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Lithochemistry of the Paleoisland-Arc Complexes in the Orogenic Belts of the Russian Far East

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Abstract—New chemical data on terrigenous rocks from the Russian Far East paleobasins different in age and geodynamic style were compared with similar data on the recent and old sediments accumulated in well-known geodynamic settings. The generalization and geodynamic interpretation of the original results revealed the island-arc nature of the studied objects and demonstrated the possibility of using the lithochemical approach, in combination with other geological data, for recognizing island-arc settings in fragments of paleobasins that represent structural elements of past orogenic belts.

Key words: chemical composition, terrane, complex, terrigenous rocks, geodynamic settings, island arc, Far East.

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INTRODUCTION

The chemical study of terrigenous rocks is of great significance for establishing the sources of detrital material; determining the rock composition of provenances; and, eventually, for defining their paleogeological formation environments.

The bulk chemical composition of terrigenous rocks is one of their most important features. Following [28], the study of the regularities in the distribution of the rock-forming chemical components in terrigenous rocks is referred to further as *lithochemistry* (by analogy with the petrochemistry of volcanic rocks).

As was established for the recent and ancient sediments, the chemical composition of the terrigenous rocks (especially, sandstones) is to a significant extent determined by the composition of the source rocks and their position in certain geodynamic settings. Moreover, the mineral composition of the sediments during their postsedimentary transformations changes toward the formation of associations most stable subsequently in the supergene zone, whereas the chemical composition of rocks remains practically unchanged.

The island-arc settings are usually recognizable based on several features: the paleogeological position of the studied sediments, the structure and composition of their sequences, and the petrochemistry of the volcanics. The purpose of this work is to reveal the chemical peculiarity of the terrigenous rocks from the island-arc complexes different in age and origin in the Russian Far East and, using them as an example, to demonstrate the possibility of their application for recognizing similar sedimentation settings in past basins. The method of the paleotectonic reconstructions based on the lithochemistry of the terrigenous rocks should play a particular role in the study of the Phanerozoic volcano-sedimentary rocks constituting terranes of uncertain nature.

Several well-known terranes of the Far East whose island-arc nature was largely substantiated by studies of volcanic rocks represent the most suitable objects for such reconstructions. Although the lithochemical data alone are insufficient to identify unambiguously an island-arc setting, they may serve, combined with other features, as a reliable criterion for this purpose in the future.

OBJECTS AND METHODS

The extensive original data derived from the chemical study of the terrigenous rocks from the different-age island-arc complexes of the Russian Far East served as a basis for this work. Four terranes with extensive analytical data were selected as the objects for these studies and attempts to demonstrate the suitability and reliability of the proposed method for recognizing the island arc settings in the ancient orogenic belts based on the lithochemical analysis. The Lower Cretaceous and Lower Cretaceous–Cenozoic sandy and clayey–silty rocks from the Olyutor Terrane of

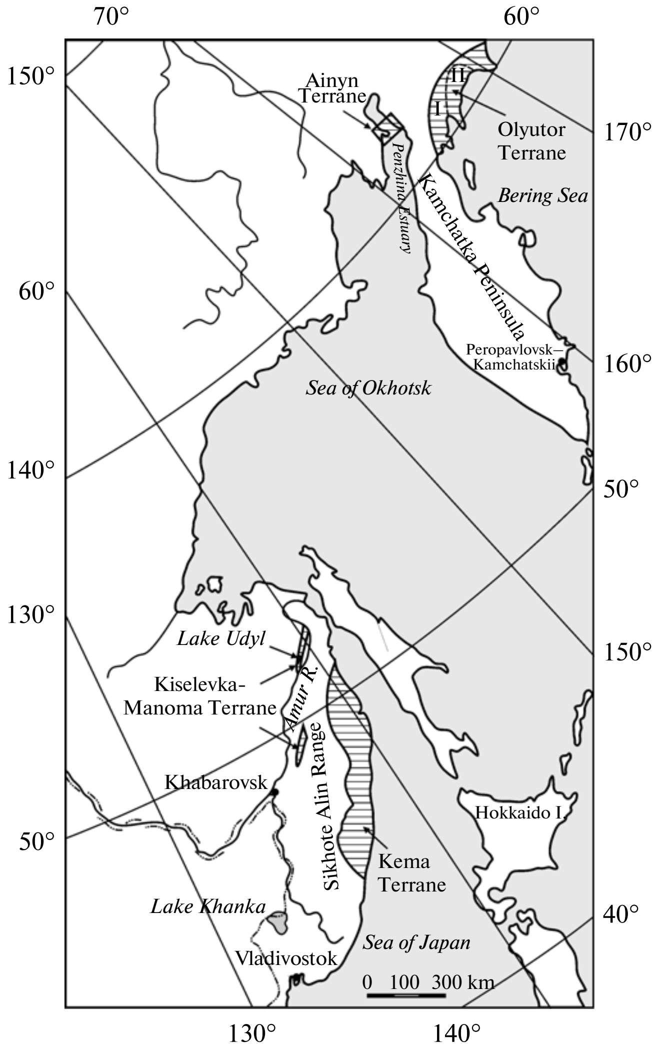


Fig. 1. Schematic location of the studied objects. Mineralogical–geochemical provinces of the Olyutor Terrane: (1) Northern, (2) Southern.

eastern Kamchatka, the Ainyn Terrane in the Penzhina Estuary coast, and the Kema and Kiselevka–Manoma terranes (Udyl fragment) of Sikhote Alin were subjected to studying (Fig. 1). The main attention was paid to sandy rocks; clayey–silty rocks represented by mudstones, silty mudstones, and siltsones recieved less attention. Such a selection is explained by the fact that sandstones are the most informative with respect to the type and rock composition of the provenances and their geodynamic settings and sedimentation in depositional basins [29–31, 33, and others].

The rock samples used in this work were collected from natural outcrops and mine workings during field works of 1978–2005. The samples that were the least (according to petrographic observations) altered by secondary processes were used for the analytical studies.

The petrographic composition of the selected samples was analyzed under a polarization microscope. The contents of the rock-forming oxides were determined by the conventional weight chemical method at the Far East Geological Institute, Far East Division, Russian Academy of Sciences and the Geological Institute, Russian Academy of Sciences. In total, 1156 samples of sandy and clayey rocks were analyzed.

The chemical composition of the terrigenous rocks was interpreted using the widely accepted well-tested techniques proposed in [29, 30, 33, and others], which enable the identification of analogs of recent geodynamic settings in ancient basins.

PRINCIPAL GEOLOGICAL–STRUCTURAL FEATURES OF THE EXAMINED OBJECTS

Inasmuch as most of the examined objects are characterized by their complex tectonic structure and are poorly exposed, their stratigraphic columns are composed of numerous fragments that characterize different tectonic blocks.

The *Ainyn Terrane* is located in the northern coastal part of the Penzhina Estuary (Sea of Okhotsk), where it occupies the largest part of the Penzhina Range being an element of the Early Cretaceous Koryak orogenic belt [23]. The rocks constituting the terrane are studied in the Elistratov and Mamet peninsulas. The intensely deformed Cretaceous sedimentary and volcano-sedimentary rocks constituting a system of slices and duplexes are interpreted, as a whole, as components of the accretionary prism [18]. The lower Cretaceous rocks of the Ainyn Terrane are overlain by upper Cretaceous sequences, which are regarded as the sedimentary cover of the accretionary prism. The terrane rocks are traceable in the form of isolated outcrops or continuous bands divisible into the following lithotectonic complexes [21, 22] (Fig. 2).

The *lower turbidite complex* is composed of inequigranular sandstones, siltstones, conglomerates, gravelstones, mixtites, turbidites, contourites, and underwater landslide sediments. The *tuffaceous–sedimentary complex* consists of alternating tuffs, volcanomictic conglomerates, gravelstones, sandstones, and siltstones with rare turbidite members. The *upper turbidite complex* is represented by alternating members of turbidites, contourites, and siltstones with intercalations of tuffs, tuff breccias, volcanomictic sandstones, and gravelstones. The *coarse-clastic complex* is dominated by sandstones and siltstones accompanied by subordinate conglomerates, gravelstones, rare tuffs, coal seams, and carbonaceous mudstone intercalations.

