abilities of losing radiogenic Ar [9]), the formation age of the Kuvalorog intrusion is 57.2 ± 1.4 Ma.

Prismatic zircons 300–400 μm in size were taken from the same mafic rocks of the Kuvalorog Massif, which were recovered by Borehole s-2 at a depth of 394 m (Fig. 3). The X-ray and cathodoluminescent study showed that the zircons have a zoned structure and con-

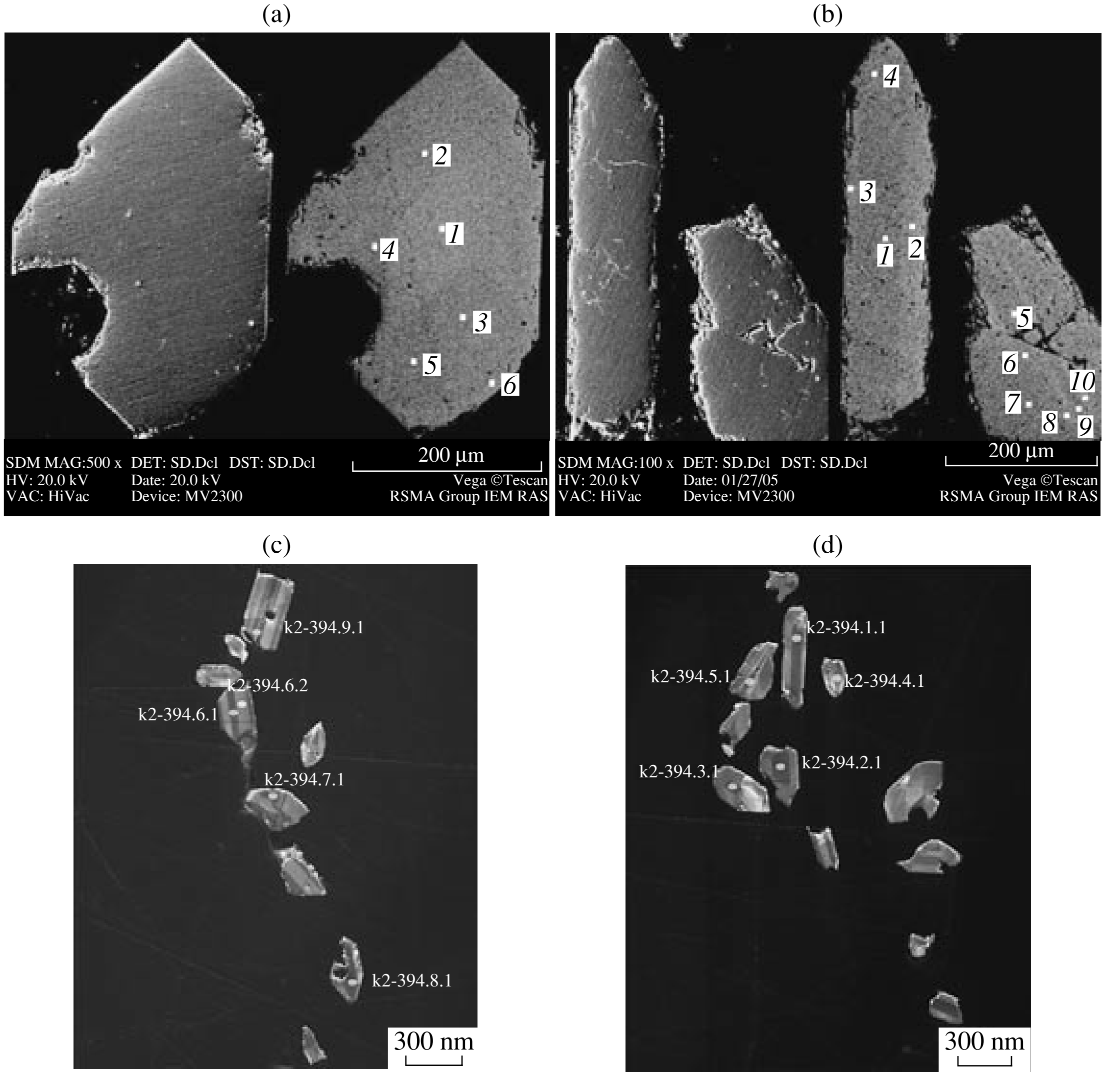

Fig. 3. (a, b) SEM images of zircons in secondary (left) and reflected (right) electrons; points and numbers are localities of X-ray analysis of zircon composition. (c, d) Cathodoluminescent images of zoned zircons and points of mass-spectrometric investigations.

