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Composition and Geodynamic Nature of the Protoliths of Diamondiferous Rocks from the Kumdy-Kol Deposit of the Kokchetav Metamorphic Belt, Northern Kazakhstan

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Abstract—The distribution of rare earth elements was analyzed in the Early Cambrian diamondiferous calc-silicate rocks and gneisses, calciphyres, and marbles of the Kumdy-Kol deposit. These data were compared with the lithogeochemical characteristics of the sedimentary assemblages of weakly metamorphosed Late Precambrian graphite-bearing sedimentary rocks of the Kokchetav metamorphic belt. The obtained results allowed us
1 to suppose that the protoliths of the Kumdy-Kol rocks were compositionally similar to the Late Precambrian graphite-bearing terrigenous–carbonate and sand–shale sequences of the continental shelf of the Kokchetav microcontinent, some of which were transformed in a subduction zone into diamondiferous rocks.

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INTRODUCTION

Petrological and geochronological studies established that the diamondiferous calc-carbonate rocks of the Kokchetav metamorphic belt in northern Kazakhstan were formed in the Early Cambrian in a subduction zone at P = 40–70 kbar and T = 1100–1200°C, i.e., at depths of more than 100 km [1–9]. It was found [1–6, 10–12, etc.] that microdiamonds (20–100 μm, occasionally up to 300 μm in size) are widespread in the calc-silicate rocks, garnet–mica gneisses and schists, and garnet–pyroxene rocks.

The calc-silicate rocks are composed of dolomite, pyroxene, garnet, and phlogopite, which form a banded structure with alternating pyroxene–garnet, pyroxene, garnet, and carbonate layers, from 0.5–2.0 to 10 cm thick. Their accessory minerals are rutile, apatite, zircon, graphite, micas, and diamond. Inclusions of graphite–mica, graphite–diamond, diamond–mica, and rutile–mica intergrowths were detected in pyroxene. The garnet–mica gneisses and schists are composed of quartz, potassium feldspar, plagioclase, garnet, pyroxene, and micas. The accessory minerals are diamond, graphite, titanite, apatite, zircon, and rutile. The garnet contains inclusions of phengite, graphite, plagioclase, carbonate, titanite, zircon, rutile, and microdiamond. The garnet–pyroxene rock is dominated by garnet and clinopyroxene with minor carbonate and potassium feldspar. The rock shows a banded structure made up of alternating layers enriched in garnet or pyroxene. Diamond is confined mainly to garnet-rich interbeds and occurs both as inclusions in garnet and in the interstitial space. The garnet often contains inclusions of carbonate, micas, graphite, apatite, zircon, rutile, pyroxene, and microdiamond, as well as diamond–graphite, diamond–mica, diamond–zircon, pyroxene–mica, graphite–mica, and rutile–mica intergrowths.

The diamondiferous gneisses and schists contain detrital zircon with a distinct zoning related to repeated metamorphic alterations, including those in the subduction zone. An age of 530 ± 7 Ma was obtained for zircon rims, whereas their cores vary in age from 2000 to 580 Ma [3]. In terms of structure and genesis, the diamondiferous rocks are closely related with the Early Precambrian granitic gneisses of the basement and the Late Precambrian sedimentary cover of the Kokchetav microcontinent. They form (Fig. 1) a complex thrust sheet structure of the Kokchetav subduction–collision zone [7–10]. The cover of the microcontinent comprises quartzite–schist, terrigenous–carbonate, and sand–shale sequences containing abundant detrital zircon with ages of 2000–850 Ma [13], which was also found in the diamondiferous gneisses [3].

This paper focuses on the identification of protoliths for the metamorphic rocks of the Kumdy-Kol diamond deposit and considers the rare earth systematics of a wide spectrum of rocks (garnet–biotite–kyanite, garnet–biotite, garnet–pyroxene–biotite, garnet–biotite–muscovite, and garnet–biotite gneissic quartzites; car-