The *Olyutor Terrane* is located in the southern part of the Koryak Highland extending in the ENE direction along the Bering Sea coast for 500 km. The terrane is ascribed to the Mesozoic–Cenozoic Sakhalin–

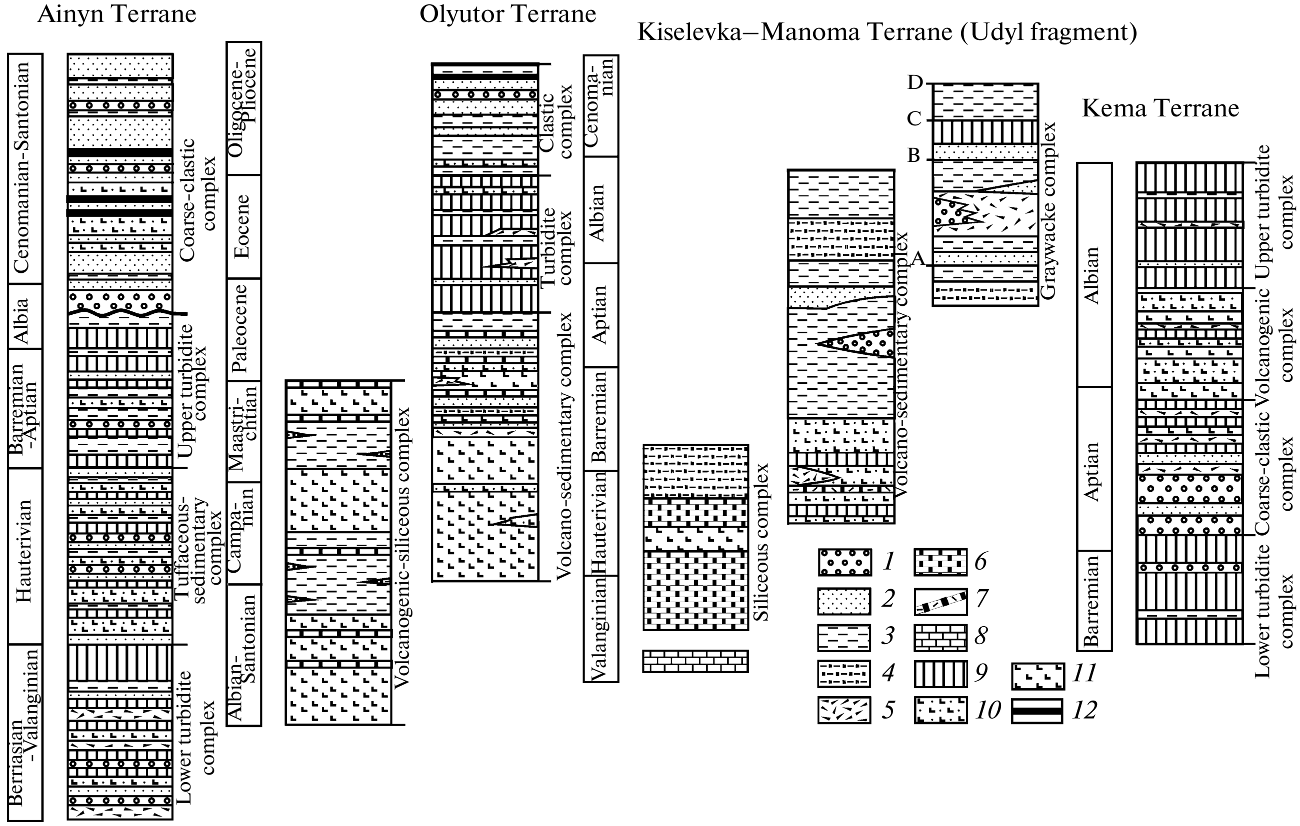


Fig. 2. Summary lithostratigraphic columns of the island-arc rocks in the studied objects.

(*1*) conglomerates and gravelstones; (*2*) sandstones; (*3*) siltstones and mudstones; (*4*) siliceous–clayey rocks; (*5*) mixtites; (*6*) cherts; (*7*) tuffaceous siliciliths; (*8*) limestones; (*9*) turbidite; (*10*) tuffs and tephroids; (*11*) basalts and basaltic andesites; (*12*) coal.

For the Udyl fragment of the Kiselevka–Manoma Terrane, the sequences are as follows: (A) mudstones, (B) mixtites, (C) sandstones, (D) siltstones.

Kamchatka orogenic belt, which is separated from the Koryak orogenic belt by the Vatyna Thrust [1]. The geological section of the terrane comprises large juxtaposed allochthonous nappes [24] composed of Lower Cretaceous–Neogene complexes that were formed in different facies settings and, probably, far away from their present-day position. The following lithothectonic complexes are definable in this terrane [1, 3, 4, 10, 19, 20] (Fig. 2).

The *volcanogenic–siliceous complex* consists of basalts, hyaloclastites, lava breccias, jaspers, cherts, and siliceous–clayey rocks with a subordinate amount of clays, sandstones, and limestones. The *volcanogenic–sedimentary complex* is made up of basalts, lava breccias, tuffs, volcanic sandstones, siltstones, cherts, and clayey and siliceous–clayey rocks. The *turbidite complex* is represented by thick members of turbidites intercalated with siltstones, sandstones, gravelstones, tuffs, and mixtites. The *clastic complex* includes sandstones, siltstones, gravelstones, conglomerates, tuffs, and coal seams.

The *Kiselevka–Manoma Terrane* of the Albian–Cenomanian accretionary prism is located in the lower Amur River region extending for 700 km in the northeastern direction in form of a discontinuous band 20–40 km wide along both sides of the Amur River. The terrane is formed by packages of tectonic slices of Jurassic and Lower Cretaceous siliceous and siliceous–clayey rocks with basalt and limestone bodies and of Lower Cetaceous siltstones and turbidites [2, 11, 12] (Fig. 2). The Hauterivian–Cenomanian volcano-sedimentary island-arc rocks are established at the northeastern flank of the terrane in the Lake Udyl area (*Udyl fragment*). This area comprises the tectonically juxtaposed fragments of island-arc, oceanic, and continental–marginal lithotectonic complexes, which allows the terrane to be considered as representing a complex accretionary prism with an imbricate thrust structure. All the rocks of the terrane are subdivided into several complexes [11, 12].

The *siliceous complex* represents a fragment of the oceanic basement of the island arc. It is composed of pelagic radiolarian jaspers, cherts, and their clayey varieties with subordinate alkaline basalts and limestones. Detrital rocks are practically missing from the complex. The *volcano-sedimentary complex* consists of alternating tuffs, tephroids, volcanic sandstones, siltstones, turbidites, mixtites, tuffosiliciliths, clayey and siliceous–clayey rocks, and rare basaltic flows. The *graywacke complex* is characterized by the notable facies variability. It consists of four sequences differing in their composition and structure: (1) mudstone (mudstones and siliceous mudstones), (2) mixtite (mixtites, clayey rocks, sandstones, tuffs, rare members of turbidites, and underwater landslide sediments), (3) sandstone (sandstones, clayey rocks, turbidites, rare mixtites, underwater landslide sediments, and tuffs), and (4) siltstone (siltstones and mudstones with thin sandstone and rare mixtite intercalations).

The *Kema Terrane* is located in the eastern part of the Sikhote Alin Range extending for 850 km in the form a band up to 80 km wide along the Sea of Japan coast. The fragments of the Kema Terrane accessible for immediate observations are exposed in erosion windows among the volcanic rocks of the Late Cretaceous East Sikhote Alin belt. The terrane is composed of Barremian(?)–Albian rocks represented by widespread turbidites, siltstone and mixtite members, flows of basic volcanics, and their pyroclastic products (Fig. 2). These rocks are considered as representing sediments of the back-arc basin of the Early Cretaceous Moneron–Samarga island-arc system [5–7]. The terrane consists of several lithotectonic complexes.

The *lower turbidite complex* is composed of turbidite members separated by beds of siltstone, sandstone, gravelstone, and underwater landslide sequences. The *coarse-clastic complex* consists of small-pebbled conglomerates, gravelstones, sandstones, mixtites, rare turbidite and underwater landslide sediment members, and single basaltic flows. The *volcanogenic complex* is largely represented by basalts; their tuffs; and tephroids with rare members of volcamonictic sandstones, turbidites, underwater landslide sediments, and mixtites. The *upper turbidite complex* consists of thick turbidite, rare sandstone, siltstones, mixtite, and underwater landslide sediment members.

COMPOSITION AND LITHOCHEMICAL CHARACTERISTICS OF THE TERRIGENOUS ROCKS

Each of the examined objects is provided with a brief description of the petrographic composition of the terrigenous rocks, which determines their lithochemical properties.

For the lithochemical characteristics of the sandy and clayey–silty rocks, the average contents of the main rock-forming oxides and some petrochemical coefficients (modules) presented in the table are used. All the data on the studied objects are grouped according to the distinguished lithothectonic complexes.

Based on the rock-forming components, the sandstones of the *Ainyn Terrane* are classed with polymictic varieties despite some differences in their composition. Their detrital constituent is represented by quartz; feldspars; fragments of terrigenous, siliceous, metamorphic, acid, and ultramafic intrusive rocks; acid, intermediate, and rare basic volcanic rocks; volcanic glass; and ore minerals. According to classification [26], the sandstones largely belong to true graywackes, feldspar, feldspar–quartz, and quartz–feldspar graywackes and, less commonly, to quartz graywackes. The differences between the complexes are primarily notable in the quartz content, which ranges from 18 to 33% in the lower turbidite complex and rarely exceeds 10% in all the others. For the feldspar, these values are 7–20% and 3–60%, respectively. The lower turbidite complex is dominated (in sum up to 95%) by acid plagioclases (albite and oligoclase) and potassic feldspars (orthoclase and microcline). The other complexes contain mainly basic and intermediate plagioclases (locally up to 90% of all the feldspars) with less common acid plagioclases (up to 55%) and potassic feldspars (up to 50%). Among the rock fragments, which constitute 55–70% in the lower turbidite complex, the dominant role belongs to sedimentary and metamorphic rocks (up to 50%), as well as to acid and intermediate volcanics (up to 40%). Basic volcanic and serpentinized rocks occur in subordinate amounts (up to 5%). In the rocks of the younger complexes, the amount of rock fragments amounts to 90% with the main role belonging to basic and intermediate volcanics (up to 70%). In addition, there are terrigenous, acid intrusive, and metamorphic rocks; gabbroids; ultramafic rocks; cherts; tuffs; and volcanic glass, the contents of which vary within a significant range.

