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Lithological Composition of Island-Arc Complexes in the Russian Far East

A. I. Malinovsky

Far East Geological Institute, Far East Division, Russian Academy of Sciences, pr. Stoletiya Vladivostoka 159, Vladivostok, 660022 Russia

e-mail: malinovsky@fegi.ru

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Abstract—The results of study of geochemistry of terrigenous rocks from the contrast (in structure) Cretaceous–Paleogene complexes of Sikhote Alin and Kamchatka are summarized. The data obtained were interpreted based on comparison with the geochemical composition of recent and ancient sediments accumulated in the well-known geodynamic settings. It is shown that the chemical composition of terrigenous rocks and some petrochemical ratios can serve as reliable indicators of various island-arc settings. These indicators make it possible to discriminate sufficiently reliably these settings in paleobasins of orogenic zones.

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Study of the lithology of terrigenous rocks has a great importance for elucidating sources of terrigenous material, determining the provenance composition, and, ultimately, elucidating paleogeological constraints of their formation.

According to investigations of recent and ancient sediments, the chemical composition of terrigenous rocks, sandstones in particular, is defined to a significant extent by the lithology of host rocks and their distribution in certain tectonic settings. It should be mentioned that postsedimentary transformations of sediments give rise to mineral assemblages that are most stable in the supergene zone, while the chemical composition of rocks remains virtually unaltered.

The author of the present communication investigated the chemical composition of terrigenous rocks from genetically different complexes (island-arc varieties included) in the Russian Far East and sediments from marginal seas of the Pacific (*Geologo-geogizicheskie…*, 1990; Malinovsky, 1993; Malinovsky et sal., 2005a; Markevich et al., 1987, 1996, 1997; and others).

The island-arc setting is commonly recognized based on several features: paleontological position, structure and composition of rock sequences therein, and petrochemical characteristics of volcanics. The aim of the present communication is to demonstrate specific features of the lithochemical compositions of terrigenous rocks from various (in age and origin) island-arc complexes of the Russian Far East and to show the possibility of such features for the identification of various settings in ancient basins. The paleoreconstruction method based on the composition of terrigenous rocks should be particularly helpful for the study of Phanerozoic volcanosedimentary rocks in terranes with insufficiently studied genetic issues.

The most favorable objects for such reconstructions in the Far East are represented by some well-known terranes, the island-arc nature of which has mainly been established based on the study of volcanic rocks. Data based only on the chemical composition of rocks are undoubtedly insufficient for the comprehensive identification of island-arc settings. However, such data coupled with other materials can be used as a sufficiently reliable criterion.

MATERIALS AND METHODS

The present work is based on original material pertaining to the chemical composition of terrigenous rocks from different aged island-arc rock complexes in the Russian Far East. We investigated sandy and clayey rocks from Early Cretaceous and Early Cretaceous–Cretaceous rocks of the Olyutor terrane (eastern Kamchatka), as well as the Kema and Kiselevka–Manoma terrane (Udyl fragment) of Sikhote Alin (Fig. 1). Our main attention was focused on sandy rocks. The silty–clayey rocks ranging from the coarse-grained siltstones to mudstones were less studied. Such attention to sandstones was dictated by the fact that they bear the most valuable information pertaining to the type and composition of provenances and to the geodynamic settings of feeding and sedimentation zones.

The rock material used in our work was taken from natural exposures and minings during field works in 1978–2005.

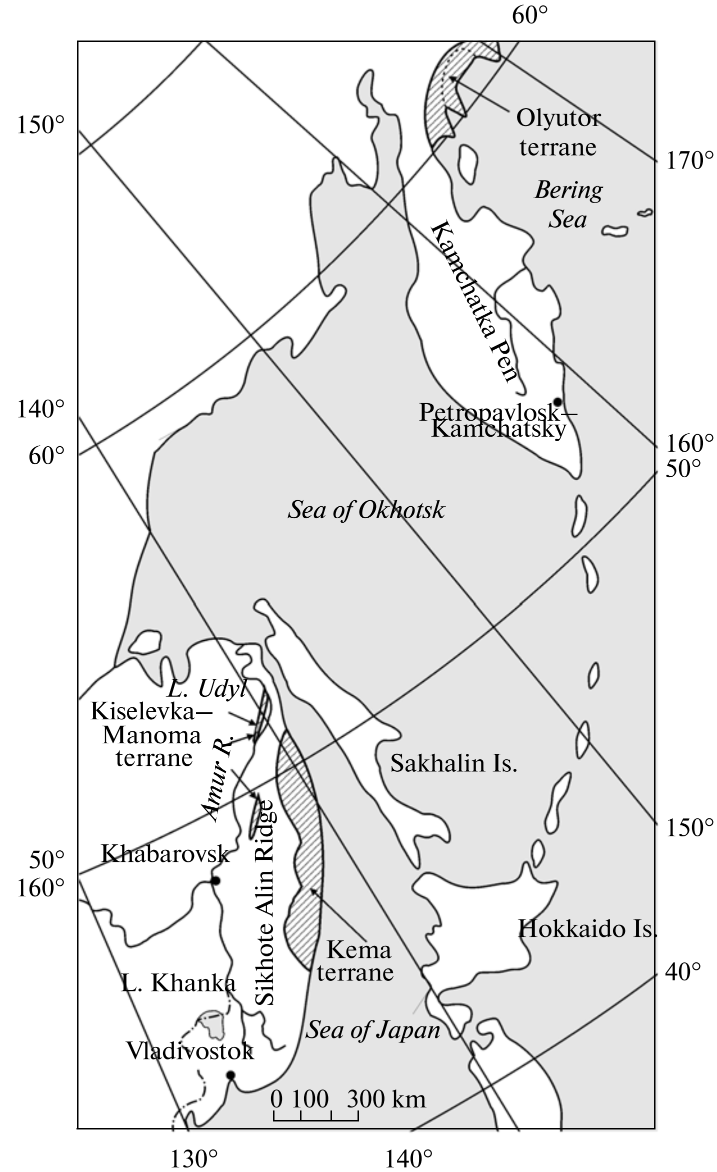


Fig. 1. Schematic location of the studied objects. Mineralogical–geochemical provinces of the Olyutor terrane: (I) Northern; (II) Southern.

