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GEOLOGY

Sources and Provenances of Lower Proterozoic Terrigenous Rocks of the Udokan Group, Southern Kodar–Udokan Depression: Results of Sm–Nd Isotopic Investigations

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The Early Proterozoic was characterized by the development of large epicratonic depressions, which often host large and unique deposits of Cu, Pb, Zn, U, Au, Fe, phosphorites, barite, fluorite, and other mineral resources. In the western part of the Aldan shield, such structures are represented by Early Proterozoic Udokan-type depressions (Kodar–Udokan Depression and Ugui, Oldongso, and Lower Khani graben-synclines). The Kodar–Udokan Depression, the largest epicratonic structure, hosts the unique stratiform deposits of cupriferous sandstones [1]. This depression is located in the southern part of the Chara–Olekma geoblock at the boundary with the Stanovoi suture zone and is composed of the Kodar and Udokan subzones, which are separated by the Chara Depression. The Kodar–Udokan Depression is filled mainly with terrigenous rocks of the Udokan Group, which is the Lower Proterozoic stratotype of Siberia and Russian Far East and, therefore, an age marker on the regional stratigraphic scale [2–4]. Udokan rocks (more than 10 km thick) unconformably overlay Archean metamorphic and magmatic rocks. The Udokan Group is subdivided into the following subgroups (from bottom to top) [3, 5]: the Kodar Subgroup (Ikabia and Ayan formations), the China Subgroup, (Inyr, Chitkanda, Aleksandsrov, and Butun formations), and the Kemen Subgroup (Sakun and Naminga formations). The thickness of these subgroups is 2200, 2000–2300, and more than 4500 m, respectively [3, 5]. Rocks of the Udokan Group metamorphosed under conditions of greenschist facies, reaching amphibolite facies in the marginal parts of the depression [3]. The Kodar Subgroup is composed mainly of terrigenous rocks (polymictic sandstones and shaly mudstones), which are characterized by narrow variations of Al_2O_3 and alkali metal contents, but elevated contents of Mg and ferrous iron (FeO/Fe_2O_3 = 0.2) due to the high organic matter content [5]. The China Subgroup consists of carbonate and terrigenous rocks. The terrigenous rocks are represented by shales and oligomictic and polymictic sandstones, which show wider variations in Al_2O_3 content and higher Na content as compared to the Kodar rocks, and are characterized by an insignificant predominance of ferrous iron over ferric. The high Na content in sandstones of the Upper Chitkanda Subformation suggests their tuffaceous nature [5]. The Kemen Subgroup consists of an intercalation of sandstones, siltstones, and mudstones. As compared to the lower subgroups, these rocks show wider variations in granulometric and chemical composition (from oligomictic sandstones to subsiallites), as well as the predominance of K and ferric iron over Na and ferrous iron, respectively.

The age of the rocks considered can be judged from the following: (1) the Kodar Group rests on granites with an age of 2675 ± 15 Ma [6]; (2) ash interlayers of the China Subgroup contain magmatic zircons with an age of 2180 ± 50 Ma [7]; and (3) the lower part of the Udokan Group is cut by alkaline granites of the Katugin Complex dated at 2066 ± 6 Ma [8], while its upper part (Kemen Subgroup) is cut by granites of the Kodar Complex (Kemen Massif) with an age of 1876 ± 4 Ma [9]. Thus, the upper age limit of the Udokan Group is 2066 ± 6 Ma, while the upper age limit of the Kodar Subgroup is 2180 ± 50 Ma.