tain ~1 wt % Y, Hf; 0.1–0.2 wt % Pb, and 0.0n % Mg, Mn, Fe, Sn, La, Ce, Th, and U (Table 1). The isotope–geochronological study of zircons was carried out by D.I. Matukov at the Center of Isotopic Research of the Karpinskii All-Russia Research Institute of Geology in St. Petersburg on a five-collector high-resolution SHRIMP-II secondary ion mass spectrometer. The superprecise focusing of the ion source allowed "point" age determinations on U^{235}, U^{238}, Pb^{206}, and Pb^{207}. Hand-picked zircons were mounted in epoxy with the TEMORA and 91500 standards. Optical and cathodoluminescent images showing the internal structure of zircons were used to select dating points at the grain surface. The U–Pb ratios were measured on a SHRIMP-II, using the technique described in [10]. The intensity of primary beam of negatively charged oxygen ions was 2.5 nA; the diameter of the spot (crater) was 25 μm. The results were processed with the SQUID program [11]. The U–Pb ratios were normalized to the value for TEMORA standard zircon (0.0668), which corresponds to an age of 416.75 Ma [12]. The errors of individual analyses are given at a 1σ level, the errors of the calculated concordant ages and intercepts are given at a 2σ level. The concordia plots were constructed using [13, 14].

Nine isotopic U–Pb determinations in eight zircons are presented in Table 2 and plotted in a $^{207}Pb/^{235}U$ – $^{206}Pb/^{238}U$ diagram in the form of confidence error ellipses (Fig. 4). The concordia of all measurements defines an age of 50.8 ± 1.4 Ma, which corresponds, according to the International Stratigraphic Scale, to the beginning of the Eocene stage of the Paleogene period.

The disagreement between Ar–Ar and U–Pb ages of the gabbro–cortlandite intrusions significantly exceed the postulated errors of these methods. Two explana-

Table 1. Chemical composition (wt %) of zircons used for U–Pb geochronological investigations

Sample No.	MgO	SiO_2	CaO	MnO	FeO	Y_2O_3	ZrO_2	SnO_2	La_2O_3	Ce_2O_3	HfO_2	PbO	ThO_2	UO_2	Total
Zr1 (6 L)*	0.04	31.24	0.01	0.04	0.03	1.23	65.78	0.08	0.06	0.03	1.22	0.12	0.06	0.08	100.02
S	0.031	0.288	0.012	0.062	0.02	0.159	0.486	0.07	0.139	0.06	0.285	0.245	0.081	0.087	–
Zr1 (6 M)**	0.04	31.41	0.01	0.04	0.03	1.24	66.49	0.08	0.06	0.04	0.43	0	0.07	0.08	100.02
S	0.032	0.29	0.012	0.063	0.03	0.158	0.353	0.07	0.142	0.061	0.078	0	0.083	0.089	–
Zr2 (10 L)*	0.06	31.11	0	0.03	0.04	1.42	65.69	0.08	0.02	0.02	1.19	0.22	0.08	0.05	100.02
S	0.047	0.22	0.004	0.027	0.05	0.21	0.294	0.09	0.029	0.041	0.136	0.235	0.118	0.068	–
Zr2 (10 M)**	0.06	31.31	0	0.03	0.05	1.43	66.51	0.08	0.02	0.02	0.36	0	0.08	0.05	100
S	0.048	0.184	0.004	0.027	0.05	0.215	0.319	0.09	0.029	0.041	0.159	0	0.12	0.07	–

*Average of six and ten analyses on L-lines.
**The same on M-lines; *S* is the standard deviation.

Table 2. Results of U–Pb zircon geochronological investigations on a SHRIMP-II mass spectrometer