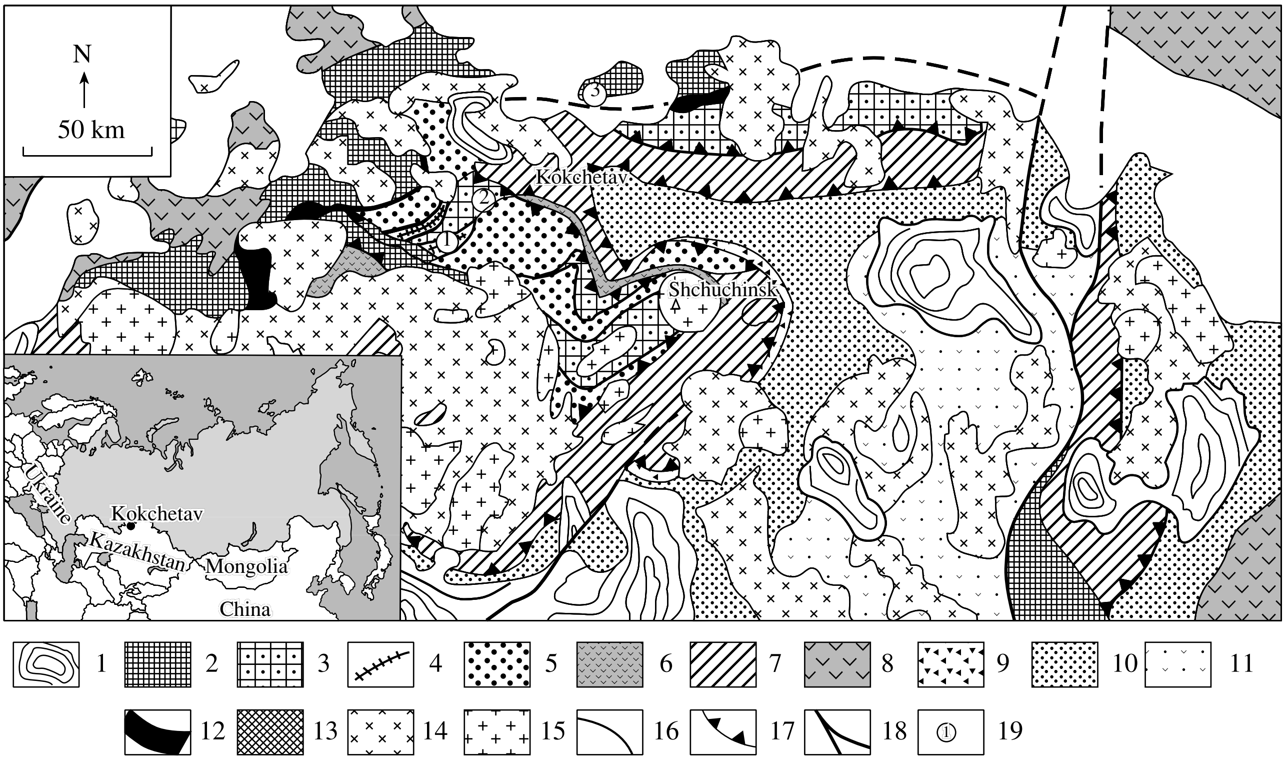

Fig. 1. Tectonic scheme of northern Kazakhstan and location of the objects studied [10]. (*1*) Devonian–Late Paleozoic volcanosedimentary basins; (*2*) and (*3*) fragments of the Kokchetav and Shatskii (northeast of Kokchetav) microcontinents: (*2*) retrogressed 2
under greenschist-facies conditions and (*3*) with sediments metamorphosed in the subduction zone up to the amphibolite facies; 3 4 5 4
(*4*) and (*5*) megamelange belt (deep fragments of a paleosubduction zone): (*4*) diamond-bearing gneisses and coesite eclogites and (*5*) granitic gneisses and mica schists with lenses of eclogites and garnet amphibolites; (*6*) Vendian (?) volcanosedimentary rocks of an accretion prism; (*7*) Early Ordovician accretion prism; (*8*) Vendian–Cambrian island-arc volcanosedimentary rocks (Ishim arc in the west and Seletinskaya arc in the east); (*9*) late Arenigian syntectonic olistostrome; (*10*) Ordovician volcanosedimentary rocks of the Stepnyak Depression; (*11*) Ordovician volcanogenic complexes of the Stepnyanskaya arc; (*12*) Late Cambrian–Tremadocian ophiolites of the Zlatogorskii complex; (*13*) Middle–Late Cambrian Krasnomaiskii complex of alkaline ultrabasic rocks; (*14)* Silurian–Ordovician granites; (*15*) Devonian granites; (*16*) deformed planes of Late Cambrian–Early Ordovician faults; (*17*) late Arenigian–early Caradocian frontal thrust of the Kokchetav massif over the Stepnyak Depression; (*18*) Late Paleozoic strike-slip; and (*19*) sampling site: 1, rocks of borehole C-42 in the Kumdy-Kol diamond deposit; 2, sand–shale rocks of the Ilekty Range near the Kokchetav–Bereznyakovka highway; and 3, terrigenous–carbonate rocks of the Sharyk Formation near the Alekseevka settlement.

bonate–silicate rocks; calciphyres; and marbles). Academician N.L. Dobretsov incited a comparative geochemical study of the metasedimentary rocks and the weakly altered Late Precambrian sediments of the Kokchetav metamorphic belt.

Previous work [14] has addressed diamondiferous rocks only. Based on mineralogical and petrographic investigations, clayey calc-dolomites and shales were suggested as protoliths for the calc-silicate rocks and biotite gneisses, respectively. Subsequently [12], taking into account the behavior of incompatible elements during metamorphism, it was noted that the diamondiferous calc-silicate rocks could not be produced by the metamorphism of a clay–carbonate mixture only. The high-potassium compositions of pyroxene and phengite from the diamondiferous calc-silicate rocks can be explained by assuming the influence of a dense potassium-rich fluid on the carbonate rocks. This fluid could be generated by the melting of the protolith of garnet–biotite gneisses and schists in a subduction environment.

COMPOSITION AND PALEOGEOGRAPHIC SETTING OF THE FORMATION OF SEDIMENTARY ROCKS FROM NORTHERN KAZAKHSTAN

Weakly metamorphosed Late Precambrian sedimentary sequences are widespread in the area of the Kokchetav metamorphic complex. In terms of composition, they are subdivided into quartzite–terrigenous, terrigenous–carbonate, and sand–shale sequences. Several schemes were proposed for the stratification of the sedimentary sequences. According to the most widely accepted scheme [15], the terrigenous–carbonate and quartzite–schist sequences form the Ilekty Group, the lower part of which is made up of carbonaceous schists, dolomites, marbles, and siderites and distinguished as the Sharyk Formation. The upper part of the group includes the quartzites, quartz metasandstones, and quartz–chlorite–sericite schists of the Kokchetav Formation. The sand–shale sequence has a limited distribution and shows the characteristics of both the Sharyk Formation (presence of graphite-bearing carbonate and terrigenous rocks) and the Kokchetav Formation (abundance of zircon- and rutil-bearing quartzites and quartz sandstones).

