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GEOCHEMISTRY

The Early Cretaceous Collisional Granite–Leucogranite Association of the Stanovoi Terrane: New Geochronological, Geochemical, and Isotope-Geochemical Data

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The granite–leucogranite plutons traditionally recognized as the Irakan Complex are widespread in the Stanovoi Terrane [1]. This plutonic association comprises (I) biotite–hornblende quartz monzodiorite, (II) biotite–hornblende granite, and (III) biotite-bearing leucogranite and subalkali leucogranite intrusive phases. According to the K–Ar datings, phase II is composed of Early Cretaceous granites, while phase III includes Late Cretaceous leucogranites. Gold placers and gold–tungsten and molybdenum ore occurrences are spatially associated with granite–leucogranite plutons.

The geochronological, geochemical, and isotope-geochemical studies of the Tokko–Sivakan pluton, which is typical of the granite–leucogranite association, allowed us to substantiate its Early Cretaceous age, characterize the rock compositions in more detail, and decipher the composition and age of the initial substrate (source material). These data are of great importance for the substantiation of the Early Cretaceous stage of granitoid magmatism in the Upper Amur region at 110 ± 3 Ma.

The major oxide composition of rocks was determined with chemical analysis at the Amur Complex Research Institute, Blagoveshchensk. The trace elements (including REE) were determined with the ICP-MS method on an Elan DRC II device (Perkin Elmer, United States) at the Khabarovsk Analytical Center of the Institute of Geophysics and Tectonics, Far East Division, Russian Academy of Sciences with an accuracy of <5%. The accuracy and reproducibility of measurements were estimated with internal and external international standards.

The trace element contents in the representative samples taken from the Tokko–Sivakan pluton in the Upper Amur region are presented in Table 1.

Quartz monzodiorites of phase I belong to the normal and subalkaline series, while granites of phase II correspond to the normal series. Both normal and subalkali leucogranites are noted among the rocks of phase III. Quartz monzodiorites of phase I are largely metaluminous rocks. Granites of phase II are classed with peraluminous I-granites; leucogranites of phase III, with peraluminous S-granites. In general, the plutonic rocks are high-K formations with a high degree of iron oxidation and PM-normalized spidergrams characterized by negative Cs, Ta, Sr, Hf, and Ti anomalies. Plutonic rocks of phase I are distinguished by the lowest Rb, Th, U, and Hf contents along with the highest P and Sm contents. The contents of most LILE and HSFE elements (Rb, Ba, Th, K, Nb, Ce, Nd, and P) in the granitic rocks are close to or above the upper crustal level, whereas the Ta, Sr, Hf, and Zr contents are close to or below the lower crustal level. The rocks are characterized by high REE contents (147–268.5 ppm) with a prevalence of LREE over HREE. Granites of phase II are characterized by the lowest MREE and especially HREE contents. Therefore, the HREE segment of this phase has a concave pattern, in contrast to the relatively even HREE pattern of quartz diorites and leucogranites. The $(La/Yb)_N$ ratio of plutonic rocks varies from 11.7 to 33.4. The most fractionated REE patterns are typical of the granites of phase II with $(La/Yb)_N$ = 24.6–33.4. Quartz monzodiorites reveal a distinct negative Eu anomaly (Eu/Eu* = 0.43). The Eu minimum in granites is poorly expressed (Eu/Eu* = 0.74–0.75), whereas a deep Eu minimum (Eu/Eu* = 0.10–0.32) is typical of leucogranites of normal and moderate alkalinity.