Depending on the lithological type of the clayey–silty rocks (siltstones, mudstones, and silty mudstones), the content of the silt-sized detrital material in them varies from 3 to 60–80 vol %. By its composition, the detrital component of the clayey rocks is close to sandstones, although they are characterized by a higher content of quartz and feldspars, and the clasts include cherts, basic and intermediate volcanics, ultramafics, and heavy minerals. The clay component is mostly represented by smectite, chlorite, subordinate mixed-layer minerals of the mica–smectite and smectite–chlorite types, and rare hydromica.

In terms of the chemical composition of the terrigenous rocks, the lower turbidite and overlying complexes substantially differ from each other [10, 21, 22] (table). These differences are most evident in the composition of the sandstones. For example, the primary relatively high SiO_2 content (61.47%) in the rocks of the lower turbidite complex substantially decreases to 57.92, 55.93, and 56.01% in the tuffaceous–sedimentary, upper turbidite, and coarse-clastic complexes, respectively. In addition, there are notable differences in the total Fe contents (6.86% vs. 7.36–8.92%, respectively), MgO (1.78% vs. 2.78–3.59%), and CaO (4.63% vs. 5.16–5.65%). The observed differences are

The average compositions (wt %) of the terrigenous rocks from different complexes of the Russian Far East

Complex	n	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	Cao	Na_2O	K_2O	P_2O_5	L.O.I.	H_2O	Total	HM	TM	FM	NAM
Sandy rocks																			
Ainyn Terrane																			
Lower turbidite	6	61.47	1.01	16.93	4.29	2.57	0.14	1.78	4.63	2.98	1.02	n.a.	3.34	n.a.	100.16	0.41	0.059	0.14	0.24
Tuffaceous–sedimentary	24	57.92	0.83	15.47	3.75	3.61	0.15	2.78	5.16	2.76	1.53	0.16	5.89	n.a.	100.01	0.41	0.054	0.18	0.28
Upper turbidite	19	55.93	1.00	16.54	5.24	3.68	0.15	3.59	5.17	2.95	0.94	n.a.	4.47	n.a.	99.66	0.48	0.060	0.23	0.24
Coarse-clastic	15	57.01	0.89	17.03	4.23	3.30	0.11	3.36	5.65	2.49	0.93	n.a.	4.98	n.a.	99.98	0.45	0.052	0.19	0.20
Olyutor Terrane																			
Northern province																			
Volcanogenic–siliceous	11	55.12	0.76	16.37	3.94	4.56	0.35	4.67	5.11	3.06	1.28	n.a.	4.92	n.a.	100.14	0.47	0.046	0.25	0.27
Volcano-sedimentary	21	57.49	0.56	15.36	4.11	3.78	0.22	3.57	4.87	3.83	0.79	n.a.	5.48	n.a.	100.06	0.41	0.036	0.20	0.30
Turbidite	28	58.67	0.69	14.96	3.19	4.00	0.12	3.71	4.38	3.62	1.44	n.a.	5.16	n.a.	99.94	0.39	0.046	0.19	0.34
Detrital	310	61.53	0.68	14.51	3.89	2.22	0.09	2.88	3.19	2.53	1.48	n.a.	6.89	n.a.	99.89	0.35	0.047	0.15	0.28
Southern province																			
Volcano-sedimentary	19	58.56	0.76	17.19	2.60	4.53	0.21	3.30	2.87	3.27	1.14	n.a.	5.05	n.a.	99.48	0.43	0.044	0.18	0.26
Turbidite	29	65.02	0.59	14.64	2.16	3.77	0.09	1.90	2.47	3.72	1.56	n.a.	4.05	n.a.	99.97	0.33	0.040	0.12	0.36
Detrital	82	65.11	0.64	13.69	2.58	3.16	0.08	2.44	2.12	2.66	1.54	n.a.	5.88	n.a.	99.90	0.31	0.047	0.13	0.31
Kiselevka–Manoma Terrane (Udyl fragment)																			
Volcano-sedimentary	8	58.14	0.65	19.16	4.32	1.56	0.33	2.71	2.41	6.87	0.96	0.30	2.04	0.31	99.77	0.45	0.034	0.15	0.41
Graywacke, sequences:																			
mixtite	20	67.05	0.67	13.26	3.04	2.40	0.15	2.29	1.56	3.15	1.93	0.22	3.46	0.39	99.56	0.29	0.051	0.12	0.38
sandstone	20	66.90	0.67	12.99	2.82	2.87	0.09	2.55	1.92	2.61	2.00	0.29	3.80	0.20	99.73	0.29	0.051	0.13	0.36
Kema Terrane																			
Lower turbidite	21	74.34	0.30	9.82	1.91	1.78	0.07	1.19	2.12	2.34	1.60	0.13	3.89	0.30	99.79	0.19	0.031	0.07	0.40
Coarse-clastic	30	74.62	0.35	10.24	1.33	2.03	0.06	1.65	1.79	2.12	1.93	0.12	3.11	0.33	99.67	0.19	0.034	0.07	0.40
Volcanogenic	10	73.26	0.38	10.76	1.83	1.35	0.07	1.33	2.24	2.25	1.60	0.31	4.15	0.37	99.89	0.20	0.035	0.06	0.36
Upper turbidite	20	77.30	0.25	8.18	1.21	0.98	0.06	1.09	2.70	2.02	1.52	0.08	3.94	0.40	99.73	0.14	0.031	0.04	0.43

Table. (Contd.)

Complex	n	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	Cao	Na_2O	K_2O	P_2O_5	L.O.I.	H_2O	Total	HM	TM	FM	NAM
Clayey–silty rocks																			
Ainyn Terrane																			
Lower turbidite	3	61.29	0.85	17.50	3.05	2.89	0.10	2.09	2.40	1.61	1.66	n.a.	5.97	n.a.	99.40	0.40	0.049	0.13	0.19
Tuffaceous–sedimentary	5	58.54	0.92	16.13	3.39	3.65	0.11	2.53	3.58	1.97	1.47	0.12	5.01	2.75	100.17	0.41	0.057	0.17	0.21
Upper turbidite	7	58.64	0.92	16.93	4.50	2.59	0.11	2.75	3.41	1.66	1.20	n.a.	6.85	n.a.	99.56	0.43	0.054	0.17	0.17
Coarse-clastic	2	55.53	0.94	19.03	3.67	4.11	0.09	3.77	3.94	1.85	0.84	n.a.	5.85	n.a.	99.62	0.50	0.049	0.21	0.15
Olyutor Terrane																			
Northern province																			
Volcanogenic–siliceous	6	56.16	0.71	16.76	2.88	4.75	0.20	4.16	5.23	3.64	2.02	n.a.	3.23	n.a.	99.74	0.45	0.042	0.21	0.34
Volcano-sedimentary	10	59.58	0.71	15.60	3.44	3.99	0.25	2.83	3.94	2.83	1.13	n.a.	5.62	n.a.	99.92	0.40	0.046	0.18	0.25
Turbidite	94	60.26	0.72	15.22	2.96	4.05	0.11	3.17	2.76	2.39	2.08	n.a.	6.08	n.a.	99.80	0.38	0.047	0.17	0.29
Detrital	110	60.34	0.76	15.23	4.06	2.38	0.09	2.57	2.67	2.03	1.76	n.a.	7.75	n.a.	99.64	0.37	0.050	0.15	0.25
Southern province																			
Volcano-sedimentary	8	63.12	0.65	15.47	1.63	4.32	0.17	2.08	1.23	4.04	2.01	n.a.	5.13	n.a.	99.85	0.35	0.042	0.13	0.39
Turbidite	32	62.23	0.78	16.14	2.96	4.13	0.08	2.15	1.56	2.80	2.33	n.a.	4.86	n.a.	100.02	0.39	0.048	0.15	0.32
Detrital	55	62.45	0.76	14.85	3.22	2.90	0.07	2.40	1.75	2.16	1.73	n.a.	7.73	n.a.	100.02	0.35	0.051	0.14	0.26
Kiselevka–Manoma Terrane (Udyl fragment)																			
Volcano-sedimentary	16	62.54	0.61	14.27	4.56	2.34	0.27	3.41	1.66	3.00	1.74	0.22	3.84	1.13	99.57	0.35	0.043	0.17	0.33
Graywacke, sequences:																			
mudstone	5	66.50	0.76	14.49	2.46	2.59	0.12	2.13	1.45	2.88	2.21	0.22	3.35	0.51	99.67	0.31	0.052	0.11	0.35
mixtite	31	66.26	0.64	14.25	2.92	2.43	0.13	2.08	1.16	2.59	2.45	0.20	4.02	0.58	99.69	0.31	0.045	0.11	0.35
sandstone	12	66.41	0.60	13.55	3.35	1.93	0.09	2.00	2.10	2.42	2.25	0.43	4.26	0.39	99.77	0.29	0.044	0.11	0.35
siltstone	11	65.42	0.62	15.24	3.73	1.88	0.08	1.76	0.80	2.35	2.47	0.21	4.65	0.47	99.69	0.33	0.041	0.11	0.32
Kema Terrane																			
Lower turbidite	17	67.08	0.54	13.89	2.21	2.82	0.06	1.39	1.60	2.07	2.49	0.22	4.89	0.50	99.75	0.29	0.039	0.10	0.33
Coarse-clastic	14	67.23	0.61	14.08	1.72	2.94	0.05	1.80	1.26	1.70	3.11	0.17	4.35	0.58	99.60	0.29	0.043	0.10	0.34
Volcanogenic	11	65.10	0.57	14.11	3.46	1.55	0.09	1.64	2.16	1.55	2.46	0.21	6.02	0.78	99.70	0.30	0.040	0.10	0.28
Upper turbidite	18	64.75	0.52	14.52	1.73	2.63	0.05	2.02	1.58	2.06	2.77	0.14	6.13	0.65	99.65	0.30	0.043	0.10	0.33

Note: (n) number of analyses; (n.a.) not analyzed. The analyses were performed at the DVGI DVO RAN (analysts V.N. Kaminskaya, G.I. Makarova, L.A. Avdevnina, and L.A. Vrzhosek) and the GIN RAN (analyst M.V. Rudchenko). (HM) hydrolyzate module; (TM) titanium module; (FM) femic module; (NAM) normalized alkalinity module.

explained by the substantially higher content of basic and intermediate volcanics and feldspars among the clastic material in the Hauterivian–Santonian sandstones. Note that the chemical composition of the Ainyn sandstones is close to that of "average" graywackes after [15] differing only in the slightly lowered SiO_2 content and elevated concentrations of Al_2O_3, Fe_2O_3 as total iron, and alkalis, which allows them to be attributed to typical graywackes.