The quartzite–schist sequence (Kokchetav Formation) exhibits a regressive tendency of sedimentation, i.e., an increase in the size of detrital material, the degree of its abrasion, and the fraction of monomineralic lithologies. From bottom to top, the role of cross-bedding and internal erosions increases, and the red coloring becomes more persistent. Changes in the structure of the sequence are accompanied by sequential rhythms [16]. The quartzite–schist sequence is dominated by sericite, sericite–quartz, and graphite–quartz schists, which are often interbedded with quartzites. There are minor amounts of chlorite schists and limestone lenses. Quartzites occur as lenses and layers up to 10–50 m thick. Taking into account folding and fault tectonics, the thickness of the sequence is up to several hundreds of meters in the stratotype section of the Kokchetav Formation at the city of Ilekty. The lower age boundary of the Kokchetav Formation is constrained by the absence of detrital zircon younger than 850 Ma [13]. The quartzite–schist sequence is the most widespread. It was correlated by many authors with the complexes of the platform cover and is, therefore, an indicator of the platform stage of the development of the Kokchetav microcontinent.

The terrigenous–carbonate sequence (Sharyk Formation) includes carbonaceous and blastopsammitic schists, which account for 60–70% of its volume. Less common are dolomites, marmorized limestones, and carbonate schists with interbeds of siderites and quartzites. Owing to the low metamorphic grade, the initial composition of sedimentary rocks can be readily identified. The schists were formed after clayey sediments; quartzites and sericite quartzites, after sandy deposits; and dolomites and limestones, after carbonate sediments. The sequence is up to several hundred meters thick. It was accumulated under deep-sea sedimentation conditions near a continental slope.

The sand–shale sequence shows the characteristics of both the Kokchetav and Sharyk formations. In a quarry near the Bereznyakovka settlement in the Ilekty Range, it includes abundant rhythmically bedded rocks with rhythms of two types. One of them begins from well-sorted medium-grained quartz sandstones, which are changed by fine-grained sandstones and siltstones with a carbonate cement. The sandstones are enriched in rutile and zircon fragments. The siltstones are rich in carbonaceous matter. The thickness of the rhythms is from parts of a centimeter to a few centimeters. Other rhythms are 1 m thick and formed by repeated alternation of quartz sandstones (up to 50 cm thick) with abundant zircon and rutile fragments, sandstones with interbeds of zircon and rutile fragments (up to 50 cm thick), and quartz sandstones (up to 30–40 cm thick). Layers (up to several meters thick) of black carbonaceous carbonate rocks intercalated with quartz–rutile–zircon and quartz sandstones were documented among the rocks with first-type rhythms.

GEOCHEMISTRY OF THE ROCKS OF THE KUMDY-KOL DEPOSIT AND SEDIMENTARY SEQUENCES: RESULTS AND DISCUSSION

The targets of our study were rocks from borehole C-42 in the Kumdy-Kol diamond deposit. The main petrographic varieties (Table 1) are aluminosilicate rocks of intermediate and silicic compositions: garnet–biotite, garnet–biotite–kyanite, and two-mica gneisses. There are also minor amounts of quartzites, carbonate–silicate, and carbonate rocks. For comparative analysis, we used graphite-bearing terrigenous–carbonate and sand–shale rocks sampled in quarries near the Alekseevka settlement (40 km north of Kokchetav) and in the Ilektin Range near the Kokchetav–Bereznyakovka highway, respectively (Fig. 1).

The major elements were measured at the Analytical Center of the Joint Institute of Geology, Geophysics, and Mineralogy, Siberian Branch of the Russian Academy of Sciences (analyst A.N. Kireev), and REE contents were determined by ICP MS at the Laboratory of Isotope Geochemistry of the Vinogradov Institute of Geochemistry, Siberian Branch of the Russian Academy of Sciences (analyst G.P. Sandomirova).

The statistical analysis of variations in the chemical composition of rocks under the conditions from medium-temperature to granulite facies of metamor- 4
phism, inclusively, indicated a relatively inert behavior of major elements, except for alkalis. These investigations supported the plausibility of the wide application of petrochemical diagrams for the identification of the initial nature of metamorphic rocks.

The initial composition of metamorphic rocks of the Kumdy-Kol deposit was reconstructed using the methods of Neelov [17] and Yudovich and Ketris [18, 19].

In the Neelov [17] diagram, the metamorphic rocks (Table 1) fall within the following groups arranged in the sequence of decreasing relative abundance.

Table 1. Compositions of metasedimentary rocks from the Kumdy-Kol diamond deposit from borehole C-42 and carbonates of the Sharyk Formation; oxides are in wt %, and trace elements, in ppm