The U–Pb dating of zircons was carried out on a SHRIMP-II microprobe at the Center of Isotopic Stud-

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Table 1. Major oxides (wt %) and trace elements (ppm) in the representative samples from the Tokko–Sivakan pluton

Component	Phase I	Phase II		Phase III		
	486	479-1	482	483-2	484	489
	1	2	3	4	5	6
SiO_2	63.50	69.70	70.10	75.20	72.50	75.30
TiO_2	0.75	0.40	0.35	0.20	0.25	0.21
Al_2O_3	17.35	14.94	14.99	12.93	13.76	12.58
Fe_2O_3	2.13	1.14	0.79	0.90	1.19	0.47
FeO	2.77	1.36	1.25	1.22	0.88	1.70
MnO	0.09	0.07	0.06	0.10	0.09	0.08
MgO	1.88	1.03	0.83	0.23	1.11	1.47
CaO	4.17	2.65	2.06	1.12	0.51	0.41
Na_2O	3.55	4.44	4.05	4.43	3.44	3.19
K_2O	2.93	3.22	3.49	3.93	4.03	3.60
P_2O_5	0.20	0.14	0.13	0.03	0.07	0.08
L.O.I.	0.41	0.42	0.45	0.19	0.27	0.53
Total	99.73	99.51	98.55	100.48	98.10	100.33
Li	17.3	19.0	11.3	34.5	31.0	19.1
Be	1.6	1.8	2.0	3.2	3.0	2.3
Sc	13.4	5.4	0.8	2.0	5.2	9.7
V	135	41	42	7	12	94
Cr	20	17	84	35	18	27
Co	17	5	4	2	2	13
Ni	17	9	8	5	9	11
Cu	24	–	12	24	4	26
Zn	55	25	34	28	31	88
Rb	61	70	79	98	108	81
Sr	599	504	462	76	145	545
Y	23.3	12.8	10.7	22.9	31.7	22.0
Zr	20.0	39.3	36.8	73.3	89.3	34.4
Nb	12.5	10.6	8.5	48.2	31.5	13.4
Mo	1.2	0.5	1.4	1.1	2.6	1.1
Sn	3.0	3.1	8.1	52.2	8.0	3.7
Cs	1.0	1.0	0.9	0.6	1.0	1.2
Ba	1529	1357	1419	1256	1434	1745
La	48.98	59.47	37.98	40.50	64.38	58.16
Ce	97.51	99.06	68.14	83.57	120.63	112.16
Pr	11.10	9.89	6.88	8.14	12.12	11.04
Nd	40.97	30.62	22.44	30.38	43.91	41.85
Sm	6.85	3.53	3.22	5.27	6.99	6.60
Eu	0.90	1.03	0.77	0.15	0.37	0.66
Gd	5.94	4.91	3.09	4.59	6.41	5.90
Tb	0.76	0.48	0.35	0.68	0.86	0.74
Dy	3.90	2.18	1.77	3.66	4.64	3.70
Ho	0.77	0.43	0.33	0.71	1.01	0.70
Er	2.19	1.28	1.03	2.15	2.93	1.99
Tm	0.33	0.19	0.16	0.36	0.47	0.32
Yb	1.96	1.20	1.05	2.34	3.26	1.92
Lu	0.30	0.18	0.16	0.37	0.51	0.29
Hf	0.90	1.11	1.36	2.83	3.76	1.26
Ta	0.88	1.00	0.69	7.86	3.26	1.13
Pb	30.3	101.0	42.7	514.4	91.9	82.9
Th	7.8	12.7	11.4	13.3	18.6	13.7
U	1.1	5.7	1.8	2.6	2.9	4.5

Note: (–) No data. (1) Quartz monzodiorite, (2, 3) granite, (4) subalkali leucogranite, (5, 6) leucogranite.

Table 2. SHRIMP-II U–Pb data on rocks of the granite–leucogranite association of the Stanovoi Terrane