By their chemical composition, the clayey–silty rocks are similar to sandstones (table), although the differences between the complexes are also notable. These differences primarily concern the SiO_2 contents, which average 61.29% in the lower turbidite complex and range from 55.53 to 58.64% for the others; they are relatively high for Al_2O_3 (17.50% vs. 16.13–19.03%, respectively) and slightly lower for the total Fe (5.94% vs. 7.04–7.78%), N_2O (1.61% vs. 1.66–1.97%), and K_2O (1.66% vs. 0.84–1.47%).

In the *Olyutor Terrane*, two mineralogical–lithochemical provinces are distinguished based on the composition of the terrigenous rocks: the Northern and Southern [4, 10] (Fig. 1).

By their rock-forming components, the sandstones of the terrane are attributed to typical graywackes. Their detrital component consists of fragments of terrigenous, siliceous, and volcanic rocks; feldspars; quartz; chlorite; pyroxenes; and ore minerals. According to classification [26], they are referred to quartz–feldspar, feldspar, and true graywackes. The differences between the provinces of the terrane are reflected in the higher contents of quartz (up to 23%), the fragments of siliceous and terrigenous rocks (up to 65%), the acid plagioclases (up to 50%), and the feldspars (up to 20%) in the sandstones of the *Southern* province and the volcanic rocks (up to 60%) and the basic and intermediate plagioclases (up to 60%) in the *Northern* province. The minimal content of the quartz (up to 8%) is peculiar to the volcanomictic sandstones from the volcanogenic–siliceous and volcano-sedimentary complexes, which are characterized by higher contents of plagioclase and volcanic rock fragments (each up to 60%). The detrital material is dominated by basic and intermediate volcanics accompanied by subordinate pyroclastic, terrigenous, and siliceous rocks. Intrusive and metamorphic rocks are rare among the detrital material and occur only in the Southern province.

The detrital component of the clayey–silty rocks constituting up to 70 vol % is generally similar to that in the sandstones, although they contain less rock fragments and slightly more feldspars and quartz. The clayey component of the rocks from the Northern province is largely represented by aggregates of fine-scale clay minerals dominated by smectite, chlorite, and mixed-layer smectite–chlorite. In the Southern province, hydromica prevails.

In terms of chemical composition, the strongest differences were found between the sandstones of the Northern and Southern provinces [4, 10]. These rocks differ primarily with respect to SiO_2: its contents averaged for the complexes range from 55.12 to 61.53% in the *Northern province* and from 58.56 to 65.11% in the *Southern province*. They also significantly differ in the contents of Fe_2O_3 (2.88–4.06% vs. 1.63–3.22%, respectively), MgO (2.57–4.16% vs. 2.08–2.40%), and CaO (2.67–5.23% vs. 1.23–1.75%). All these features indicate the more femic composition of the rocks of the Northern province as compared with the Southern one. By their chemical composition, the sandstones from both the provinces belong to typical graywackes, which is evident from their closeness to "average" graywackes after [15] as well as to graywackes and tuffstones from the Franciscan Formation of California [26], from which they differ by lowered SiO_2, FeO, K_2O and elevated Al_2O_3, Fe_2O_3, and MgO concentrations.

Chemically, the clayey–silty rocks are generally similar to sandstones (table). However, since they are characterized by higher and lower contents of clay minerals and detrital components, respectively, as compared with sandstones; these rocks have higher contents of Al_2O_3 (14.85–16.76%), TiO_2 (0.65–0.78%), and K_2O (1.13–2.33%) and lower contents of SiO_2 (56.16–63.12%) and Na_2O (2.03–4.04%). The chemical composition of the clay rocks also reveals the differences between the provinces: lower SiO_2 and K_2O and higher Al_2O_3, MgO, CaO, and total Fe contents are characteristic of the rocks from the *Northern province*.

In the *Udyl fragment of the Kiselevka–Manoma Terrane*, sandstones occur only in the volcano–sedimentary and graywacke complexes. They are represented by polymictic, frequently volcanic varieties referred, according to classification [26], to feldspar, quartz–feldspar, and true graywackes. The particular position is occupied by feldspar graywackes from the volcano-sedimentary complex largely consisting of pyroclastic products and volcanic material. The differences between the complexes are reflected in the contents of the rock-forming components. This is particularly well evident from the quartz contents: it is up to 7% and from 10 to 40% in the volcano-sedimentary and graywacke complexes, respectively. The respective feldspars contents are 60–80 and 10–50%. The latter are dominated (by 95%) by albite and oligoclase. Potassic feldspar largely represented by orthoclase amounts up to 5%. The clastic material constituting in the volcano-sedimentary complex 15–30% is dominated by basic and intermediate volcanics (up to 70%) accompanied by subordinate sedimentary rocks (up to 30%) and altered volcanic glass (up to 15%). In the graywacke complex, the detrital material (40–55% in sum) is represented by fine-grained sedimentary (30–50%) and siliceous (20–40%) rocks with a subordinate amount of volcanic (5–15%) and rare acid intrusive and metamorphic rocks.

The detrital component of the clayey–silty rocks (5–80 vol %) consists of silt-sized and rare psammitic grains of plagioclase, basic volcanics, and glass accompanied by fragments of cherts, intermediate volcanics, pyroxenes, and ore minerals. The clay minerals in all the complexes are uniform, being represented only by hydromica and chlorite. Sometimes, the volcano-sedimentary complex contains smectite and smectite–chlorite.

The contents of the main rock-forming oxides in the different complexes of the terrane are highly variable [12]. The sandstones from the volcano-sedimentary complex are primarily characterized by notably lower SiO_2 contents as compared with their counterparts from the graywacke complex (58.56% and 66.90–67.05%, respectively). In addition, they exhibit lower FeO (1.56% vs. 2.40–2.87%) and K_2O (0.96% vs. 1.93–2.00%) and substantially higher Al_2O_3 (19.16% vs. 12.99–13.26%), Na_2O (6.87% vs. 2.61–3.15%), Fe_2O_3 (4.32% vs. 2.82–3.04%), MgO (2.71% vs. 2.29–2.55%), and CaO (2.41% vs. 1.56–1.92%) contents. Such differences are explained by the high concentrations of clasts of basic volcanics and feldspars in the sandstones of the volcano-sedimentary complex. It should be noted that, by their composition, the sandstones from the graywacke complex are correlative with "average" graywackes" [15], as well as with graywackes and tuffstones from the Franciscan Formation.

The clayey–silty rocks from the different complexes also show significant compositional differences. The maximal difference is recorded for the SiO_2 contents (averaging 62.54% and 65.42–66.50% for the volcanogenic–clastic and graywacke complexes, respectively), and a slightly smaller difference is recorded for Fe_2O_3 (45.6% and 2.46–3.73%), MnO (0.27% and 0.08–0.13%), MgO (3.41% and 1.76–2.13%), and K_2O (1.74% and 2.21–2.47%).

With regard to the rock-forming components, the sandstones from the *Kema Terrane* are relatively uniform and attributed to polymictic varieties. Their detrital constituent is represented by quartz; feldspars; fragments of terrigenous, siliceous, and volcanic rocks; volcanic glass; and ore minerals. According to classification [26], the sandstones mostly belong to feldspar–quartz and quartz–feldspar graywackes with subordinate feldspar arkoses. Quartz is the most abundant component in the sandstones: its content varies from 30 to 52%. Its maximal and minimal abundances are characteristic of the lower turbidite (35–52%) and volcanogenic (31–42%) complexes, respectively. The feldspars in the sandstones constitute 22–41%. They are mostly plagioclases (60–95%) with albite and oligoclase being dominant. Potassic feldspars represented by dominant orthoclase and rare microcline are relatively rare (up to 20%). The detrital material constituting 17–42 vol % of the sandstone is represented by siliceous (30–45% on average), sedimentary (25–35%), and subordinate basic volcanic (15–30%) rocks. The maximal content of volcanic clasts is observed in the sandstones of the lower graywacke complex (up to 70%). Clasts of intrusive and metamorphic rocks are rare.