Compo-nent	C-42-16	C-42-20	C-42-29	C-42-13	C-42-37	C-42-52	C-42-38	C-42-51	C-42-45	C-42-39	C-42-25	C-42-42	C-42-32	C-42-50	C-42-53	C-42-14	Sh-1
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2	58.1	59.01	61.06	63.26	62.88	65.64	60.31	26.33	67.46	65.21	35.65	54.2	60.48	33.43	6.94	64.3	0.14
TiO_2	0.878	0.776	0.85	0.439	0.68	0.402	0.902	0.17	0.554	0.574	0.334	0.268	0.79	0.225	0.03	0.511	0.03
Al_2O_3	16.04	14.07	15.03	12.14	13.84	11.9	14.85	4.24	13.56	14.14	5.32	7.75	15.59	5.95	0.96	12.15	0.19
Fe_2O_3	9.13	7.47	8.41	6.59	7.2	11.32	8.34	3.18	5.49	6.39	6.04	3.42	7.23	2.09	2.72	7.93	0.44
MnO	0.145	0.163	0.13	0.213	0.19	0.396	0.155	0.125	0.129	0.115	0.48	0.176	0.125	0.107	0.182	0.214	0.03
MgO	3.12	4.22	2.83	3.23	3.11	3.43	3.66	16.38	3.12	2.51	11.92	9.99	3.32	14.87	19.97	3.02	22.73
CaO	3.3	6.94	2.57	8.27	4.91	2.9	4.66	25.06	3.11	3.36	27.46	15.69	4.47	24.4	29.37	5.86	30.61
Na_2O	1.68	0.87	0.92	0.86	0.92	0.7	1.29	0.3	1.27	0.69	0.45	0.32	1.06	0.3	0.3	0.51	0.30
K_2O	4.49	4.43	4.41	3.04	3.01	2.26	2.35	1.54	3.24	3.83	0.4	3.17	2.58	1.58	0.36	3.53	0.07
P_2O_5	0.119	0.149	0.187	0.168	0.14	0.042	0.118	0.083	0.071	0.155	0.038	0.07	0.093	0.047	0.044	0.155	0.03
LOI	2.51	1.75	3.7	1.77	2.88	0.85	2.58	22.84	1.57	1.96	12.04	4.63	3.21	17.23	39.39	1.54	45.80
Total	99.57	99.9	100.15	100.00	99.81	99.86	99.25	99.95	99.59	98.98	100.14	99.69	98.98	99.92	99.94	99.75	100.03
La	19.29	34.55	23.40	34.97	30.79	2.30	37.58	10.35	3.83	36.15	3.12	19.22	45.61	13.29	12.11	29.35	3.64
Ce	56.87	72.33	76.78	73.51	69.16	5.29	84.11	21.86	13.71	90.93	8.07	41.85	109.49	24.87	24.56	64.79	1.98
Pr	4.95	7.94	5.97	7.99	7.29	0.61	8.84	3.01	1.57	8.74	1.36	4.71	10.54	2.89	3.12	6.87	2.04
Nd	19.25	31.34	21.78	27.28	26.57	2.86	32.02	11.54	7.44	32.19	6.59	17.46	38.09	11.59	11.81	24.82	1.72
Sm	4.71	6.16	4.85	6.10	5.21	1.96	6.83	2.46	2.44	7.09	2.11	3.26	7.59	2.26	2.16	5.56	1.26
Eu	1.23	1.30	0.95	0.79	0.91	0.62	1.26	0.56	0.56	1.14	0.53	0.74	1.50	0.52	0.52	0.72	0.92
Gd	5.61	6.32	4.80	5.73	5.29	3.91	6.25	2.42	3.15	6.17	2.59	2.62	6.90	2.05	1.91	5.98	1.66
Tb	0.92	0.90	0.80	1.06	0.87	0.81	1.01	0.32	0.61	0.99	0.48	0.36	1.02	0.30	0.24	1.09	1.34
Dy	5.82	5.60	5.23	6.71	5.43	5.20	6.35	1.82	4.17	6.02	3.29	2.13	6.13	1.86	1.28	7.19	1.34
Ho	1.26	1.15	1.15	1.49	1.16	1.10	1.34	0.38	0.92	1.23	0.73	0.45	1.27	0.41	0.26	1.60	1.3
Er	3.58	3.37	3.39	4.49	3.28	3.12	3.83	1.09	2.74	3.42	2.09	1.23	3.52	1.19	0.70	4.71	1.17
Tm	0.54	0.50	0.53	0.71	0.49	0.45	0.59	0.16	0.43	0.52	0.31	0.18	0.53	0.18	0.09	0.72	1.05
Yb	3.75	3.42	3.55	4.69	3.38	3.05	4.06	1.15	2.96	3.52	2.00	1.29	3.68	1.22	0.65	4.77	0.92
Lu	0.55	0.52	0.53	0.66	0.48	0.43	0.57	0.17	0.44	0.49	0.29	0.18	0.51	0.18	0.09	0.67	0.87
HI	0.448	0.378	0.394	0.303	0.345	0.36	0.399	0.288	0.291	0.324	0.328	0.211	0.39	0.247	0.535	0.32	
TI	0.55	0.055	0.57	0.036	0.049	0.034	0.061	0.04	0.041	0.041	0.063	0.035	0.051	0.038	0.031	0.042	
Fe/Mn	56.87	41.39	58.43	27.94	34.23	25.82	48.6	23.0	38.44	50.18	11.37	17.5	52.24	17.64	13.5	33.47	

Note: Gneisses: (1, 2, 5, 7, 10) garnet–biotite–kyanite, (3, 13) garnet– biotite, (4, 16) garnet–pyroxene–biotite, and (9) garnet–biotite–muscovite; (6) garnet–biotite gneissic quartzite; (11, 12) carbonate–silicate rocks; (8, 14) calciphyres; (15) marble; and (16) average composition of carbonates of the Sharyk Formation (Sh-1). The HI, TI, and Fe/Mn parameters are discussed in the text.

(1) Graywacke silty sandstones and siltstones (garnet–biotite, kyanite–garnet–biotite, and two-mica gneisses).

(2) Carbonate rocks (calciphyres and marbles).

(3) Carbonatolites with minor sandy material (carbonate–silicate rocks).

(4) Graywacke silty sandstones and siltstones, carbonatolites with an admixture of tuff material of intermediate composition (garnet–muscovite–biotite gneisses, garnet–biotite gneissic quartzites, and carbonate–silicate rocks).

Using the methods of Yudovich and Ketris [18], the following initial rock varieties were distinguished among the metamorphic aluminosilicate rocks of intermediate and silicic compositions (Table 1).