Sources and provenances of the terrigenous rocks of the Udokan Group, an issue closely related to that of the source of Cu in the Udokan rocks [3, 5], are ambiguous. According to [1, 4], sedimentary material was delivered to the Kodar–Udokan Depression from the north. However, other authors [3, 10] suggest that the northern (Archean) provenance participated only at the early stages and abruptly gave way to the southern and southwestern provenances in Sakun time. Precisely the

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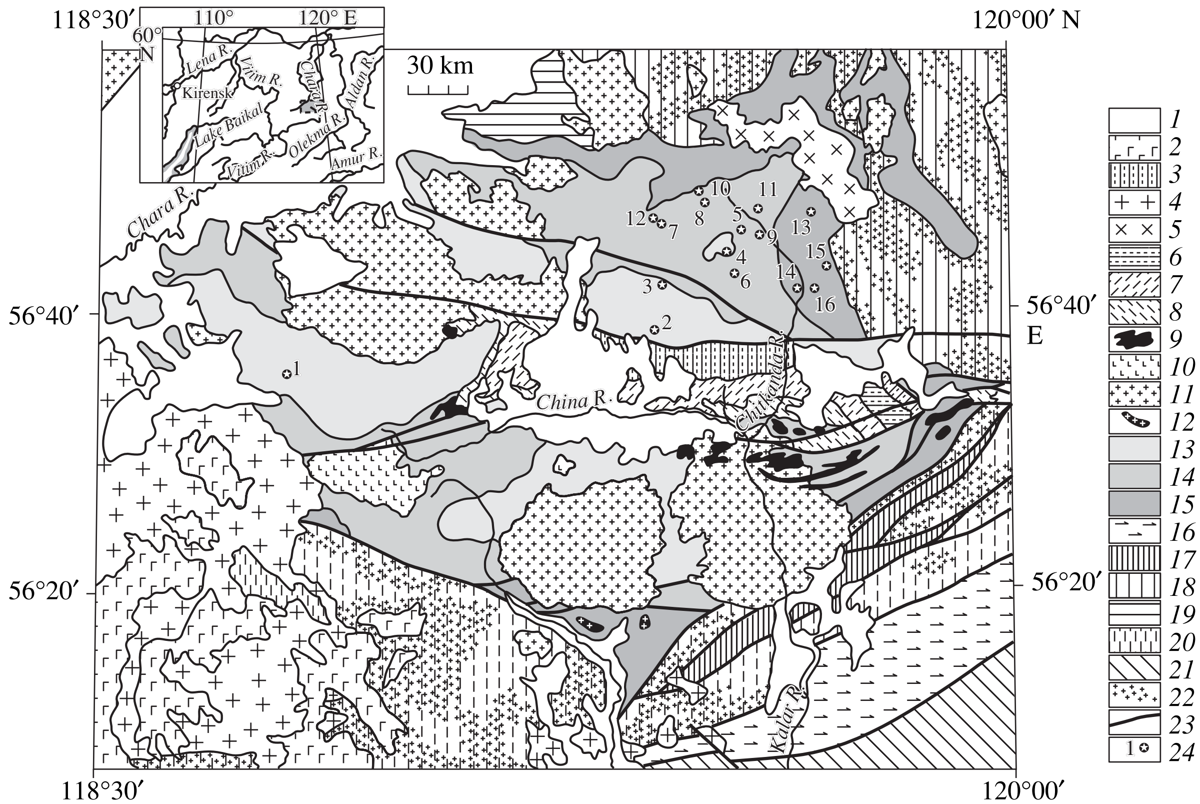