Depending on their lithological type, the clayey–silty rocks contain from 5 to 70–80% silt-sized detrital material represented by dominant quartz and feldspars and less common cherts, volcanics, fine-grained rocks, biotite, volcanic glass, and ore minerals. The clay component includes dominant hydromica and subordinate smectite and chlorite. The exception is provided by the volcanogenic complex, where smectite and chlorite are the dominant clay minerals.

By their chemical compositions, the sandstones are relatively uniform [6, 7]. Only the sandstones from the volcanogenic complex insignificantly differ from their counterparts in the other complexes in their lower SiO_2 (73.26% vs. 74.34–77.30%, respectively) and higher TiO_2 (0.38% vs. 0.25–0.35%) and Al_2O_3 (10.76% vs. 8.18–10.24%) contents. By their main rock-forming oxides, the Kema sandstones occupy the intermediate position between arkoses and graywackes. From an "average" arkose, they differ by lower SiO_2; elevated Al_2O_3, MgO, and total Fe contents; and by the prevalence of N_2O over K_2O, which is typical of graywackes [15].

The chemical composition of the clayey–silty rocks is similar in all the complexes, while differing from that of the sandstones in the lower SiO_2 (from 64.75 to 67.23%) and CaO (1.26–2.16%) but higher TiO_2 (0.54–0.62%), Al_2O_3 (13.89–14.52%), and $FeO+Fe_2O_3$ (4.36–5.03%) contents and the prevalence of K_2O over Na_2O.

In the diagram proposed by Predovsky [16] (Fig. 3), the aluminosilicate clastic sediments are subdivided into two groups that differ from each other in the aluminosilicate (A) and femic modules (F). In these parameters, the studied sandstones from the sedimentary complexes of the Far East exhibit both similarities and differences. All the data points of the sandstones from the Ainyn, Olyutor, and Kiselevka–Manoma terranes are located in fields of clayey and high-clayey rocks with regard to the aluminosilicate module and in the graywacke segment with respect to their femic index. Moreover, in terms of the femic module, the data points of the sandstones from the Southern province of the Olyutor Terrane are located closer to the graywacke field than the rocks from its Northern province. The data points obtained for the sandstones from the Udyl fragment of the Kiselevka–Manoma Terrane and from the lower turbidite complex of the Ainyn Terrane are located even closer to this field. The rocks of the Kema Terrane demonstrate a substantially greater difference in these parameters. In terms of the femic index, they correspond to

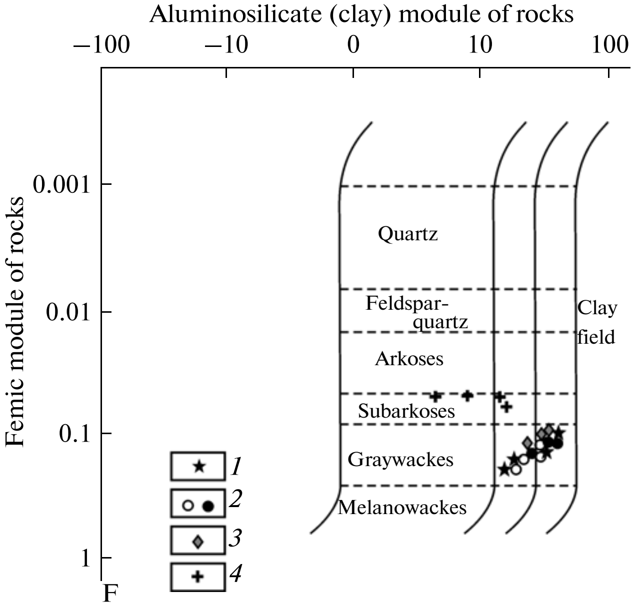


Fig. 3. The A–F diagram for the sandy rocks from the studied objects [16].

A = Al_2O_3–(K_2O+Na_2O+CaO); F = (Fe_2O_3+FeO+MgO)/SiO_2 (molecular weights).

(I–IV) sandy rocks: (I) transitional to tuffites and true tuffites, (II) low-clayey, (III) clayey, (IV) high-clayey.

(*1–4*) terranes: (*1*) Ainyn, (*2*) Olyutor, provinces: (*a*) Northern, (*b*) Southern, (*3*) Kiselevka–Manoma, Udyl fragment, (*4*) Kema.

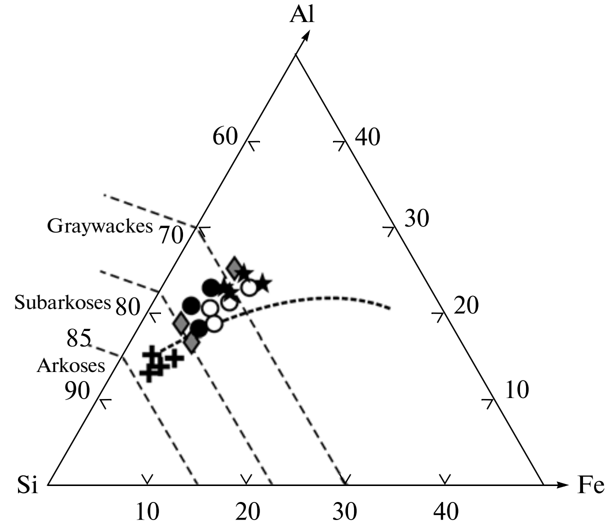


Fig. 4. Si–Al–Fe diagram for the sandy rocks of the studied objects [32] (atomic weights).

Line D–B shows the granite–basaltic trend. See Fig. 3 for the legend.

graywackes while being even close to arkoses; according to the aluminosilicate module, their data points are plotted in the field of clayey and low-clayey rocks. The scatter in the data points of the average sandstones from the examined terranes with respect to their aluminosilicate module is explained by the different fractions of the clayey matrix or pyroclastic admixture material in them.

In the Si–Al–Fe diagram from [32] (Fig. 4), the data points of the sandstones from the examined objects fall on the granite–basalt line or are located approximately along the latter (Fig. 4). According to this classification, the sandstones of the Ainyn, Olyutor, and Kiselevka–Manoma terranes belong to graywackes. The sandstones from the Ainyn Terrane and from the volcano-sedimentary complex of the Kiselevka–Manoma Terrane occupy the extreme right position closest to the basalt composition, while the rocks from the two provinces of the Olyutor Terrane define two separate clusters. In addition, the sandstones of the Kema Terrane in this diagram sharply differ from the other rocks: their data points are located in the subgraywacke field, while their composition is close to that of granite.

In the diagram of Pettijohn et al. [14] (Fig. 5) based on logarithms of the Na_2O/K_2O and SiO_2/Al_2O_3, the data points of all the sandstones from the Ainyn, Olyutor, and Kiselevka–Manoma terranes are compactly grouped in the graywacke field (Fig. 5). Similar to the previous diagram, the most typical “graywacke” composition is characteristic of the sandstones from the Ainyn Terrane and the volcanogenic-sedimentary complex of the Kiselevka–Manoma Terrane, while the rocks from the two provinces of the Olyutor Terrane show significant differences. The data points of the sandstones from the Kema Terrane are located beyond the graywacke field in the field of lithoid arenites, which represent in fact subgraywackes, i.e., rocks transitional to arkoses [15].

Inasmuch as the contents of the rock-forming oxides reflect the composition of both the detrital

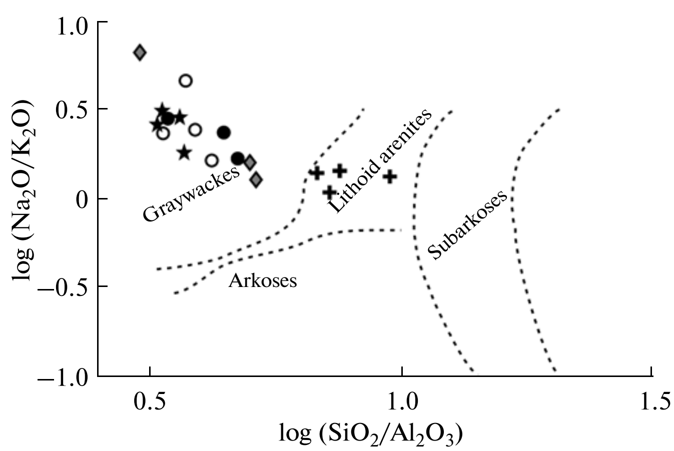


Fig. 5. The log (Na_2O/K_2O–log(SiO_2/Al_2O_3) diagram for the sandy rocks from the studied objects [14].

See Fig. 3 for the legend.