(1) Clay rocks (siallites).

(2) Clay rocks with an admixture of sandy material (miosilites).

(3) Siltstones with minor tuffaceous (volcanomictic) material of intermediate composition (pseudosilites).

(4) Siliceous shales (clayey silicites).

The following parameters were calculated: hydrolysate index, $HI = (Al_2O_3 + TiO_2 + Fe_2O_3 + FeO)/SiO_2$, which is considered as a universal indicator for the identification of the compositions of any terrigenous and siliceous rocks, and titanium index, $TI = TiO_2/Al_2O_3$, which allows us to additionally constrain the primary nature of metasedimentary rocks.

The recalculations of the compositions of metamorphic aluminosilicate rocks of intermediate and silicic compositions using the two methods yielded similar results.

The depth of deposition of the protoliths of metased-
4 imentary rocks was estimated using the Fe/Mn facies indicator [19]. Its value decreases with increasing depth
4 in a basin from the shelf to pelagic facies. Since the value of this parameter is no higher than 40 in the rocks studied, it is reasonable to suppose that the protolith sediments were deposited in a deep environment.

The distribution of REE was evaluated in three main types of reconstructed metasedimentary rocks (Table 1, Fig. 2).

(1) Clay rocks

The homogenizing (averaging) influence of sedimentary processes resulted in almost uniform REE distributions in the sedimentary rocks, especially in the clay rocks. The compositional uniformity indicates that the REE characteristics of typical shales reflect the average composition of the upper part of the crust [20]. In terms of REE distribution patterns (Fig. 2a), the metapelites are very similar to the PAAS (post-Archean Australian shales, which were formed under deep conditions [20]), although their total REE content is somewhat higher. The enrichment is probably due to the fine elutriation of deep sediments [11]. The influence of seawater as an REE source could be responsible for the increase of heavy REE content [21].

A comparison of REE distribution patterns in the metamorphosed shales of the Kumdy-Kol deposit (Fig. 2a) and shales of the Sharyk Formation (Fig. 3a) shows their similarity with respect to average parameters and a rather considerable scatter for individual samples. The latter may indicate either the compositional heterogeneity of the sources or facies transitions related to depth 4
changes, which is characteristic of shelf regions.

Geochemical differences between the metamorphosed clay rocks from the Kumdy-Kol deposit and clays from the sand–shale sequence are clearly seen in the spider diagram (Fig. 4) normalized to the average composition of post-Archean shales (PAS, [22]). The normalized contents for the metamorphosed clay rocks are close to one, i.e., they are similar in composition to PAS. In contrast, the Sharyk shales are strongly depleted in phosphorus and enriched in Zr and Hf. The enrichment in these elements is explained by the specific conditions of deposition in the subplatform basin, where favorable conditions existed for the formation of zircon–rutile placers. For instance, sandstone sample IL-7 from the sand–shale sequence containing zircon and rutile fragments shows high contents of Zr (up to 960 ppm) and Hf (up to 20.39 ppm).

The REE distribution patterns of quartz sandstones from the sand–shale sequence are similar to those of PAAS, although at lower REE contents (Table 2, Fig. 3b). This indicates that the clay cement of the sandstones is similar in composition to PAAS. The low content of phosphorus in the clay rocks of the Sharyk Formation (Fig. 4) can be attributed to the deposition of sediments in the subplatform basin, because phosphorus is usually accumulated in deeper environments characterized by low sedimentation rates [23].

(2) Carbonate rocks

In contrast to clays and sands, carbonate rocks usually do not correspond to the composition of the upper part of the crust, but rather reflect the exodynamic and physicochemical conditions of sedimentation. The REE characteristics of metacarbonate rocks are similar to each other and represented by gently sloping patterns with a minor LREE enrichment and a weak Eu anomaly (Fig. 2b). Similar REE distribution patterns were observed, for instance, in the subplatform carbonates of the Vendian–Cambrian Bokson Group (East Sayan) [22] and Sharyk Formation (Fig. 3c), but the total REE contents of the metacarbonate rocks are significantly higher. This is explained by the quiet-water conditions in the deep basin; in particular, high REE contents may indicate low sedimentation rates [23]. Such an environment can occur at the base of a shelf slope. For the sake of comparison, also shown is the field of REE patterns for the carbonatites of the Late Precambrian Penchenga complex of the Yenisei Range [24], because carbonatite

