Doklady Earth Sciences, Vol. 397A, No. 6, 2004, pp. 878–882. Translated from Doklady Akademii Nauk, Vol. 397, No. 6, 2004, pp. 810–814.

The Oldest Adakites of the Fennoscandian Shield

S. A. Svetov[1], H. Huhma[2], A. I. Svetova[1], and T. N. Nazarova[1]

Presented by Academician V.A. Koroteev March 15, 2004

Received April 10, 2004

Adakites are andesidacite–rhyolite rocks of trondhjemitic affinity characterized by high Na_2O, Al_2O_3, Ba, and Sr contents and high Sr/Y and $(La/Yb)_n$ ratios [1, 2]. Adakitic rocks are only formed in a subduction setting [3]. They are typical components of Phanerozoic rock associations of active continental margins and island arcs. In the Archean, adakite findings are rare and mainly date to 2.7–2.8 Ga.

This work presents the results of geochemical and Sm–Nd isotopic study of adakites that were found in the oldest (3.05–2.95 Ga) Fennoscandian basalt–andesite–dacite–rhyolite (BADR) island-arc association of the Upper Archean Vedlozero–Segozero greenstone belt.

The Vedlozero–Segozero greenstone belt includes several local structures (Hautavaara, Koikary, Palaselga, Semch, Sovdozero, Oster, and others) and extends in a submeridional direction over approximately 300 km (width of 50–60 km) in the southeastern part of the Karelian Craton at the western framing of the Vedlozero Block.

The Vedlozero–Segozero Belt includes komatiite–basalt associations with an age of 3.05–2.95 Ga (see [4] for details) and andesite–dacite volcanic rocks dated at 3.05–2.95 [5] and 2.90–2.85 Ga [6].

Facies-formation analysis of the ancient andesite association made it possible to reconstruct a chain of paleovolcanic central-type buildups (Nyal'mozero–Ignoila–Hautavaara–Chalka–Palaselga–Oster) formed under shallow marine conditions in the Vedlozero–Segozero Belt.

The U–Pb zircon dating yielded an age of 2995 ± 20 Ma [7] for the Ignoila subvolcanic andesidacite neck, 2945 ± 19 Ma for andesite lavas [8], 3000 ± 40 Ma for andesite dikes of the Palaselga structure, and 3020 ± 10 Ma for subvolcanic stock of the Oster structure [9].

The BADR association is best preserved in the Chalka paleovolcanic zone (northern part of the Hautavaara structure). The vent zone of the Chalka Volcano reconstructed in this area includes several necks surrounded by boulders and agglomerate tuffs of facies of explosive ejections and agglomerate flows. They are supplemented with lenslike beds of intercalated large-pillow lavas, clastolavas, as well as clumpy, massive, and amygdaloidal lavas with pillow breccias, boulder, agglomerate, and lapilli tuffs, and numerous andesite and dacite dikes. The total thickness of the reconstructed section of the Chalka paleovolcano is 2.5 km.

The rocks have metamorphosed under epidote–amphibolite facies of andalusite–sillimanite type. Therefore, their primary magmatic structures have been retained.

Relicts of the most ancient andesite sequence are found in the Hautavaara, Ignoila, Oster, and Nyal'mozero volcanic structures, which contain morphologically different lavas, pyroclastic rocks, and subvolcanic bodies. In the Palaselga structure, andesite magmatism is represented by numerous dikes.

Recent geochemical investigations allowed us to distinguish adakitic subvolcanic and volcanic facies from among the island-arc BADR series of the calc-alkaline association.

Major elements were analyzed in the Institute of Geology (Petrozavodsk). Rare and rare-earth elements were measured by ICP-MS in the Analytical Laboratory of the Institute of Geology and Geochemistry (Yekaterinburg) with a measurement error of <2%. Sm–Nd isotopic analysis was performed using the technique of Peltonen *et al.* [10] on a Sector VG 54 mass spectrometer in the Isotopic Laboratory of Geological Survey of Finland (Espoo). The measurement accuracy of $^{147}Sm/^{144}Nd$ was 0.4%. The $^{143}Nd/^{144}Nd$ ratio was normalized to $^{146}Nd/^{144}Nd = 0.7219$. Measurements of $^{143}Nd/^{144}Nd$ in the La Jolla standard yielded a ratio of 0.511851 ± 6 ($n = 8$).