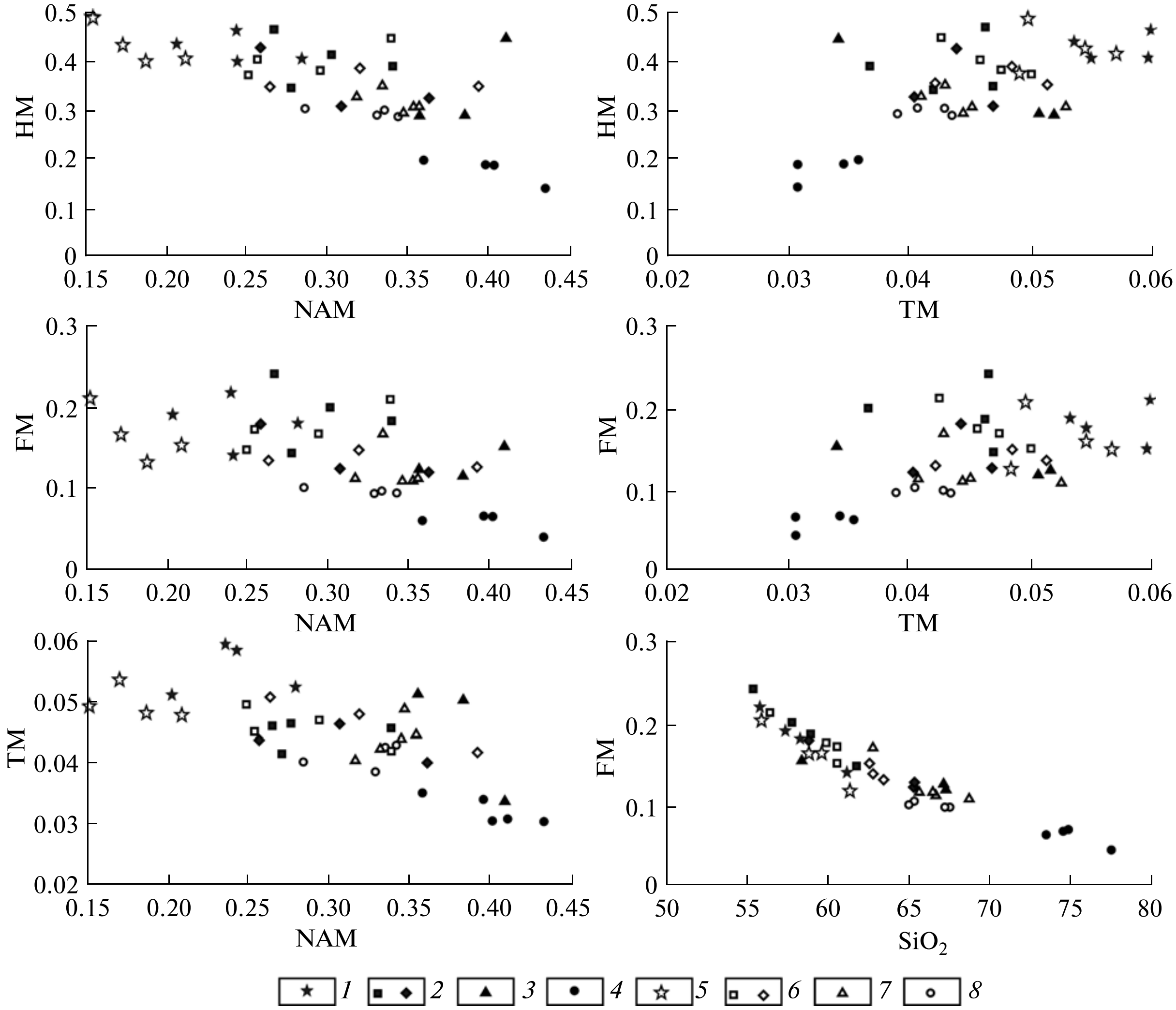


Fig. 6. Module diagrams for the sandy and clayey–silty rocks from the studied objects [27, 28].
(*1–4*) sandy rocks; (*5–8*) clayey–silty rocks. Terranes: (1, 5) Ainyn, (*2*, *6*) Olyutor; provinces: (a) Northern, (b) Southern; (*3*, *7*) Kiselevka–Manoma, Udyl fragment, (4, 8) Kema.

component of the terrigenous rocks and their cement, more objective conclusions concerning the similarities and differences between the examined objects may be drawn considering the most informative ratios between the oxides and their sums (petrochemical modules) (table) and the module diagrams (Fig. 6) proposed by Yudovich and Ketris in [27, 28].

The *hydrolyzate module* (HM = $(Al_2O_3+TiO_2+Fe_2O_3+FeO+MnO)/SiO_2$) is used for the quantitative assessment of the chemical rock weathering, i.e., the "maturity." Its value depends on the amount of detrital quartz or Si-enriched rock fragments, on the one hand, and on the composition of the feldspars as well as the clayey components in the cement, on the other.

By this parameter, the sandstones from all the examined objects are characterized by their low maturity, which indicates their formation largely by the mechanical disintegration of source rocks of basic and intermediate composition under the subordinate role of chemical weathering.

The HM values vary from 0.48–0.41 for the least mature rocks of the Ainyn Terrane to 0.14–0.19 for the most mature rocks of the Kema Terrane. The relatively high maturity degree of the Kema sandstones is likely determined by the elevated content of detrital quartz and siliceous rocks in them and the lowered amount of feldspars and clayey cement. The clayey–silty rocks typically have higher HM values than the sandstones, which is explained by the lower content of quartz and feldspars in them and the higher clay matter. The exception is provided by the rocks from the upper turbidite complex of the Ainyn Terrane and from the volcanogenic–siliceous and volcano-sedimentary complexes of the Olyutor and Kiselevka–Manoma terranes, where the sandstones are depleted in quartz but enriched in clasts of basic volcanics and clay matter constituting the cement and matrix.

The *femic module* (FM = (Fe_2O_3+FeO+MnO+MgO/SiO_2) is very convenient for the identification of graywackes and arkoses [15]. Its maximal values are characteristic of volcaniclastic graywackes [28], which is usually determined by the high content of Fe- and Mg-rich volcanic rocks and glasses among the detrital material as well as of the clayey cement and matrix in them. As a whole, the femic module reflects the intensity and the rates of the weathering and burial: the more femic elements pass into the solution during the weathering, the greater the difference is between the sandstones and the typical graywackes.

In terms of the femic module, the sandstones from the Kiselevka–Manoma (0.12–0.15), Ainyn (0.14–0.23), and Olyutor (0.12–0.25) terranes are attributed to typical graywackes. At the same time, the rocks of the Northern and Southern provinces of the Olyutor terrane are characterized by different femic modules: 0.12–0.18 and 0.15–0.25, respectively. In addition, noteworthy are the high FM values in the sandstones of its volcanogenic–siliceous and volcano-sedimentary complexes and in the upper turbidite complex of the Ainyn Terrane, which allow them to be classified as volcaniclastic graywackes. Substantially lower FM values (0.04–0.07) are characteristic of the sandstones from the Kema Terrane, which is well consistent with the lower content of basic volcanics and the higher content of quartz, siliceous rocks, and granitoids among their detrital material. In terms of this parameter, they occupy the intermediate position between graywackes and arkoses. According to Yudovich and Ketris [28], the clayey rocks are characterized by higher FM values as compared with the sandy varieties. In the considered case, this rule is clearly confirmed for the rocks of the Kema Terrane. In the clayey–silty rocks of the Ainyn, Olyutor, and Kiselevka–Manoma terranes, the FM values are lower than or identical to those in the sandstones. Similar results were obtained by Markevich [9] for the flysch sequences from the Il'pinskii Peninsula of eastern Kamchatka.

The *normalized alkalinity module* (NAM = Na_2O+K_2O/Al_2O_3), which was proposed long ago [31], makes it possible to recognize an admixture of volcanic material in sedimentary rocks [28]. This parameter is usually higher in arkoses owing to the wide development of micas and feldspars, including the potassic varieties, and lower in graywackes due to the abundance of clay cement, fragments of basic volcanics, and the clayey–silty matrix.

With respect to this module, the sandstones of the Kema Terrane (0.36–0.43), where the volcanic material is likely mixed with some amount of sialic clastics, are most close to arkoses. Slightly lower NAM values (0.35–0.41) are recorded in the sandstones of the Kiselevka–Manoma Terrane. The lowest values of this module were documented in the typical graywackes of the Olyutor and Ainyn terranes (0.26–0.36 and 0.20–0.28, respectively), where the detrital component is largely composed of basic and intermediate high-alumina volcanics with a significant contribution of clay material mostly represented by chlorite and smectite. In the clayey–silty rocks of the studied objects, the NAM value is usually lower than that in the sandstones, which is evidently related to the lower content of feldspars and the higher content of clayey matter in them. An exception is provided by the volcanogenic–siliceous and volcano-sedimentary complexes of the Olyutor Terrane, where the clayey rocks are almost completely (up to 95%) composed of smectite [4].

The *titanium module* (TM = TiO_2/Al_2O_3) was proposed by Migdisov [13] to estimate the rock composition (including their Ti content) in source areas and the dynamics of the sedimentation settings, which are responsible for sorting Ti-bearing minerals and clay matter [28].

High values of the titanium module in sandstones are usually determined by the admixture of basic volcaniclastics. Despite the significant fraction of volcanic and pyroclastic material among the detrital component, the sandstones from all the examined objects are characterized by relatively low NAM values ranging from 0.052 to 0.060, from 0.36 to 0.047, and from 0.034 to 0.052 in the Ainyn, Olyutor, and Kiselevka–Manoma terranes, respectively. Such a distribution of the NAM values is probably explained by the origination of clastic material via erosion of island-arc low-Ti (but high-Al) volcanic series. The minimal, almost arkosic NAM values (0.031–0.035) are registered in the Kema sandstones, which is related to the admixture of clastics of acid volcanics with low TM values. A characteristic feature of the clayey–silty rocks from most of the studied complexes is their elevated Ti contents relative to the sandstones, which is usually characteristic of volcaniclastic rocks, the formation of which is not accompanied by substantial mechanical differentiation of the pelitic and psammitic fractions [28].