Fig. 1. Schematic geological map of the Udokan subzone of the Kodar–Udokan Depression. (*1*) Quaternary sediments; (*2*) Flood basalts (N_2–Q); (*3*) Jurassic carbonaceous terrigenous rocks; (*4*) granites, granodiorites, granosyenites, and monzonites of the Ingamakit Complex (PZ_3); (*5*) nepheline syenites, granosyenites, and monzonites of the Khani Complex (PZ_3); (*6*) Ordovician variegated rocks; (*7*) Cambrian variegated rocks; (*8*) Vendian variegated rocks; (*9*) gabbrodiabases, gabbros, and diabase porphyrites of the Doross Complex; (*10*) layered plutons of the China Complex; (*11*) granites of the Kodar Complex; (*12*) rare-metal granites of the Katugin Complex; (*13–15*) carbonate–terrigenous rocks of the Udokan Group: (*13*) Kemen Subgroup, (*14*) China Subgroup, (*15*) Kodar Subgroup; (*16*) anorthosites of the Kalar Complex; (*17*) weakly metamorphosed volcanosedimentary rocks of the Subgan Complex; (*18*) tonalite–trondhjemite orthogneisses of the Olekma Complex; (*19*) Chara sequence: garnet–biotite and garnet–hypersthene biotite (± sillimanite, ± cordierite) plagiogneisses, mafic crystalline schists, quartzites, and magnetite quartzites; (*20*) Kalar sequence: garnet–biotite (± sillimanite, ± hypersthene) plagiogneisses with intercalations and lenses of two-pyroxene crystalline schists, calc-silicate rocks, quartzites, and magnetite quartzites; (*21*) metamorphic and magmatic complexes of the Dzhugdzhur–Stanovoi fold system; (*22*) areas of predominant development of the Precambrian granitoids; (*23*) faults; (*24*) sampling sites for Sm–Nd isotope–geochemical investigations (outcrop numbers in the map are as in table).

Sakun stage was responsible for the formation of copper deposits [3].

Sm–Nd isotopic investigations were carried out to decipher sources and provenances of the terrigenous rocks of the Kodar Subzone of the Kodar–Udokan Depression. The $^{147}Sm/^{144}Nd$ ratio is constant in the clastic sedimentary rocks (≈0.11 ± 0.02), which significantly differs from the value in mantle sources (≥0.2). The ratio is almost unaffected by weathering, transport, diagenesis, and metamorphism. Therefore, Nd isotope data make it possible to determine the *average* model age of provenances and their location. Consequently, one can identify sources of sedimentary material and the lower age boundary of the corresponding sequences [11, 12].

Sm–Nd isotopic investigations were carried out with sandstones and shales. Special attention was given to samples bearing lithological, petrographic, and petrochemical evidence of volcanogenic origin. A total of 21 samples were studied, including 5 samples from the Kemen Subgroup, 11 samples from the China Subgroup, and five samples from the Kodar Subgroup. Sampling sites are shown in Fig. 1, while obtained Sm–Nd isotope data are presented in table and Fig. 2.

As seen in the table, terrigenous rocks of the Udokan Group have T_{Nd} = 2.3–2.7 Ga. The majority of the studied samples, regardless of their composition and position in the sequence, have T_{Nd}(DM) within 2.3–2.6 Ga, thus indicating the contribution of the disintegration products and/or volcanogenic material with an average Early Proterozoic Nd model age in their formation. The youngest values of T_{Nd}(DM) = 2.3 Ga were obtained for the rocks of the Lower (Kodar) Subgroup of the Udokan Group: metasandstones of the Ikabia Formation and metamudstones of the Ayan Formation. Petrographic study showed that the Ikabia metasand-

Results of Sm–Nd isotope–geochemical investigations of the terrigenous rocks of the Udokan Group, the Kodar–Udokan Depression