In terms of SiO_2 content (56–69 wt %), the adakites (2995-Ma-old subvolcanic rocks and less common 2940-Ma-old volcanic rocks) found in the Ignoila, Chalka, and other structures of the Vedlozero–Segozero

---

[1] *Institute of Geology, Karelian Scientific Center, Russian Academy of Sciences, Pushkinskaya ul. 11, Petrozavodsk, 185610 Karelia, Russia; e-mail: ssvetov@krc.karelia.ru*

[2] *Geological Survey of Finland, P.O. Box 96, Betonimiehenkuja 4, Fin-02150 Espoo, Finland*

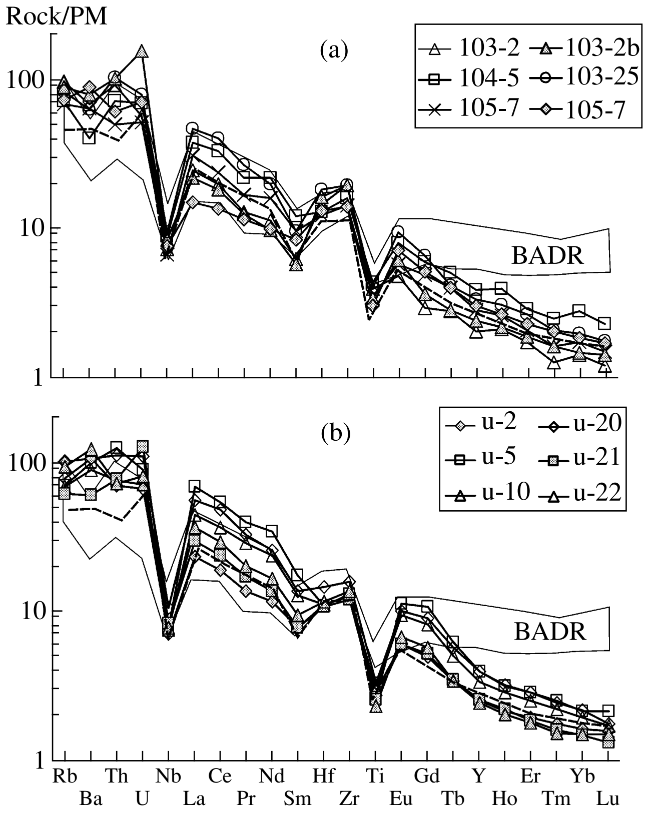

Fig. 1. PM (primitive mantle)-normalized spidergram [11] for the BADR–adakite rock association of the Vedlozero–Segozero greenstone belt. (a) Adakites of the Chalka structure. (b) Adakites of the Ignoila structure. The light field shows the typical compositions of BADR series of the Vedlozero–Segozero greenstone belt; dashed line, typical composition of adakites from Cook Island [1].

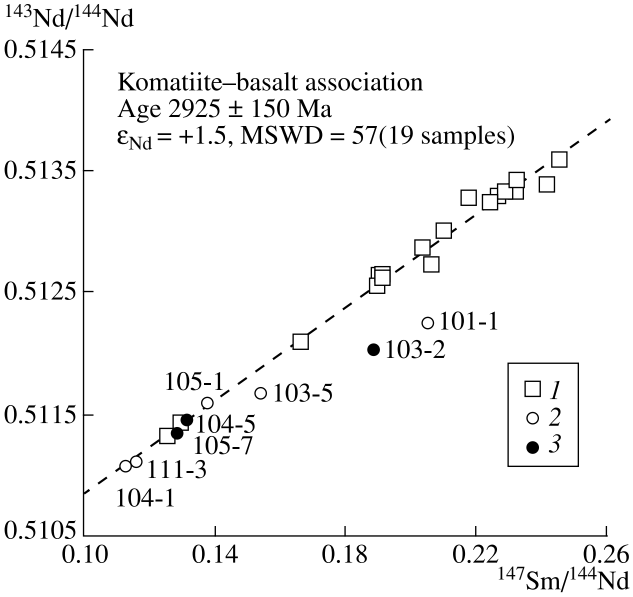

Fig. 2. Sm–Nd evolution diagram for komatiite–basalt and BADR–adakite associations of the Vedlozero–Segozero greenstone belt. (*1*) Komatiites and basalts, (*2*) andesites and dacites, (*3*) adakites.