The trends in the variations of the average chemical composition of the sandy and clayey–silty rocks from all the studied objects, as well as their similarities and differences, are best illustrated by the module diagrams of Yudovich and Ketris [27, 28]: HM–NAM, FM–NAM, TM–NAM, HM–TM, FM—TM, and FM–SiO_2 (Fig. 6). In all the presented diagrams, the rocks under consideration form the following succession: the Ainyn Terrane—the Northern and Southern provinces of the Olyutor Terrane—the Kiselevka–Manoma Terrane—the Kema Terrane. The observed positive correlations between the FM–TM and HM–TM pairs and the negative correlations between the HM–NAM, FM–NAM, TM–NAM, and FM–SiO_2

indicate the petrogenic (volcanomictic) origin of the rocks and their affiliation to graywackes.

At the same time, in all the diagrams, the data points of the examined rocks are clustered as two autonomous distinctly isolated fields. The first of them is formed by the sandstones of the Kema Terrane, which are close to arkoses and characterized by elevated contents of silica and maximal NAM and lower HM, FM, and TM values. Such a peculiarity of the Kema sandstones is likely explained by their formation from island-arc volcaniclastic material and admixtures of clastics from eroded sialic continental crustal blocks.

Thus, the lithochemical composition of the terrigenous rocks from the studied objects indicates their low chemical maturity, weak lithodynamic reworking, and high rates of physical weathering and burial of matter. The main source of clastic material was the island arc voclaniclastics with variable admixtures of sialic material from the eroded uplifted blocks of the continental crusts.

PALEOGEODYNAMIC INTERPRETATION

The lithochemical data were interpreted based on the actualistic approach, i.e., by the comparison of the obtained results with data on the recent sediments from present-day deep-sea basins. According to many researchers, there is a close relation between the chemical composition of the rocks and the geodynamic settings of the provenances and sedimentation basins [29, 30, 33, and others].

Sandstones from different tectonic settings are discriminated using diagrams of the genetic interpretation of their chemical compositions [29] (Fig. 7a). The parameters used in these diagrams (Al_2O_3/SiO_2, K_2O/Na_2O, $Al_2O_3/(CaO+Na_2O)$, TiO_2, and Fe_2O_3 (tot)+MgO) reflect the mineral composition of the rocks from provenances and the geochemical behavior of some elements in seawater. By these parameters, the sandstones of the *Ainyn Terrane* mostly correspond to oceanic island-arc settings, and only the data points of the rocks from the Berriasian–Valanginian complex are displaced toward the field of continental island arcs. The geotectonic settings of the sedimentation basins proper are reconstructed using the diagram proposed by [30] (Fig. 7b), where deepwater sands are discriminated based on the SiO_2/Al_2O_3 and K_2O/Na_2O ratios. In this diagram, the Ainyn sandstones are grouped in the fields corresponding to the settings of fore-arc (FA) basins of oceanic island arcs.

The paleotectonic interpretation of the chemical composition of the clayey–silty rocks derived from the SiO_2/Al_2O_3–K_2O/Na_2O diagram [30] (Fig. 8) is in general consistent with that based on the composition of the sandstones. All the data points are plotted in the fields of island-arc settings tending to settings of fore-arc (FA) basins, and only the rocks from the lower turbidite complex fall in the field of continental island arcs.

A slightly different tectonic interpretation of the chemical composition of the sandy and clayey rocks was proposed in [33]. In the K_2O/Na_2O–SiO_2 diagrams (Fig. 9), these authors distinguished basins of oceanic island arcs (ARC) and passive (PM) and active (ACM) continental margins. The data points for the sandy and clayey–silty rocks of the Ainyn Terrane are clustered in the field of basins associated with oceanic island arcs, and only the data points of the clayey–silty rocks from the lower turbidite complex are located in the field of active continental margins, which include continental island arcs.

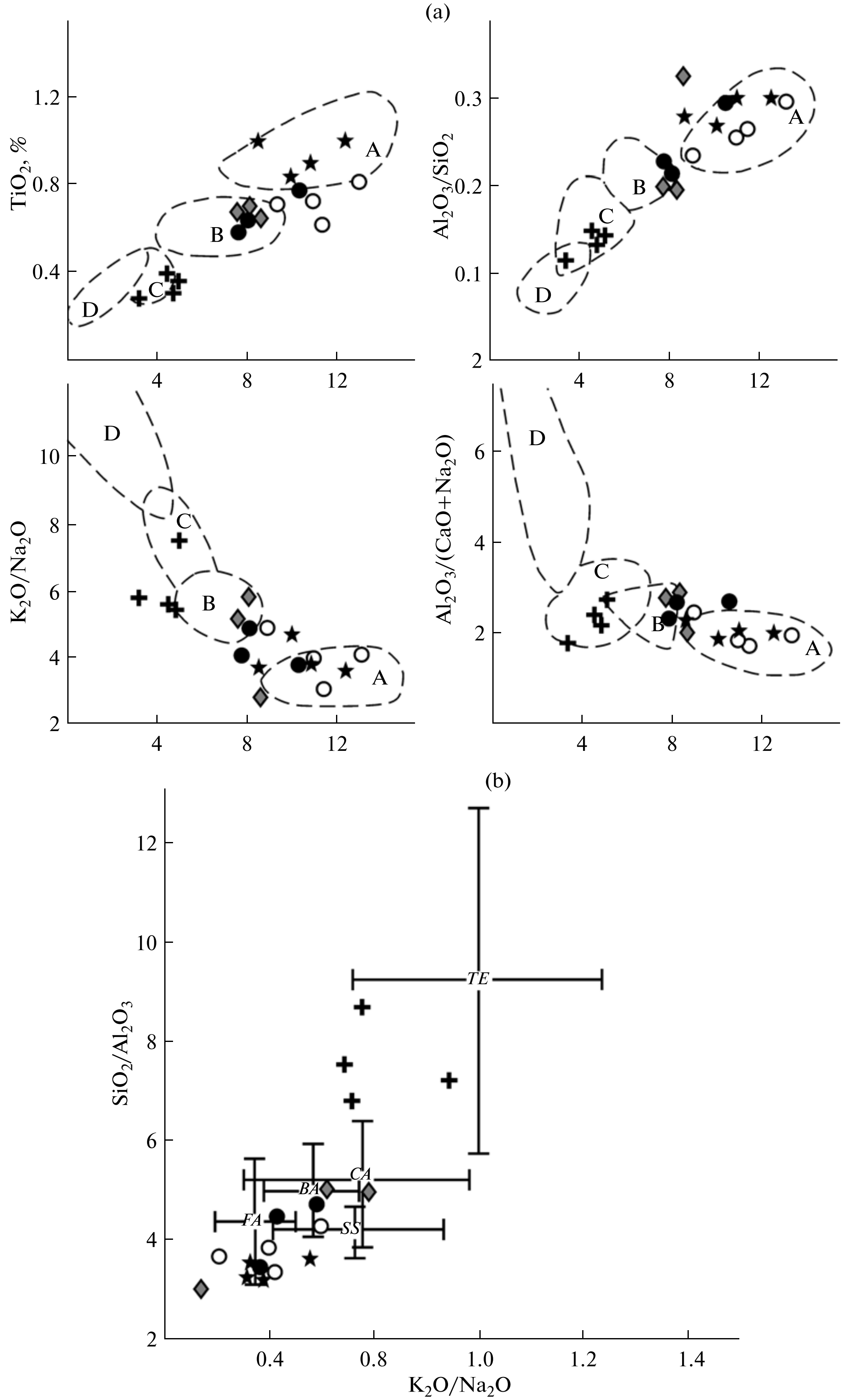
The main sources of the rocks of the detrital material for the Ainyn Terane were likely the basic and intermediate volcanic rocks and products of syn-sedimentary volcanic activity; the contribution of eroded granite–metamorphic rocks of the mature continental margin may be assumed only for the rocks of the lower turbidite complex, which is confirmed by the notable admixture of sialic heavy minerals (zircon, garnet, tourmaline, and sphene) in the heavy fraction of the sandstones [21, 22].

The analysis of the data points of the sandstones from the *Olyutor Terrane* in Bhatia's diagrams (Fig. 7a) implies that they were formed in geodynamic settings corresponding to or close to the conditions of Mariana-type oceanic island arcs and, to a lesser extent, continental island arcs. In the SiO_2/Al_2O_3–K_2O/Na_2O diagram [30], the Olyutor sandstones are close to the sands of fore-arc (*FA*) and back-arc (*BA*) basins of oceanic island arcs (Fig. 7b). Island-arc clastics and products of synsedimentary volcanism likely served as a main source of the detrital material for them. At the same time, the diagrams demonstrate some compositional differences between the sandstones from the two provinces of the terrane, which implies the existence of additional sialic (continental) source of detrital material that permanently affected

Fig. 7. Diagrams of the chemical composition of the sandy rocks from different geodynamic settings.

(b) The basin types [29]. The dashed lines outline the fields of the geochemical parameter values for the ancient sandstones from the basins conjugate with the oceanic (A) and continental (B) island arcs and the active (C) and passive (D) continental margins. (Fe_2O_3*) total iron.

(b) basin settings [30]. The crossing lines are the standard deviations from the average composition of the recent deepwater sands deposited in the basins of the passive continental margins (*TE*), the active continental margins conjugate with the shear dislocations (*SS*), the continental–margin magmatic arcs (*CA*), and the oceanic volcanic arcs: (*FA*) fore-arc and (*BA*) back-arc basins. See Fig. 3 for the legend.