No.	Number of analytical spot	% $^{206}Pb_c$	ppm U	ppm Th	$^{232}Th/^{238}U$	ppm $^{206}Pb^*$	$^{206}Pb/^{238}U$ Age, Ma	$^{207}Pb^*/^{235}U$	Error ±%	$^{206}Pb/^{238}U$	Error ±%	Correlation coefficient
1	K2-394.9.1	4.21	176	77	0.46	1.21	49.1 ± 1.7	0.064	32	0.00765	3.4	0.105
2	K2-394.5.1	6.38	164	76	0.48	1.15	49.2 ± 2.2	0.040	80	0.00766	4.6	0.057
3	K2-394.6.2	17.99	96	30	0.32	0.799	50.8 ± 3.1	0.099	55	0.00792	6.1	0.111
4	K2-394.8.1	3.61	301	120	0.41	2.13	51.1 ± 1.5	0.051	37	0.00797	2.9	0.079
5	K2-394.4.1	0.91	163	73	0.47	1.13	51.1 ± 1.8	0.071	32	0.00796	3.5	0.110
6	K2-394.6.1	5.60	202	92	0.47	1.47	51.6 ± 2.6	0.055	72	0.00803	5.1	0.070
7	K2-394.2.1	3.58	153	65	0.44	1.10	51.6 ± 2.0	0.066	43	0.00804	4.0	0.093
8	K2-394.3.1	5.74	139	59	0.44	1.03	52.1 ± 2.3	0.040	83	0.00812	4.5	0.054
9	K2-394.7.1	10.92	153	68	0.46	1.21	52.4 ± 2.4	0.104	35	0.00817	4.7	0.132

Note: Correction for common lead was introduced on ^{204}Pb; Pb_c and Pb^* are fractions of common and radiogenic lead, respectively; errors are at a 1σ level; standard was calibrated with an error of 1.14%.

tions can be proposed. First, both methods are characterized by systematic errors, which are not taken into account during the statistic determination of the errors. Second, different ages were obtained on different minerals. Amphiboles and biotites were extracted from the main facies of the Kuvalorog Massif, while zircons were taken from the latest derivatives, which bear evidence of a hybrid origin.

It should be noted that the Early Paleogene ages obtained for the Ni-bearing norite–cortlandite intrusions of Kamchatka seemed to be unexpected. The Ni-bearing intrusions of this type up to recently were considered to form simultaneously, during the early, Campanian–Maestrichtian, stages of marginal–oceanic rifting within the Asian continental margin [15]. New geochronological data indicate that the cortlandites of Kamchatka formed during the final stage of rifting, presumably simultaneously with the volcanic rocks of the Vetlovsk Formation. Given geochronological data on the aforesaid analogues in northeastern China, riftogenic magmatism in the Asian marginal–Pacific zone occurred repeatedly (at least, twice): in the Indo-Cinian (Late Triassic) and Alpine (Early Paleogene) periods. The first stage was coeval with flood basaltic magmatism at the Siberian Platform, while the second occurred simultaneously with the collision of the Indostan plate with Asia and the outpouring of Deccan flood basalts [16]. It is interesting that Buntdzen and coauthors [17] drew the same conclusion about the two stages (Triassic and Tertiary) of mafic–ultramafic magmatism accompanied by PGE–Ni–Cu sulfide mineralization in Alaska and Kamchatka [17]. They obtained $^{40}Ar/^{39}Ar$ ages of 255.6 and 233.7 Ma for the Shear Creek sills from the Farewell area and those of 49.8 and

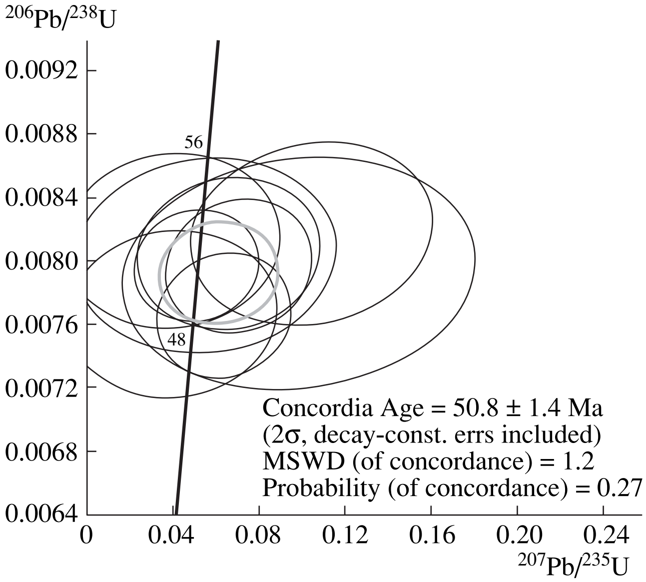

Fig. 4. U–Pb concordia diagram for gabbroids from the Kuvalorog Massif.

53.0 Ma for the six gabbro–cortlandite sills with sulfide–Ni ore mineralization from the Sredinny Range, Kamchatka. It can be readily seen that the latter ages are similar to those obtained by two different methods on the Kuvalorog Massif of the same rock association.

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