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GEOLOGY

Provenance and Source of Metaterrigenous Rocks of the Ladoga Group: Results of Geochemical and Sm–Nd Isotope–Geochemical Study

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The Ladoga Group makes up a significant part of the northern Ladoga region. This group represents the Kalevian stratotype of the Karelian region and is considered an analogue of the Kalevian terrigenous rocks of Finland [1]. Systematic geochemical and isotope–geochemical studies have not yet been carried out. Therefore, one cannot identify the sources or provenance of these sedimentary rocks. To fill this gap, we conducted petrochemical (120 samples), geochemical (30 samples), and Sm–Nd isotope–geochemical (15 samples) studies of terrigenous rocks of the Ladoga Group along the 45-km-long submeridional Lake Janisjarvi–Lake Ladoga profile (Fig. 1). The results of this study are considered in this paper.

The Ladoga region confined to the junction of the Karelian Craton and Early Proterozoic Svecofennian foldbelt is generally subdivided into two independent (northern and southern) tectonic blocks (domains) separated by the Meyeri overthrust [5]. The northern block consists of the Archean basement overlain by variably metamorphosed Jatulian–Ludicovian rocks and volcanosedimentary sequences of the Sortavala group that are correlated with Ludicovian and terrigenous rocks of the Kalevian Ladoga Group. In the coastal zone of Lake Ladoga, the block is complicated by granite gneiss domes fringed by the rocks of the Sortavala Group (Fig. 1). The southern block is mainly made up of high-grade terrigenous rocks of the Lahdenpohja Group, which is presently correlated with the Ladoga Group [6].

The Jatulian–Ludicovian rocks are represented by quartzites, arkoses, and carbonate rocks with stratal bodies of metagabbro diabases and amphibole schists. The Sortavala Group is subdivided into two sequences [5]. The lower sequence is composed of mainly mafic volcanic rocks with less common intermediate and silicic volcanics. The upper sequence is dominated by carbonate and terrigenous rocks. It should be noted that volcanogenic rocks of the Sortavala Group are abundant in the volcanic rocks and tuffites classed as within-plate flood basalts. The Sortavala Group (1.97–1.95 Ga) is coeval with Suisarian flood basalts of the Onega Structure and Outokumpu and Jormua ophiolites in Finland [6].

Most of the northern block is composed of the Kalevian rocks of the Ladoga Group, which are represented by a rhythmically bedded (turbidite) terrigenous sequence affected by zonal (greenschist to amphibolite facies) metamorphism (Fig. 1, inset). According to [7, 8], the Kalevian turbidites were deposited in a relatively short time span (1.91–1.88 Ga), which practically coincides with the formation age (1.92–1.89 Ga) of the Early Proterozoic island-arc systems of central Finland [6].

Petrogeochemical reconstructions showed that the metamorphic rocks of the Ladoga Group were formed after graywacke–mudstone association with subordinate arenites. All these sediments are ascribed to the moderately-alkaline rocks with insignificant predominance of K over Na.

In chemical composition, the terrigenous rocks of the Ladoga Group are clearly distinguished into two groups. The first group includes silica-depleted rocks of the lower part of the Ladoga Group, which are spatially associated with rocks of the Sortavala Group in the Kirjavolahti granite gneiss dome region (Kharlu and Laskela areas, Fig. 1). The second group consists of alumina-enriched rocks of the upper part of the section, which are spatially separated from rocks of the Sortavala Group (Janisjarvi and Impiniemi areas, Fig. 1). The main difference in the chemical composition of the distinguished groups is as follows. The arenite-dominated