Point	Content, ppm			Isotope ratios				Age, Ma
	U	Th	$^{206}Pb^*$	$^{207}Pb^*/^{235}U$	± %	$^{206}Pb^*/^{238}U$	± %	$^{206}Pb/^{238}U$
482.5.1	71	66	1.02	0.075	57	0.01591	2.9	101.8 ± 2.9
482.2.1	107	155	1.51	0.085	47	0.01612	2.6	103.1 ± 2.6
482.1.1	161	221	2.36	0.074	42	0.01676	2.6	107.1 ± 2.8
482.8.1	112	159	1.64	0.11	26	0.01678	1.6	107.3 ± 1.7
482.7.1	156	193	2.27	0.11	11	0.01686	1.5	107.8 ± 1.6
482.4.1	257	399	3.75	0.105	13	0.01689	0.7	107.99 ± 0.75
482.6.1	85	81	1.25	0.098	34	0.01692	2.7	108.1 ± 2.9
482.3.1	1434	745	21.8	0.1073	6.5	0.0174	0.77	111.19 ± 0.85
489.10.1	89	134	1.33	0.123	25	0.01708	2.3	109.2 ± 2.5
489.9.1	124	270	1.86	0.123	26	0.01719	2.2	109.8 ± 2.4
489.3.1	99	197	1.52	0.135	13	0.0176	2.6	112.5 ± 2.9
489.1.2	88	214	19.7	4.085	1.9	0.2601	0.87	1490 ± 12
489.4.1	576	169	159	4.86	0.46	0.3219	0.32	1799 ± 5
489.7.1	242	216	68.4	5	0.79	0.328	0.51	1828.9 ± 8.1
489.5.1	136	71	39.7	5.386	1	0.3393	0.65	1883 ± 11
489.6.1	152	117	44.3	5.444	0.95	0.3397	0.63	1885 ± 10
489.1.1	1190	171	469	10.39	3.9	0.4582	1.6	2432 ± 33
489.2.1	360	239	155	12.811	0.5	0.5002	0.4	2614.7 ± 8.7
489.8.1	103	123	46.4	13.56	0.95	0.5247	0.74	2719 ± 16

Notes: * Radiogenic lead. The isotope ratios have been corrected for ^{204}Pb. Uncertainties of the measured isotope ratios are given at 1σ.

ies of the All-Russia Research Institute of Geology, St. Petersburg. The technique of measurements was described in [2]. The intensity of the primary beam of oxygen anions was 5 nA, and the diameter of spot (crater) was 25 μm. The data obtained were processed with a SQUID program [3]. The U–Pb ratios were normalized to the standard TEMORA zircon value of 0.0668 corresponding to an age of 416.75 Ma [4]. Uncertainties of individual analyses (both ratios and ages) are given at a level of 1σ; uncertainties of the calculated concordant ages and intercepts with concordia, at a level of 2σ. The graphs with concordia [5] were plotted with an ISOPLOT/EX program [6].

As has been established by the SHRIMP-II U–Pb dating of zircons, granites of phase II and leucogranites of phase III in the Tokko–Sivakan pluton are close to each other in age: 108.6 ± 1.3 Ma for granites of phase II and 110.3 ± 2.9 Ma for leucogranites of phase III (Table 2; Fig. 1). Thus, both rocks are related to the Early Cretaceous stage of the evolution of the Stanovoi volcanoplutonic belt. The leucogranites contain relict zircons dated at 1.5–2.4 and 2.6–2.7 Ga that suggest the Paleoproterozoic–Neoarchean age of the initial substrate.

To estimate the composition and age of granitic melt sources, we analyzed the Sr and Nd isotopic compositions on a TRITON (Thermo) multicollector mass spectrometer at the Center of Isotopic Studies of the All-Russia Research Institute of Geology, St. Petersburg using the standard technique (Table 3). The procedure blank was 0.01 ng for Rb, 0.2 ng for Sr, 0.01 ng for Sm, and 0.05 ng for Nd. The average accuracy of the determination of isotopic ratios (2σ) is 0.7% for $^{87}Rb/^{86}Sr$, 0.002% for $^{87}Sr/^{86}Sr$, 0.3% for $^{147}Sm/^{144}Nd$, and 0.005%