Outcrop number	Sample no.	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ $\pm 2\sigma$	$\varepsilon_{Nd}(0)$	$\varepsilon_{Nd}(T)$	$T_{Nd}(DM)$, Ma	Rock
Sakun Formation									
1	323-50	5.18	30.26	0.1034	0.511251 ± 6	–27.06	–3.11	2611	Mudstone
1	323-34	6.32	36.17	0.1056	0.511294 ± 2	–26.22	–2.83	2604	Sandstone
2	438-5	6.58	41.78	0.0951	0.511150 ± 6	–29.02	–2.96	2559	Sandstone
3	432-15	5.55	34.19	0.0982	0.511175 ± 2	–28.53	–3.24	2592	Sandstone
4	288-3	3.12	16.82	0.1121	0.511332 ± 5	–25.48	–3.76	2712	Mudstone
Undifferentiated Aleksandrov and Butun formations									
5	277-1	2.34	11.73	0.1205	0.511535 ± 9	–21.51	–1.96	2629	Mudstone
Chitkanda Formation									
6	425-74	6.99	37.71	0.1120	0.511419 ± 6	–23.79	–2.04	2583	Sandstone
6	425-69	5.24	30.53	0.1077	0.511401 ± 11	–24.13	–1.28	2504	Sandstone
7	303-24	4.53	26.01	0.1053	0.511374 ± 5	–24.66	–1.19	2486	Mudstone
8	285-2	7.80	33.23	0.1419	0.511766 ± 6	–17.00	–2.95	–	Mudstone
9	279-3	13.57	76.60	0.1071	0.511324 ± 3	–25.64	–2.63	2598	Sandstone
10	278-4	3.64	20.79	0.1059	0.511443 ± 8	–23.32	0.01	2404	Mudstone
10	278-3	6.10	35.73	0.1032	0.511412 ± 7	–23.92	0.09	2388	Sandstone
11	299-6	3.57	21.29	0.1012	0.511304 ± 4	–26.03	–1.51	2490	Sandstone
11	299-1	3.34	18.83	0.1074	0.511357 ± 6	–24.99	–2.06	2559	Mudstone
12	305-29	6.61	36.88	0.1083	0.511408 ± 8	–23.99	–1.28	2507	Sandstone
Ayan Formation									
13	422-3	6.05	32.38	0.1129	0.511602 ± 10	–20.21	1.32	2332	Sandstone
14	267-9	6.23	33.85	0.1113	0.511303 ± 10	–26.04	–4.11	2733	Sandstone
Ikabia Formation									
15	446-2	5.62	30.86	0.1101	0.511466 ± 8	–22.87	–0.64	2468	Sandstone
16	268-12	11.24	68.08	0.0998	0.511435 ± 6	–23.46	1.43	2286	Mudstone
16	268-10	5.39	30.99	0.1050	0.511395 ± 5	–24.26	–0.72	2452	Sandstone

Note: The technique of Sm–Nd investigations is described in [13]. The laboratory 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 $^{143}Nd/^{144}Nd = 0.511860$ in the La Jolla Nd standard. The measurement accuracy was ±0.5% (2σ) for Sm and Nd contents, ±0.5% for $^{147}Sm/^{144}Nd$, and ±0.005% for $^{143}Nd/^{144}Nd$. The average $^{143}Nd/^{144}Nd$ values in the La Jolla standard were 0.511862 ± 22 (2σ, $n = 25$). The $\varepsilon_{Nd}(0)$ and model ages $T_{Nd}(DM)$ were calculated using the present-day values for CHUR ($^{143}Nd/^{144}Nd = 0.512638$, $^{147}Sm/^{144}Nd = 0.1967$) [10] and DM ($^{143}Nd/^{144}Nd = 0.513151$, $^{147}Sm/^{144}Nd = 0.2136$) [11]. All errors are given at 2σ-level. The values of $\varepsilon_{Nd}(T)$ were calculated for 2066 Ma (upper age limit of the deposition of the terrigenous rocks of the Udokan Group).

stones (Sample 268-12, table) contain significant admixture of volcanogenic material, while the Ayan metamudstones (Sample 422-3, table) represent pudding tuffaceous mudstone.

In the ε_{Nd}–T diagram (Fig. 2), the Nd evolution curve of the sandstones and shales of the Udokan Group are plotted either in the field of the metavolcanic rocks of the Fedorovka Sequence (2006 ± 3 Ma), which occurs in the central Aldan Shield and belongs to the typical Early Proterozoic island-arc complexes [13, 14], or between this field and the field of the Archean tonalite–trondhjemite gneisses of the Chara–Olekma geoblock, which occupy no less than 40% of the Aldan Shield. Hence, the terrigenous rocks of the Udokan Group were mainly derived from rocks similar to the Fedorovka metavolcanic rocks (the indicators of the Early Proterozoic juvenile crust of the Aldan Shield [13]) and the Archean tonalite–trondhjemite orthogneisses of the Olekma Complex in terms of Nd isotopic composition.