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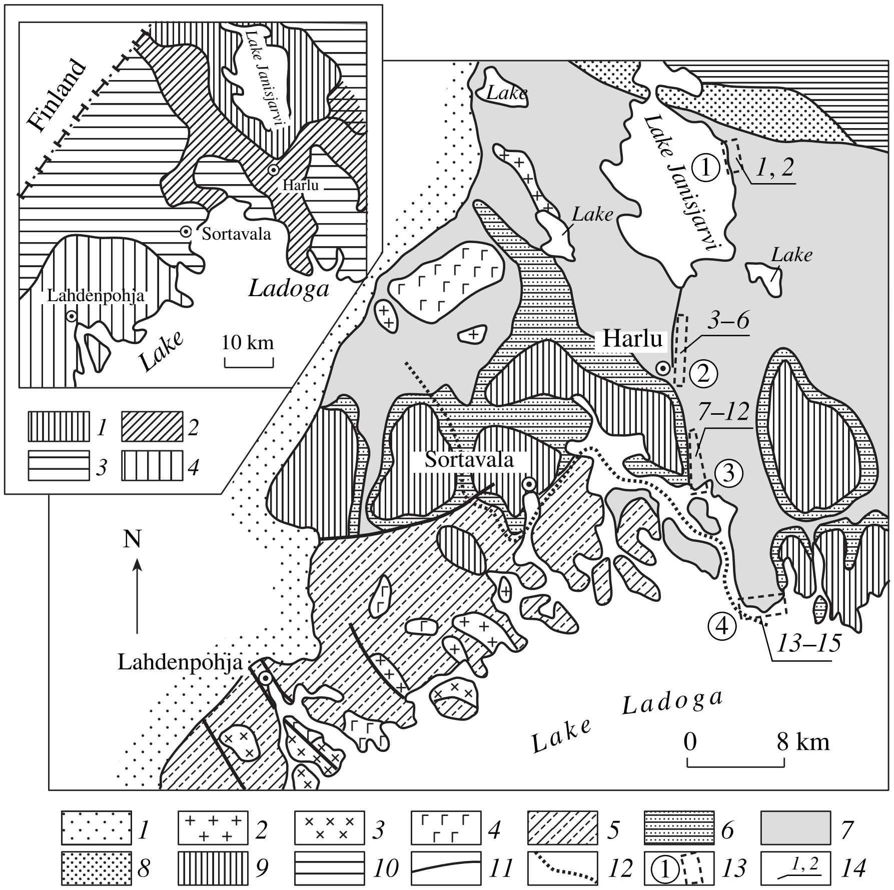

Fig. 1. Geological scheme of the northern Ladoga region (modified after [2–4]). (*1*) Quaternary sediments; (*2*) microcline granites; (*3*) plagiogranites, tonalites, and enderbites; (*4*) gabbroids and pyroxenites; (*5*) terrigenous rocks of the Lahdenpohja Group; (*6*) terrigenous rocks of the Ladoga Group; (*7*) volcanosedimentary rocks of the Sortavala Group; (*8*) Jatulian–Ludicovian terrigenous–carbonate rocks; (*9*) granite gneiss domes; (*10*) granite gneisses of the Karelian Craton basement; (*11*) main faults; (*12*) northern boundary of the ultrametamorphic zone; (*13*) reference sites : (1) Janisjarvi, (2) Harlu, (3) Laskela, (4) Impiniemi; (*14*) sampling sites for Sm–Nd isotope–geochemical investigation (numbers correspond to ordinal numbers in the table). Inset shows metamorphic zoning scheme of the northern Ladoga region. Metamorphic facies: (*1*) green-schist, (*2*) epidote–amphibolite, (*3*) amphibolite, (*4*) granulite.

rocks of the lower part of the Ladoga Group represent recycled rocks [9], which are enriched in TiO_2, Fe_2O_3, and MgO but depleted in Al_2O_3.

These rocks also show distinct differences in geochemical features. The rocks of the lower part are enriched in Cr, Co, and Ni, indicating the presence of mafic rocks in provenance. By contrast, the rocks from the upper part are significantly enriched in Th, which indicates that provenances were dominated by silicic rocks. The La–Th–Sc relations show that the major source for the lower part of the section is represented by granodiorites, in addition to mafic rocks, whereas rocks from the upper part were mainly derived from tonalite and trondhjemite rocks. The average Th/Sc ratios in the rocks from the lower and upper parts of the section are 0.61 and 0.88, respectively, while La/Sc ratios are 1.8 and 2.6, respectively. According to [10], this indicates a significant contribution of Archean rocks in the formation of the lower parts of the Ladoga Group.

Sm–Nd isotope study shows that metaterrigenous rocks of the lower and upper part of the Ladoga Group have $T_{Nd}(DM)$ within 2.5–2.7 and 2.4–2.6 Ga, respectively (table). Only one metagraywacke sample from the lower part of the section defined $T_{Nd}(DM) = 3.1$ Ga. In the ε_{Nd}–age diagram (Fig. 2), the Nd isotopic evolution line of the most studied terrigenous rocks of the Ladoga Group is plotted in the evolution field of the Early Proterozoic metaterrigenous rocks of southern and central Finland [14] or between this field and the evolution field of the Archean continental crust of the Karelian megablock of the Baltic Shield. The exceptions are two samples of terrigenous rocks from the lower part of the Ladoga Group, whose evolution lines are near or in the field of the Archean continental crust of the Karelian megablock. All these data indicate that the Ladoga Group includes disintegration products of rocks with Early Proterozoic and Archean Nd model ages. However, as seen in Fig. 2, the lower part of the

Results of Sm–Nd isotope–geochemical study of the metaterrigenous rocks of the Ladoga Group, Northern Ladoga region