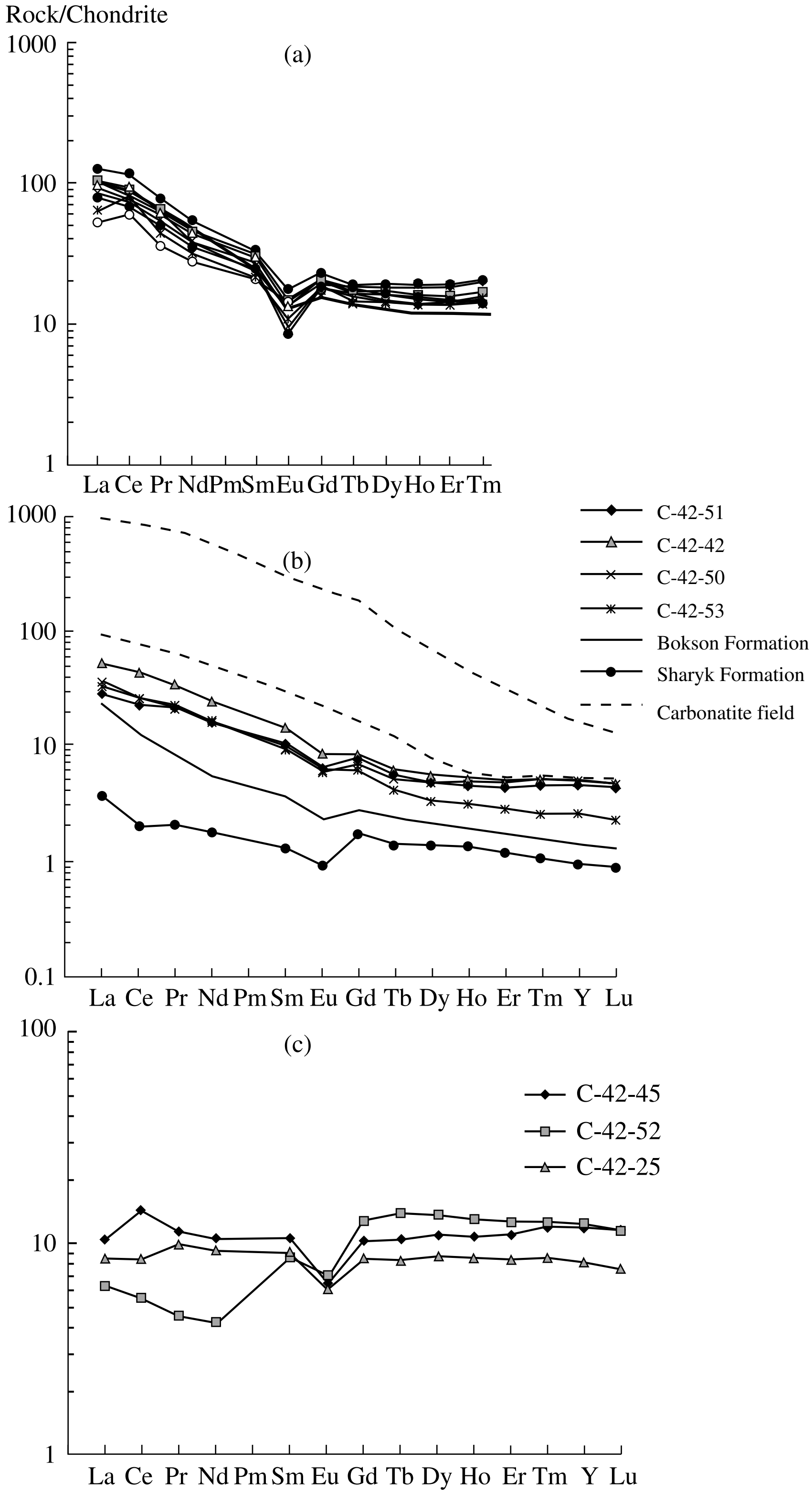

Fig. 2. Chondrite-normalized [27] REE distribution patterns for the metasedimentary rocks of the Kumdy-Kol deposit: (a) metapelites, (b) metacarbonates, and (c) metapelites and metacarbonates with an initial admixture of tuffaceous material of intermediate composition.

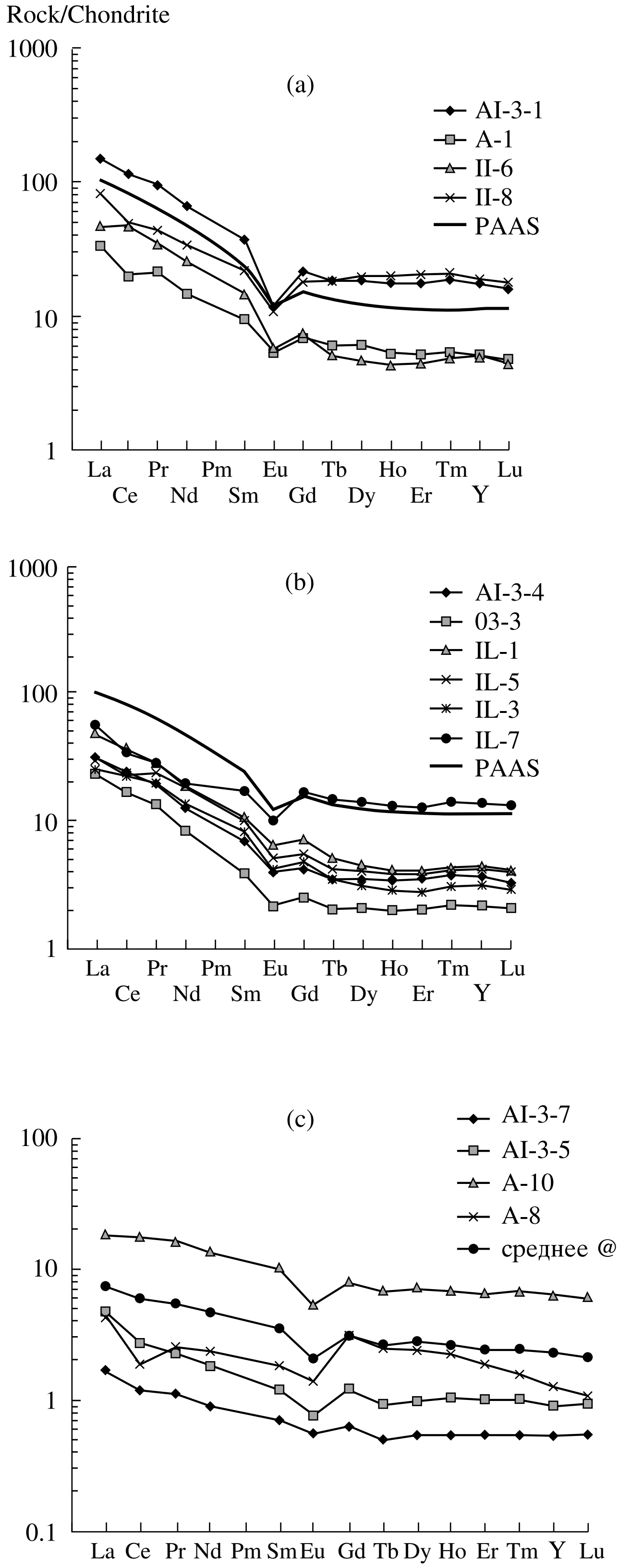

Fig. 3. Chondrite-normalized [27] REE distribution patterns for the rocks of the Sharyk Formation: (a) siltstones and mudstones, (b) quartz sandstones, and (c) carbonate rocks.