Belt belong to andesite-dacite (Table 1), In terms of major element contents, adakites differ from calc-alkaline rocks in having higher concentrations of Na_2O, K_2O, and Al_2O_3 (Table 2) at Mg# >0.4.

The maximum differences are observed in concentrations of rare and rare-earth elements. The adakites of the Vedlozero–Segozero Belt are characterized by high contents of Sr (>400 ppm), Ba (>400 ppm), and Zr (>140 ppm), a strongly fractionated REE distribution pattern ($(La/Yb)_n > 15$) (Tables 1, 2), and extremely low HREE concentrations. In terms of REE distribution, the studied rocks are similar to typical adakites from Cook Island, the northern volcanic zone in Ecuador, and southeastern Japan, but they strongly differ from the calc-alkaline lavas and tuffs (BADR series) of the Vedlozero–Segozero Belt (Fig. 1). The Archean adakites of the Vedlozero–Segozero Belt significantly differ from their modern analogs in their higher Cr and Ni concentrations.

The initial $\varepsilon_{Nd(2995)}$ ratios for the BADR–adakite rock association of the Chalka structure range from +1.3 to +2.6 (Table 3). Most data points are plotted in the Sm–Nd isochron with an age of 2925 ± 150 Ma (ε_{Nd} = + 1.5, MSWD = 57, and n = 19), which was previously obtained for coeval komatiite–basalt volcanic rocks of the belt (Fig. 2). Several samples reveal extremely low $\varepsilon_{Nd(2995)}$ values (as low as –10.6) and high $^{147}Sm/^{144}Nd$ values, which are caused by significant Nd loss probably related to metamorphism at 1.8–1.9 Ga.

Model ages of adakites of the Chalka structure (based on the model of De Paolo [12]) vary between 2959 and 3036 Ma, indicating the absence of ancient crustal contribution in the composition of the magmatic sources.

Adakites from the Ignoila subvolcanic stock with $\varepsilon_{Nd(2995)}$ ranging from + 1.0 to + 2.1 yield similar model ages within 2973–3083 Ma.

The geochemical and isotopic characteristics of adakites reflect specific conditions of their genesis. According to model calculations, the liquidus temperatures of the adakite magmas of the Vedlozero–Segozero Belt are estimated at 1020–1090°C, while the parental magmas for the adakites of the Chalka and Ignoila structures can be derived at a melting degree of 10–15% of garnet amphibolite (subducted oceanic basalts) in equilibrium with Cpx (59%) + Gr (10%) + Pl (25%) + Hbl (6%) restite and subsequent fractionation of Pl ± Cpx.

At present, temporally close Archean adakites are known in the Birch Uchi (2739 ± 2 Ma [13]) and Wawa (2670 ± 66 Ma [12]) greenstone belts of the Superior Craton (Canada) and the Kamennozero structure (2875 ± 2 Ma) of the Karelian Craton [14].

Thus, our investigations showed that island-arc BADR–adakite assemblages had already been formed

Table 1. Chemical composition of adakites of the Vedlozero–Segozero greenstone belt