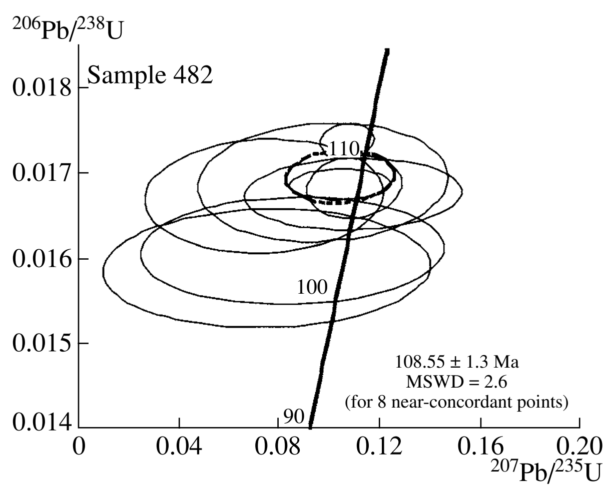

Fig. 1. Diagram with concordia for zircons from granites of phase II, the Tokko–Sivakan pluton (Table 2, sample 482).

Table 3. Isotopic Sr and Nd compositions of rocks of the granite–leucogranite association in the Upper Amur region

Sample no.	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd}	t_{Nd} (DM), Ma	t_{Nd}(DM-2st), Ma	$(^{87}Sr/^{86}Sr)_o$
482	75.1	480.2	0.45223	0.707371	3.37	24.11	0.08453	0.511932	–12.20	1437	1937	0.706664
489	78.2	553.8	0.40879	0.707124	5.76	37.34	0.09329	0.511961	–11.77	1506	1901	0.706485

Note: (482) Granite, (489) leucogranite. The age of both granitic rocks is taken at 110 Ma.

for $^{143}Nd/^{144}Nd$. The isotopic composition of NIST 987 standard was measured at $^{87}Sr/^{86}Sr = 0.710244 \pm 0.000011$; the isotopic composition of Nd JNdi-1 standard, at $^{143}Nd/^{144}Nd = 0.512106 \pm 0.000002$. The $\varepsilon_{Nd}(T)$ values and the model ages T_{Nd}(DM) were calculated based on the present-day CHUR values [7] ($^{143}Nd/^{144}Nd = 0.512638$, and $^{147}Sm/^{144}Nd = 0.1967$) and DM parameters [8] ($^{143}Nd/^{144}Nd = 0.513151$ and $^{147}Sm/^{144}Nd = 0.2136$). The average crustal ratio $^{147}Sm/^{144}Nd = 0.12$ [9] was accepted in the calculation of two-stage model ages T_{Nd}(DM-2st). Granites of phase II and leucogranites of phase III are close in $(^{87}Sr/^{86}Sr)_0$ and ε_{Nd} values. Hence, their melt sources are homogeneous. The two-stage model age T_{Nd}(DM-2st) of both rocks fall within the range of 1937–1901 Ma, which indicates the Paleoproterozoic age of their initial substrate.