Data and maps of Sm–Nd isotope provinces of the Aldan Shield [13] show that Archean clastic material could only be delivered from the Chara–Olekma geoblock; i.e., this material was transported from north to south. (Hereinafter, the transport direction and provenance location are shown in present-day coordinates.) More difficult to determine are the source areas of the Early Proterozoic material. Given that terrigenous sequences of the Udokan Group ceased to accumulate at the onset of the formation of Early Proterozoic island-arc associations (including the Fedorovka island arc) in the eastern Aldan Shield and the western part of the shield consists mainly of the Archean continental crust [13], the terrigenous material could only be delivered from the south and/or southwest, i.e., from the modern Dzhugdzhur–Stanovoi and Baikal fold systems.

It is noteworthy that the smallest admixture of the early Proterozoic juvenile crustal component is typical of the upper parts of the Udokan Group, in particular, of the Sakun Formation of the Kemen Subgroup (T_{Nd}(DM) = 2.6–2.7 Ga). The Early Proterozoic material was delivered to the Kodar–Udokan Depression from primitive island arcs at the early stages and from active continental margins or mature island arcs in Sakun time. Geochemical data are consistent with this assumption. According to [5], the terrigenous rocks of the lower horizons of the Udokan Group were formed by erosion of Na-series magmatic rocks, while the upper horizons were related to disintegration of the K–Na-series magmatic rocks.

Thus, the data indicate that the terrigenous rocks of the Udokan Subzone of the Kodar–Udokan Depression were derived mainly from two main sources: (i) Archean rocks of the Chara–Olekma geoblock of the Aldan Shield and (ii) rocks of the Early Proterozoic continental crust. The Early Proterozoic material was presumably transported to Udokan-type sedimentation basins from volcanic arcs and active continental margins of Early Proterozoic orogens, which existed at that time at the sites of the present-day Dzhugdzhur–Stanovoi and, possibly, Baikal fold systems. Hence, the Kodar–Udokan Depression cannot be ascribed to the intracratonic structures. This structure was presumably situated at the passive continental margin [15]. The terrigenous rocks of the Udokan Group were accumulated during the mature (post-spreading) evolutionary stage of the adjacent oceanic structure, when juvenile (island-arc) Early Proterozoic crust already existed.

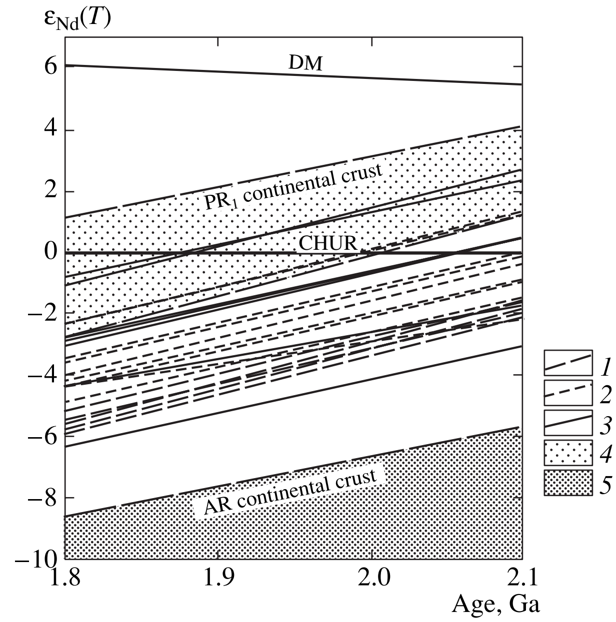

Fig. 2. The ε_{Nd}–T diagram for metaterrigenous rocks of the Udokan Group of the Kodar subzone, Kodar–Udokan Depression: (1–3) subgroups of the Udokan Group: (*1*) Kemen, (*2*) China, (*3*) Kodar; (*4*) Early Proterozoic acid–intermediate metavolcanic rocks of the Fedorovka sequence of the Aldan granulite–gneiss terrane; (*5*) Archean gneissic granites and tonalites of the Olekma granite–greenstone terrane.

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