Ordinal no.	Sample no.	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd \pm 2\sigma$	$\varepsilon_{Nd}(0)$	T_{Nd}(DM), Ma	Rock	Sampling site
1	6-2	7.36	42.6	0.1088	0.511459 ± 9	–23.0	2449	Mudstone	Janisjarvi (upper part of the section)
2	6-3	4.91	25.7	0.1204	0.511522 ± 8	–21.8	2648	Graywacke	
3	114-1	6.22	32.4	0.1161	0.511433 ± 5	–23.5	2671	Mudstone	Harlu (lower part of the section)
4	107-4	5.17	26.2	0.1195	0.511479 ± 5	–22.6	2697	Graywacke	
5	112-1	4.59	25.3	0.1097	0.511398 ± 4	–24.2	2558	Graywacke	
6	10-5	1.29	6.87	0.1138	0.511399 ± 9	–24.2	2661	Arenite	
7	20-1	4.19	20.0	0.1317	0.511447 ± 5	–23.2	3149	Graywacke	Laskela (lower part of the section)
8	21-4	5.27	29.3	0.1130	0.511471 ± 4	–22.8	2532	Mudstone	
9	18-10	5.04	30.1	0.1052	0.511332 ± 4	–25.5	2544	Graywacke	
10	18-3	5.67	31.1	0.1147	0.511418 ± 9	–23.8	2655	Mudstone	
11	17-4	4.59	24.4	0.1182	0.511438 ± 7	–23.4	2721	Graywacke	
12	17-1	2.75	14.5	0.1193	0.511468 ± 9	–22.8	2704	Arenite	
13	23-1	5.22	29.2	0.1125	0.511430 ± 7	–23.6	2582	Graywacke	Impiniemi (upper part of the section)
14	24-4	7.30	41.9	0.1097	0.511430 ± 14	–23.6	2511	Mudstone	
15	25-4	4.23	25.6	0.1040	0.511311 ± 5	–25.9	2546	Arenite	

Note: The Sm–Nd isotopic research method was described in [11]. The procedure blanks were 0.03–0.2 ng for Sm and 0.1–0.5 ng for Nd. The measured $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$ and adjusted to the ratio of $^{143}Nd/^{144}Nd = 0.511860$ in the La Jolla Nd standard. The accuracy of the analyses for Sm and Nd was ±0.5% (2σ), and the isotopic ratios were measured accurate to ±0.5 and 0.005% for $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$, respectively (2σ). The weighted mean values of the $^{143}Nd/^{144}Nd$ ratio in the La Jolla Nd standard (average of 25 measurements) was 0.511862 ± 22 (2σ). In calculating the values of $\varepsilon_{Nd}(0)$ and model ages T_{Nd}(DM), we used the modern values for CHUR after [12] and DM after [13] ($^{143}Nd/^{144}Nd = 0.512638$ and 0.513151, respectively; $^{147}Sm/^{144}Nd = 0.1967$ and 0.2136, respectively). All errors are given at 2σ level.

section contains a higher share of rocks with the Archean T_{Nd}(DM).

Thus, the available geological, geochronological, geochemical, and isotope–geochemical data indicate that the main sources of the terrigenous rocks of the Ladoga Group were Early Proterozoic island-arc complexes of the Svecofennian foldbelt, as well as granitoids of the Archean basement of the Karelian megablock of the Baltic Shield. This, in turn, suggests that terrigenous material of the Ladoga Group was delivered from a proximal provenance.

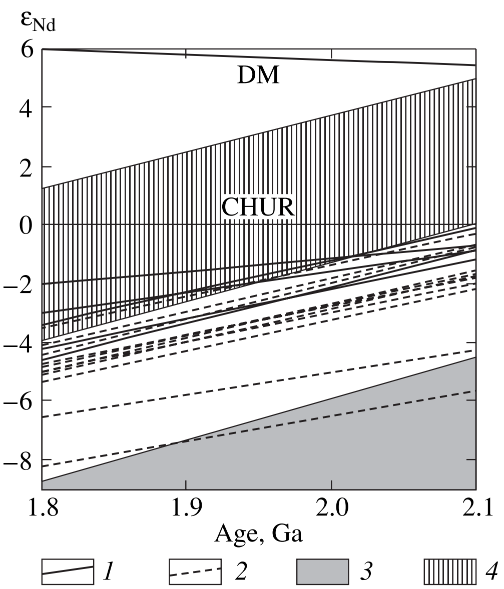

Fig. 2. The ε_{Nd}–age diagram for the metaterrigenous rocks of the Ladoga Group. (*1, 2*) metaterrigenous rocks of the upper and lower parts of the Ladoga Group, respectively; (*3*) field of Nd isotope evolution of the Archean continental crust of the Karelian megablock, Baltic Shield [6]; (*4*) Nd isotope evolution field of the metaterrigenous rocks of southern and central Finland [14].

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