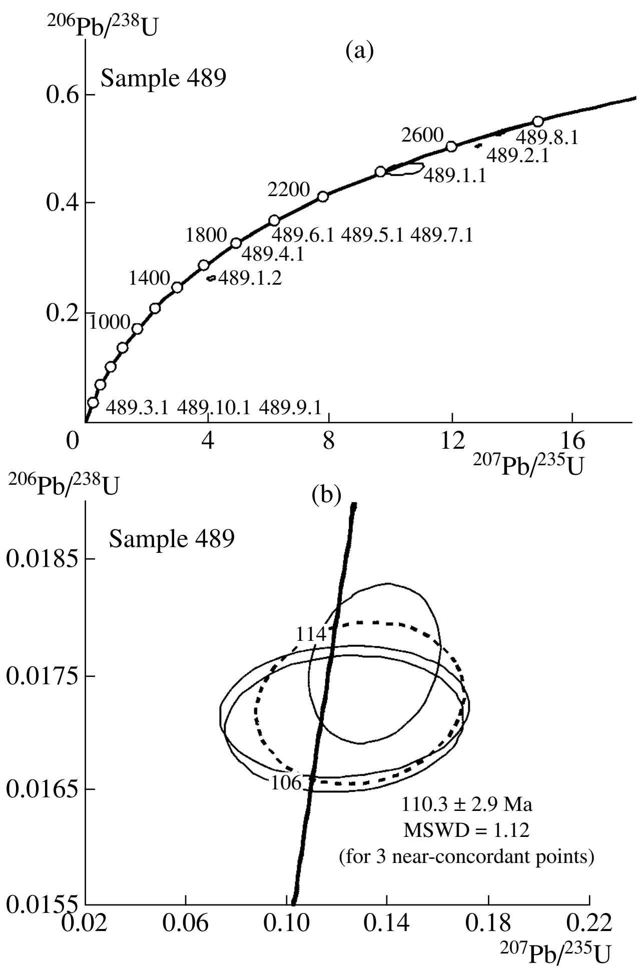

Fig. 2. Diagram with concordia for zircons from leucogranites of phase III, the Tokko–Sivakan pluton: (a) for all zircon grains of sample 489 (Table 2); (b) for grains 489.3.1, 489.9.1, and 489.10.1.

The appreciable prevalence of LREE over HREE along with low HREE and Y contents in the granitic rocks indicate that garnet and amphibole occurred in the source as restitic phases. The lower crustal garnet-bearing metamorphic rocks of amphibolite facies enriched in biotite are the most probable source material. Quartz monzodiorites of phase I and granites of phase II are characterized by low $(Na_2O + K_2O)/(FeO_{tot} + MgO + TiO_2)$ and $Al_2O_3/(FeO_{tot} + MgO + TiO_2)$ ratios and by high $Al_2O_3 + FeO_{tot} + MgO + TiO_2$ and $CaO + FeO_{tot} + MgO + TiO_2$ sums, corresponding in these parameters to products of the partial melting of amphibolites [10]. Leucogranites of phase III, which are distinguished by a higher $(Na_2O + K_2O)/(FeO_{tot} + MgO + TiO_2)$ ratio and $(Al_2O_3 + FeO_{tot} + MgO + TiO_2)$ sum, are close in composition to melts produced by the partial melting of metagraywackes.

In tectonic terms, the plutonic association postdated the closure of the Mongolian–Okhotsk ocean as a result of the collision of the Siberian and North Chinese cratons and the formation of the Mongolian–Okhotsk Foldbelt. The compositions of granitic rocks plotted on the Rb–Hf–Ta discriminant diagram [11] also support their formation in the postcollision setting.

REFERENCES

1. M. V. Martynyuk, S. A. Ryamov, and V. A. Kondrat'ev, *Schematic Subdivision and Correlation of Igneous Complexes in the Khabarovsk Territory and the Amur Region: Explanatory Notes* (Khabarovsk, 1990), Report on project no. 330 (1987–1990) [in Russian].
2. I. S. Williams, Rev. Econ. Geol. **7**, 1 (1998).
3. K. R. Ludwig, *SQUID 1.00. A User's Manual* (Berkeley Geochronol. Center Spec. Publ., 2000), No. 2.

4. L. P. Black and S. L. Kamo, Chem. Geol. **200**, 155 (2003).
5. G. W. Wetherill, Trans. Am. Geophys. Union **37**, 320 (1956).
6. K. R. Ludwig, *User's Manual for Isoplot/Ex, Version 2.10. A Geochronological Toolkit for Microsoft Excel* (Berkeley Geochronol. Center Spec. Publ., 1999), No. 1a.
7. S. B. Jacobsen and G. J. Wasserburg, Earth Planet. Sci. Lett. **67**, 137 (1984).
8. S. J. Goldstein and S. B. Jacobsen, Earth Planet. Sci. Lett. **87**, 249 (1988).
9. S. R. Taylor and S. M. McLennan, *The Continental Crust: Its Composition and Evolution* (Blackwell, Oxford, 1985; Mir, Moscow, 1988).
10. A. E. Patiño Douce, Geol. Soc. London, Spec. Publ., No. 168, 55 (1999).
11. N. B. W. Harris, J. A. Pearce, and A. G. Tindle, Geol. Soc. London, Spec. Publ., No. 19, 67 (1986).