(a)
TiO2, %
Al2O3/SiO2
K2O/Na2O
Al2O3/(CaO+Na2O)
A
B
C
D
(b)
SiO2/Al2O3
K2O/Na2O
TE
CA
BA
FA
SS

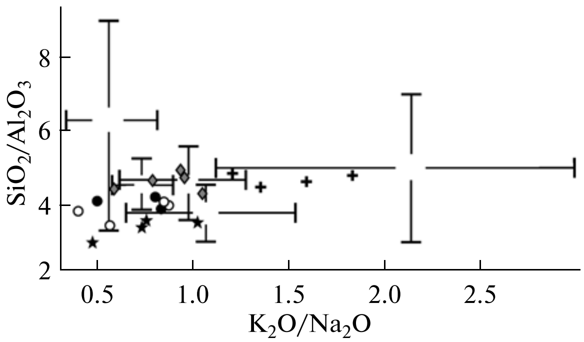


Fig. 8. The diagram of the chemical composition of the clayey–silty rocks from the different basin settings [30]. See Figs. 3 and 7 for the legend and abbreviations.

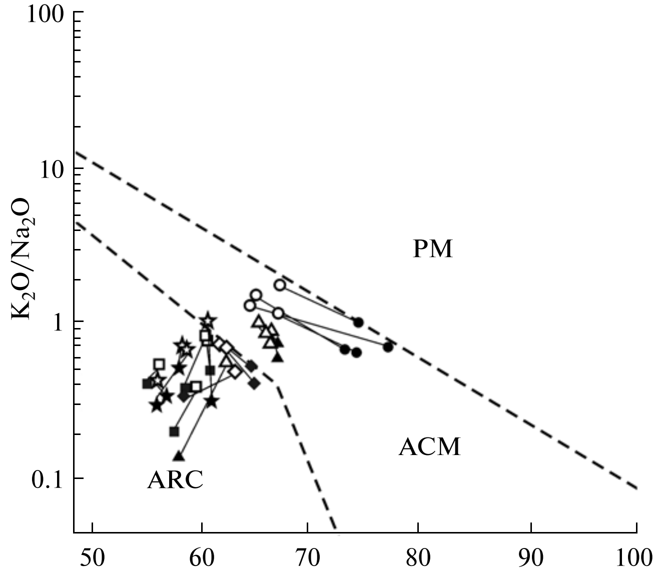


Fig. 9. The $K_2O/Na_2O–SiO_2$ diagram for the sandy and clayey–silty rocks from the studied objects [33].

Basins of tectonic settings: (PM) passive continental margins, (ACM) active continental margins, (ARC) oceanic island arcs.

The lines connect the sandy and clayey–silty rocks from the same complex. See Fig. 6 for the legend.

the sedimentation in the Southern province. This source could be represented by blocks of mature continental crust composed of granitoids and metamorphic rocks [4].

The paleotectonic interpretation of the chemical composition of the clayey–silty rocks in the diagram of Maynard et al. (Fig. 8) is consistent with that derived from the composition of the sandstones. All the data points for such rocks are located in the fields of island-arc settings, being more restricted to the settings of fore-arc (FA) and back-arc (BA) basins of oceanic island arcs.

In the diagram of Roser and Korsch [33] (Fig. 9), the sandy–clayey rocks of the Olyutor Terrane are grouped in the field of basins associated with oceanic island arcs, which well agrees with the above-mentioned data.

The interpretation of the chemical composition of the terrigenous rocks from the *Udyl fragment of the Kiselevka–Manoma Terrane* based on the above-mentioned principles allows several sources of detrital material and sedimentation settings to be assumed. As was mentioned, the siliceous complex of the terrane is practically barren of detrital rocks. Therefore, its geodynamic nature may be interpreted only from indirect features, in particular, from the set of heavy minerals extracted from the clayey rocks. The prevalence of the femic mineral association in the rocks of the complex with clinopyroxene being predominant is characteristic of deep marginal seas of the Pacific Ocean, where island-arc clastics were mainly supplied by the Idzu–Bonin-type oceanic arc [8]. In all the presented diagrams, the data points of the rocks from the volcano-sedimentary complex also correspond to the oceanic island arc, falling in the field of fore-arc (FA) basins (Figs. 7–9). The data points of the sandy and silty–clayey rocks from the graywacke complex are displaced toward the fields corresponding to the basins of the continental-margin volcanic island arcs in the $SiO_2/Al_2O_3–K_2O/Na_2O$ diagrams [30] (Figs. 7, 8) and toward the active continental margins, which include these island arcs, in the $K_2O/Na_2O–SiO_2$ diagram [33] (Fig. 9). Such a deviation is caused by the lower femic index but elevated maturity of the rocks from this complex due to the admixture of material from eroded sialic (continental) sources.

The genetic interpretation of the chemical composition of the sandstones from the *Kema Terrane* is ambiguous. In Bhatia's diagrams [29], the Kema sandstones correspond to or are close to their counterparts from the basins of the active continental margins and the basins associated with island arcs developed on the mature continental crust (for example, the Japanese Islands) (Fig. 7A). Some discrepancy between the data points and the field of the continental island arcs is explained by the low content of total Fe and Mg (low femic index) in the sandstones and the relatively high maturity of the rocks due to their enrichment in quartz and siliceous clastics. In the diagram of Maynard et al. [30], the sandstones occupy the intermediate position between the sands from the basins associated with passive continental margins (*TE*) and continental–marginal arcs (CA) (Fig. 7b). The deviation of the sandstone data points from the fields of the basins associated with active continental margins and continental–margin arcs is explained by the prevalence of K over Na (which is usually untypical of such sandstones) due to the admixture of fragments of basalts (shoshonites) ascribed to high-K calc-alkaline series characteristic of rear parts of island arcs [17]. In the diagram of Roser and Korsch [33] (Fig. 9), the data points of these sandstones are located in the field corresponding to the basins of active continental margins, which include continental island arcs (Fig. 9). The paleotectonic interpretation of the chemical composition of the clayey–silty rocks is consistent with that derived from the composition of the sandstones being, however, less ambiguous. Their data points in both diagrams are largely located in the fields of the active continental margins and island arcs developed on the continental crust.

CONCLUSIONS

The analysis and interpretation of the lithochemical data on the terrigenous rocks from the different-age and structurally contrasting complexes developed in the Russian Far East made it possible to confirm the island-arc nature of these objects and to establish their following specific features.

The lithochemical composition of the terrigenous rocks from the *Ainyn Terrane* indicates their derivation mainly from island-arc clastics and products of synsedimentary volcanism in the ensimatic Uda–Murgal island arc [18, 21, 22]. The sedimentary material was deposited on the slope of the fore-arc basin adjacent to this arc. At the same time, the Berriasian–Valanginian sedimentation was influenced by material from the granite–metamorphic complexes of the mature continental crust. In addition, the eroded Okhotsk–Chukotka volcanic belt became an additional source of volcanic clastic material beginning from the terminal Albian [21, 22].

The *Olyutor Terrane* comprises two mineralogical–lithochemical provinces that differ in the composition of the terrigenous sediments and received materials from different sources. The dominant sources for the clastic material in both provinces were the eroded Cretaceous–Paleogene Achaivayam oceanic island arc [25] and the synsedimentary volcanic activity. At the same time, the sedimentation in the Southern province was additionally fed by sialic sources beyond the basin. These sources were likely represented by continental blocks located south of the Olyutor Terrane in the present-day Bering Sea area [4].

The provenance of the sedimentation basins corresponding to the *Udyl fragment of the Kiselevka–Manoma Terrane* was heterogeneous. The main source of the detrital material was volcaniclastics that were transported from the Cretaceous Udyl oceanic island arc [12] and added to by material from the eroded continental margin.

The *Kema Terrane*, in addition to typical island arc volcaniclastics, was significantly contributed to by continental sialic material. Its provenance likely comprised the continental–marginal volcanic arc and uplifted blocks of the continental crust, which underlain the latter. Detrital material was transported from the Moneron–Samarga island arc [6, 7], thus feeding its back-arc basin with volcaniclastics and products of eroded metamorphic and acid intrusive rocks. The latter compose the arc basement, which represents the seaward-advanced fragment of the continental crust.

Thus, the lithochemical research of the terrigenous rock combined with other geological data offers an opportunity to recognize island-arc settings in the fragments of paleobasins incorporated into the structure of ancient orogenic belts.

The island-arc settings are recognizable based on the following lithochemical features of the terrigenous rocks: (1) their affiliation to typical graywackes (or subgraywackes for sequences of continental–marginal arcs), which is primarily reflected in the lower SiO_2 and high Al_2O_3 and $FeO+Fe_2O_3$ contents, as well as in the prevalence of Na_2O over K_2O; (2) the low maturity and high femic index of the rocks, which reflect the high intensity and rates of the physical weathering and burial of material determined by the proximity of its volcanic sources; (3) the relatively low values of the titanium and normalized alkalinity modules due to the abundance of clayey cement; the clayey–silty matrix; and, especially, clastics of basic volcanics belonging to low-Ti (but high-alumina) island-arc series. At the same time, the observable variations in the lithochemical compositions of the terrigenous rocks from the different island-arc complexes reflect their formation in diverse geodynamic settings: fore- and back-arc basins of both the oceanic and continental-margin island arcs. In addition, the lithochemistry of the rocks allows sufficiently reliable recognition of the continental provenances influencing the island-arc sedimentation.

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