Component	103-2	104-5	105-7	103-2b	103-25	105-70	u-2	u-5	u-10	u-20	u-21	u-22
	D	LAT	D	D	D	D	CAT	L	LAT	SS	SS	SS
	Chalka structure						Ignoila structure					
SiO_2	65.66	54.14	65.78	66.84	56.28	66.25	60.22	60.03	57.24	65.24	65.74	66.00
TiO_2	0.74	1.82	0.63	0.65	0.88	0.62	0.65	0.63	0.63	0.49	0.54	0.50
Al_2O_3	14.26	15.10	16.37	16.79	15.52	16.34	16.35	14.53	14.78	15.66	16.16	15.41
Fe_2O_3	2.07	3.52	2.52	1.31	1.94	2.12	2.01	2.09	1.11	1.26	1.68	1.00
FeO	3.88	4.74	1.87	2.51	7.26	1.98	3.81	3.74	3.59	2.80	2.51	2.23
MnO	0.07	0.32	0.053	0.10	0.20	0.061	0.073	0.088	0.093	0.062	0.039	0.060
MgO	1.76	3.61	1.9	0.55	4.80	2.9	4.57	6.52	4.73	3.06	2.58	3.21
CaO	4.76	11.20	4.14	4.06	7.29	4.11	2.41	3.21	5.40	1.97	1.97	2.34
Na_2O	3.86	2.56	4.48	3.87	2.85	3.32	5.47	5.07	5.39	5.41	5.67	5.14
K_2O	1.72	1.30	1.3	2.20	1.05	1.55	2.31	1.89	1.77	1.61	1.04	1.96
H_2O	0.11	0.10	0.11	0.08	0.10	0.13	0.12	0.20	0.10	0.13	0.14	0.12
L.O.I.	0.72	1.24	0.66	1.02	1.30	0.59	1.72	1.67	4.70	2.34	1.60	2.09
Total	99.61	99.65	99.81	99.98	99.47	99.97	99.71	99.67	99.53	100.03	99.67	100.06
Cr	202	180	201	142	297	78	394	493	649	289	268	254
Ni	35	86	24	49	123	26	183	197	239	148	115	93
Co	10	24	10	12	32	8	21	23	22	20	13	11
V	66	129	63	113	148	109	153	181	179	163	132	117
Pb	8.55	7.89	24.60	10.09	10.37	12.13	6.63	4.96	3.34	7.62	7.48	7.91
Rb	61.57	45.52	43.38	56.16	52.95	46.79	63.55	44.05	43.58	49.35	38.86	59.15
Ba	476.91	280.60	447.77	553.68	438.75	617.46	736.95	694.37	617.89	734.56	417.36	853.79
Sr	472.21	463.83	486.92	495.58	406.40	595.41	292.68	237.90	246.82	445.91	601.65	304.54
Nb	5.20	6.37	4.77	6.09	6.83	5.48	5.03	5.54	5.42	7.52	5.97	5.58
Zr	218.35	180.50	161.96	220.10	221.07	158.91	143.52	146.78	141.92	178.42	134.48	153.32
Y	8.965	16.684	11.695	10.533	16.265	12.774	10.144	15.637	13.357	16.126	10.518	9.630
Th	7.840	6.092	4.258	8.662	8.720	5.227	5.871	10.553	6.429	9.433	6.454	6.117
La	16.894	26.221	21.329	15.183	32.014	10.350	15.967	47.123	30.241	38.023	20.225	25.211
Ce	35.648	59.220	42.373	32.806	71.348	24.294	33.463	95.477	64.832	85.046	42.308	51.737
Pr	3.600	6.107	4.702	3.497	7.362	3.204	3.757	10.940	7.868	9.070	4.743	5.585
Nd	15.442	29.686	21.942	13.369	27.227	13.626	15.814	46.377	32.161	34.658	18.425	22.559
Sm	2.807	5.399	4.326	2.574	4.320	3.746	3.460	7.793	5.725	6.059	3.459	4.210
Eu	0.821	1.358	0.975	1.044	1.587	1.201	1.019	1.911	1.581	1.696	1.016	1.137
Gd	1.768	3.577	2.922	2.187	3.946	3.091	2.988	6.394	4.885	5.400	3.138	3.440
Tb	0.302	0.548	0.438	0.311	0.448	0.437	0.374	0.672	0.547	0.621	0.377	0.372
Dy	1.521	2.884	2.117	1.777	2.487	2.266	1.858	2.927	2.519	2.934	1.911	1.801
Ho	0.349	0.650	0.433	0.361	0.513	0.442	0.355	0.525	0.473	0.531	0.368	0.337
Er	0.841	1.406	1.013	0.912	1.281	1.101	0.943	1.388	1.211	1.375	0.902	0.872
Tm	0.095	0.186	0.122	0.121	0.156	0.154	0.132	0.187	0.165	0.183	0.119	0.115
Yb	0.713	1.381	0.868	0.735	0.983	0.915	0.810	1.074	0.969	1.079	0.737	0.743
Lu	0.090	0.170	0.112	0.106	0.132	0.128	0.118	0.160	0.129	0.131	0.099	0.112
U	1.207	1.465	1.093	3.256	1.668	1.494	1.386	1.843	1.478	2.298	2.650	1.683
Sc	6.583	14.416	5.188	7.117	9.191	5.564	12.309	13.833	13.334	12.068	8.079	8.890
Hf	4.476	3.991	3.809	5.065	5.676	4.056	3.466	3.362	3.465	4.538	3.307	3.618
Ta	0.283	0.395	0.340	0.305	0.255	0.344	0.297	0.283	0.239	0.309	0.264	0.316