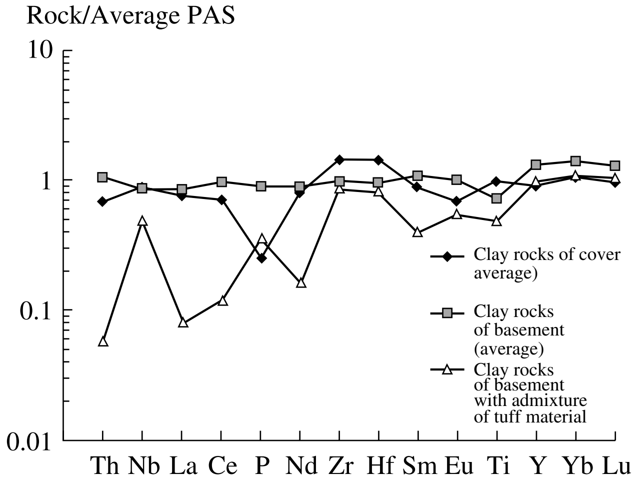

Fig. 4. REE distribution patterns normalized to the average composition of post-Archean shales (PAS) [23].

magmas were also considered [25, 26] as possible protoliths for the metacarbonate rocks of the Kumdy-Kol deposit. It can be seen in Fig. 2b that the carbonatites are an order of magnitude richer in REE compared with the metacarbonates; therefore, it is more reasonable to suppose a chemogenic sedimentary origin for the protoliths of the metacarbonate rocks.

The REE distribution patterns of carbonate and clay rocks from the terrigenous–carbonate sequence (Sharyk Formation) show a considerable scatter in total REE abundances (Figs. 3a, 3c), which is characteristic of rocks formed at variable depths of a continental shelf.

(3) Clayey rocks with an admixture of volcanomictic material of intermediate composition

The rocks with an admixture of intermediate volcanomictic material usually have flat REE distribution patterns and a distinct Eu anomaly (Fig. 2c). Perhaps, the rocks of this type were significantly depleted after deposition in Th and light and middle REE (especially sample C-45-52). This effect was probably related to submarine hydrothermal systems, which promote REE depletion by their precipitation with iron and magnesium hydroxides [22].

The limited occurrence of initial rocks of such a type suggests moderate intermediate volcanism cogenetic with sedimentation. It is conceivable that it occurred in the remote island arc beneath which the Kokchetav microcontinent was eventually subducted.

Thus, the obtained results allow us to suggest that the protoliths of the diamondiferous rocks of the Kumdy-Kol deposit were compositionally similar to 1
terrigenous–carbonate and sand–shale rocks and were formed in a deep-sea environment. Perhaps, the terrigenous–carbonate, sand–shale, and quartzite–schist

Table 2. Compositions of sedimentary rocks from the cover of the Kokchetav microcontinent (IL, sand–shale sequence and A, Sharyk Formation); oxides are in wt % and trace elements, in ppm

Component	A l-3-1	A-1	IL-6	IL-8	A l-3-4	03-3	IL-1	IL-5	IL-3	IL-7	A l-3-7	A l-3-5	A-10	A-8
	shales				quartz sandstones						carbonate rocks			
SiO_2	59.07	60.32	82.15	56.92	91.68	96.34	90.08	95.02	90.19	92.10	0.06	0.27	6.95	0.10
TiO_2	1.02	0.99	0.68	1.19	0.08	0.05	0.13	0.05	0.90	0.97	0.03	0.03	0.05	0.03
Al_2O_3	20.69	20.55	9.49	24.01	4.71	1.73	5.58	2.90	4.48	3.47	0.01	0.22	1.29	0.34
Fe_2O_3	7.65	7.40	1.23	2.88	1.01	1.06	0.74	0.70	1.53	1.24	0.45	0.43	1.64	0.45
MnO	0.09	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.04	0.03
MgO	1.13	0.78	0.71	1.41	0.21	0.10	0.21	0.10	0.48	0.10	22.69	22.70	20.16	22.81
CaO	0.30	0.10	0.08	0.08	0.07	0.04	0.16	0.08	0.11	0.06	30.88	30.68	28.70	30.26
Na_2O	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
K_2O	4.69	4.87	3.87	9.18	1.53	0.40	1.73	0.37	1.81	1.05	0.07	0.08	0.39	0.07
P_2O_5	0.09	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.03	0.03	0.03	0.03
Ba	0.20	0.03	0.07	0.09	0.01	0.00	0.02	0.00	0.02	0.03	0.00	0.00	0.00	0.00
LOI	5.03	1.41	1.68	3.98	0.66	0.30	1.07	0.70	0.96	0.84	45.84	45.62	40.59	45.94
Total	99.95	99.48	99.94	99.75	99.97	99.91	99.71	99.82	99.67	99.81	100.01	100.01	99.82	99.97
Sc 45	1.50	2.16	1.50	1.65	1.01	0.51	1.67	1.15	1.82	3.59	0.24	0.27	3.60	0.37
V 51	127.74	152.42	31.90	176.78	9.69	4.41	13.01	6.85	8.07	18.87	2.45	3.20	18.11	2.62
Cr 52	106.60	105.97	38.80	97.02	34.86	58.73	41.13	45.51	16.87	30.47	87.38	15.19	69.08	46.90
Co 59	10.64	40.51	0.92	1.14	0.42	0.43	0.59	0.52	0.48	0.81	0.34	0.59	5.97	9.78
Ni 60	21.56	91.22	4.01	15.51	1.96	11.06	11.31	16.46	3.49	7.71	1.11	0.96	14.91	2.76
Cu 63	16.64	96.99	5.83	19.70	3.85	4.22	2.22	5.40	9.49	9.82	0.63	0.68	8.00	0.40
Zn 66	37.89	244.65	20.59	15.91	2.52	1.17	5.26	2.02	13.05	13.85	4.93	8.30	7.88	28.25
Ga 71	21.25	26.52	10.72	31.51	4.67	1.22	4.17	2.75	3.82	3.30	0.04	0.11	2.15	0.05
Ge 74	1.70	2.44	1.54	2.41	1.02	0.91	1.16	0.88	1.14	1.27	0.08	0.06	0.26	0.11
Rb 85	32.51	91.10	48.75	132.14	39.12	9.03	46.56	10.48	54.36	31.23	0.06	0.61	14.15	0.25
Sr 88	20.72	1.75	1.49	0.73	7.38	2.85	1.10	2.46	1.38	6.06	38.71	34.14	50.61	42.10
Y 89	36.26	8.74	8.47	44.06	6.76	4.27	8.20	7.87	6.05	29.23	1.61	2.85	13.18	4.75
Zr 90	238.38	187.73	523.14	256.15	58.12	64.07	88.10	48.88	70.12	960.73	1.19	3.22	32.43	2.00
Nb 93	22.00	14.89	11.54	20.04	1.95	1.16	2.70	1.61	2.32	9.80	0.07	0.27	1.51	0.11
Mo 95	1.12	0.74	3.07	0.35	0.25	1.74	1.39	2.55	1.20	1.85	0.29	0.19	0.39	0.19
Sn 120	1.76	4.12	2.30	5.43	0.46	0.17	0.67	0.32	0.44	1.35	n.d.	0.00	0.32	n.d.
Sb 121	0.55	0.82	2.14	3.80	0.75	0.10	0.79	1.15	5.47	3.64	0.12	0.16	1.99	0.11
Cs 133	4.41	1.30	1.24	4.87	0.91	0.53	1.08	1.04	0.78	3.35	0.13	0.23	1.61	0.32
Ba 138	0.60	0.18	0.17	0.68	0.12	0.08	0.16	0.15	0.11	0.51	0.02	0.04	0.23	0.04
Hf 178	5.98	4.57	12.02	5.93	1.49	1.35	1.95	1.20	1.52	20.39	n.d.	0.09	0.85	0.02
Ta 181	1.62	1.15	0.79	1.26	0.16	0.07	0.19	0.12	0.13	0.28	0.04	0.33	0.17	0.03
W 184	1.41	2.45	1.12	2.32	0.28	1.07	0.91	1.22	0.43	1.72	0.09	0.12	0.34	0.10
Tl 205	0.57	0.72	0.41	1.12	0.17	0.04	0.19	0.06	0.22	0.14	0.01	0.00	0.06	0.01
Pb 208	9.57	7.30	1.13	1.81	4.53	0.90	1.00	11.08	4.96	18.65	0.52	0.54	11.80	0.21
Th 232	22.41	3.88	4.34	9.11	1.95	1.21	2.86	2.10	2.98	6.35	0.07	0.15	1.90	0.09
U 238	3.70	2.59	1.91	1.43	0.67	0.64	0.76	0.90	1.24	2.85	0.14	0.30	0.90	0.75

sequences characterize different depth levels of the Late Precambrian shelf slope of the Kokchetav microcontinent.

CONCLUSIONS

A comparison of lithogeochemical characteristics of the sedimentary assemblages of the Kokchetav massif and the analysis of REE distribution in the metasedimentary deposits of the Kumdy-Kol deposit lead us to the following conclusions.

—The lithological composition and REE distribution patterns of the sand–shale rocks suggest that they were formed under shallow-water conditions of the continental shelf, whereas the terrigenous–carbonate rocks of the Sharyk Formation were deposited under deep quiet-water conditions of the continental shelf.

—The REE distribution patterns of metapelites from the Kumdy-Kol deposit are well correlated with those of PAAS and indicate sediment formation under quiet-water conditions of a deep basin. High REE contents in the metacarbonate rocks (calciphyres and marbles) of the Kumdy-Kol deposit compared with REE contents in the carbonate rocks of platform and subplatform deposits also indicate the accumulation of their sedimentary protoliths in a deep basin.

—The analysis of REE distribution patterns in the Early Cambrian diamondiferous rocks of the Kumdy-Kol deposit and their comparison with the lithogeochemical characteristics of sedimentary assemblages of weakly metamorphosed Late Precambrian graphite-bearing sedimentary rocks from northern Kazakhstan allowed us to suggest that the protoliths of the diamondiferous rocks were similar in composition to the Late Precambrian terrigenous–carbonate and sand–shale rocks, which were formed in a continental shelf environment. Some of them were transformed to diamond-bearing rocks in the subduction zone.

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