Note: (D) Dike, (LAT) lithoclast from agglomerate tuff, (CAT) cement of agglomerate tuff, (L) lava breccia, (SS) subvolcanic stock.

Table 2. Chemical variations of typical subvolcanic rocks of calc-alkaline (BADR series) and adakite series in the structures of the Vedlozero–Segozero greenstone belt (major components are given in wt %; trace elements, in ppm)

Structure	Chalka	Ignoila	Chalka	Ignoila	Oster	Palaselga	Nyal'mozero	Adakite*
rock	subvolcanic rocks (ca)		subvolcanic rocks (ad)					
N	6	19	10	9	4	6	3	81*
SiO_2	61.30 ± 4.0	62.61 ± 4.1	65.72 ± 4.2	64.63 ± 4.3	64.39 ± 3.8	58.91 ± 3.4	62.11 ± 5.13	64.66 ± 3.2
TiO_2	0.94 ± 0.31	0.57 ± 0.19	0.68 ± 0.21	0.56 ± 0.22	0.76 ± 0.14	0.61 ± 0.21	0.69 ± 0.2	0.51 ± 0.2
MgO	3.35 ± 1.81	3.57 ± 1.23	1.83 ± 1.94	2.89 ± 1.18	1.94 ± 0.62	2.14 ± 0.83	2.01 ± 0.45	2.20 ± 1.0
CaO	5.65 ± 1.22	4.02 ± 2.11	4.45 ± 1.43	3.52 ± 1.89	4.12 ± 0.73	4.28 ± 0.81	3.45 ± 0.14	5.00 ± 1.3
Na_2O	3.52 ± 0.81	4.36 ± 0.93	3.57 ± 1.42	5.11 ± 1.12	3.86 ± 0.22	3.91 ± 0.74	3.98 ± 0.14	4.09 ± 0.4
K_2O	1.21 ± 0.66	1.58 ± 0.60	1.21 ± 0.69	1.71 ± 0.21	1.51 ± 0.47	1.23 ± 0.35	1.81 ± 0.34	1.72 ± 0.6
Cr	209 ± 64	210 ± 79	201 ± 14	302 ± 52	104 ± 25	117 ± 35	85 ± 11	30–50
Ni	82 ± 41	81 ± 40	39 ± 17	141 ± 16	78 ± 12	71 ± 14	60 ± 7	20–40
Co	26 ± 4	21 ± 5	15 ± 4	18 ± 4	19 ± 3	21 ± 4	20 ± 4	<20
Ba	212 ± 89	320 ± 66	461 ± 28	518 ± 32	425 ± 58	315 ± 64	495 ± 18	>400
Sr	286 ± 112	250 ± 34	454 ± 21	304 ± 77	379 ± 91	320 ± 38	509 ± 54	>450
Nb	6 ± 0.2	5 ± 0.8	4 ± 0.9	5 ± 0.9	9 ± 2.4	5 ± 0.5	6 ± 0.7	<10
Zr	160 ± 25	130 ± 13	190 ± 39	148 ± 10	225 ± 34	139 ± 24	180 ± 16	130–165
Th	6.1 ± 1.7	8.4 ± 2.2	5.1 ± 2.3	6 ± 3.4	2.4 ± 0.8	3.1 ± 0.4	3.9 ± 0.9	3–7
$(La/Yb)_n$	3.11 ± 1.21	5.18 ± 1.24	19.59 ± 2.42	21.60 ± 1.18	19.24 ± 1.21	18.49 ± 3.67	20.98 ± 2.04	21.98 ± 5.07

Notes: (ca) Normal calc-alkaline series, (ad) adakite series, (*n*) number of samples, (*) composition of typical adakite (sampling from 81 analyses) adopted from [1].

Table 3. Sm–Nd data on the BADR–adakite association of the Chalka structure, Vedlozero–Segozero greenstone belt

Sample no.	Rock	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}(T)$	T_{DM}
105-7	Adakite (dike)	3.96	18.59	0.1286	0.511358	1.3	3036
104-5	Adakite (lithoclast in tuff)	5.03	23.20	0.1311	0.511447	2.1	2959
111-3	Andesite (massive porphyritic lava)	3.91	20.36	0.1161	0.511122	1.5	3012
104-1	Andesite (psammitic tuff)	5.21	27.98	0.1125	0.511084	2.1	2959
105-1	Andesite (psammitic tuff)	3.31	14.53	0.1379	0.511612	2.6	2891
103-5	Andesite (massive lava)	3.36	13.21	0.1538	0.511670	–2.3	3584
101-1	Andesite (massive lava)	2.88	8.50	0.2051	0.512267	–10.5	
103-2	Adakite (dike)	2.33	7.45	0.1887	0.512038	–8.6	

Notes: $\varepsilon_{Nd}(T)$ was calculated at 2995 Ma. T_{DM} is based on the model of De Paolo [12].

in the Archean (3.05 Ga ago) within the Fennoscandian and other cratons in similar geodynamic settings. The origination of convergent (interplate) ocean–continent transition zones played a significant role in the development of such geodynamic settings. Adakitic melt is the material that serves as an indicator of the initial stage of subduction in these systems.

ACKNOWLEDGMENTS

We are grateful to Yu.A. Ronkin for the performance of analytical work.

This study was supported by the Russian Foundation for Basic Research, project no. 02-05-97507, and Program of the Earth Sciences Section of the Russian Academy of Sciences "Deep Structure and Geodynamics of the Karelian Part of the Fennoscandian Shield."

REFERENCES

1. H. Martin, Lithos **46**, 411 (1999).
2. A. Polat and R. Kerrich, Earth Planet. Sci. Lett. **202**, 345 (2002).
3. E. Bourdon, J. P. Eissen, M. A. Gutscher, *et al.*, Earth Planet. Sci. Lett. **205**, 123 (2003).

4. S. A. Svetov, A. I. Svetova, and H. Huhma, Geochem. Int. **39** Suppl. 1, 24 (2001).
5. S. A. Svetov, Dokl. Akad. Nauk **388**, 664 (2003) [Dokl. Earth. Sci. **389**, 195 (2003)].
6. A. I. Svetova, *Archean Volcanism of the Vedlozero–Segozero Greenstone Belt of Karelia* (Karel. Nauch. Tsentr, Petrozavodsk, 1988) [in Russian].
7. S. A. Sergeev, Candidate's Dissertation in Geology and Mineralogy (Leningrad, 1989).
8. G. V. Ovchinnikov, V. A. Matrenichev, O. A. Levchenkov *et al.*, Petrologiya, **2**, 266 (1994).
9. A. F. Lobikov, in *Problems of Isotopic Dating of Volcanism and Sedimentation* (Kiev, 1982), pp. 90–91 [in Russian].
10. P. Peltonen, A. Kontinen, and H. Huhma, J. Petrogoly **37**, 1359 (1996).
11. S. S. Sun and W. F. McDonough, Geol. Soc. Spec. Publ. **42**, 313 (1989).
12. D. J. De Paolo, A. M. Linn, and G. Schubert, J. Geophys. Res. **96**, 2071 (1991).
13. P. Hollings and R. Kerrich, Contrib. Mineral. Petrol. **139**, 208 (2000).
14. I. S. Puchtel, A. W. Hofmann, Y.V. Amelin *et al.*, Geochim. Cosmochim. Acta **63**, 3579 (1999).