The petrographic composition of rocks was studied with a polarization microscope. Contents of the major oxides in rocks were determined by the traditional chemical method. In total, we analyzed 1077 specimens of sandy and sandy–silty rocks. Analyses were performed in physicochemical analysis laboratories of the Far East Geological Institute (Vladivostok).

1 Interpretation of the chemical composition of terrigenous rocks was based on the well-known and sufficiently tested methods described in (Bhatia, 1983; Maynard et al., 1982; Roser and Korsch, 1986) that allow one to recognize analogues of the recent geodynamic settings in the geological past.

GEOLOGICAL POSITION AND STRUCTURAL FEATURES OF ROCKS IN THE REGION

The Olyutor terrane is located at the southern Koryak Highland and extends in the east-northeastern direction along the coast of the Bering Sea over 500 km. The terrane, a part of the Mesozoic–Cenozoic Sakhalin–Kamchatka orogenic belt, is separated in north from the Koryak Highland by the Vatyn overthrust fault (*Geologiya*..., 1987). The geological section of the terrane comprises large allochthonous slabs (Chekhovich, 1993) composed of Early Cretaceous–Neogene rocks that were formed in different facies settings, probably, at a great distance from the present-day position. Based on (*Geologiya*..., 1987; Kovalenko, 2003; Malinovsky, 1993; Markevich et al., 1987; Solov'ev et al., 1998, 2000), the region incorporates the following lithostructural complexes (Fig. 2): (1) volcanogenic–siliceous complex (basalts, hyaloclastites, lava breccia, jaspers, cherts and clayey varieties, and less common clayey rocks, sandstones, and limestones); (2) volcanosedimentary complex (basalts, lava breccia, tuffs, volcanomictic sandstones, siltstones, cherts, and clayey and siliceous–clayey rocks); (3) turbidite complex (thick piles of turbidites with horizons of siltstones, sandstones, gritstones, tuffs, and mixtites); and (4) molasse complex (sandstones, siltstones, gritstones, conglomerates, tuffs, and coals).

The Kiselevka–Manoma terrane of the Albian–Cenomanian accretion prism is situated in the lower Amur River region and extends as a discrete band (20–40 km wide) in the northeastern direction along both banks of the Amur River over 700 km. As is evident from Fig. 2, the terrane is composed of packages of tectonic slabs of Jurassic–Early Cretaceous siliceous and siliceous–clayey rocks (with basalt and limestone inclusions) and Early Cretaceous siltstones and turbidites (Markevich et al., 1996, 1997; Zyabrev et al., 2005). The Hauterivian–Cenomanian volcanosedimentary island-arc rocks occur at the northeastern flank of the terrane in the Lake Udyl area (Udyl fragment). Her one can see a tectonic juxtaposition of lithostructural complexes of island arcs, ocean, and continental margin. Therefore, this terrane can be considered a complex accretion prism with imbricate overthrust structure. All rocks are divided into the following complexes (Markevich et al., 1996, 1997).

The siliceous complex, a fragment of the oceanic basement of an island arc, is composed of pelagic radiolarian jaspers and cherts, their clayey varieties, and the less common alkaline basalts and limestones. Clastic rocks are virtually missing in this rock complex. The volcanosedimentary complex comprises an alternation of tuffs, tephroids, volcanomictic sandstones, siltstones, turbidites, mixtites, tuffosilicites, clayey and siliceous–clayey rocks, and rare basalts. The graywacke complex is characterized by an appreciable facies variation. They can be divided into four sequences with different composition and structures: (1) mudstones (proper mudstones and siliceous mudstones); (2) mixtites (proper mixtites, clayey rocks, sandstones, tuffs, rare turibidites and submarine slumps); (3) sandstones (proper sandstones, clayey rocks, turbidites, rare mixtites, submarine slumps, and tuffs); and (4) siltstones (siltstones and mudstones with thin sandstone interlayers, and rare mixtites).

The Kema terrane makes up a band (up to 80 km wide) at the eastern Sikhote Alin Ridge and extends along the coast of the Sea of Japan over 850 km. Some sectors of the Kema terrane are exposed in erosion windows among the Late Cretaceous volcanics of the East Sikhote Alin belt. The terrane comprises the Barremian(?)–Albian rocks dominated by turbidites, horizons of siltstones and mixtites, and beds of basic volcanics and their pyroclasts (Fig. 2). These rocks are considered as sediments of an Early Cretaceous back-arc basin in the Moneron–Samarga island-arc system (Malinovsky et al., 2002, 2005a, 2005b). Rocks of this terrane are subdivided into the following lithostructural complexes.

The lower turbidite complex is composed of turbidite piles separated by horizons of siltstones, sandstones, gritstones, and submarine slumps. The coarse-clastic complex comprises the fine-pebble conglomerates, gritstones, sandstones, mixtites, rare turbidite lenses, horizons of submarine slumps and tuffs, and rare basalt sheets. The volcanogenic complex is mainly composed of basalts, their tuffs, and tephroids. The rare members are represented by volcanomictic sandstones, turbidite piles, and horizons of submarine slumps and mixtites. The upper turbidite complex includes thick piles of turbidites coupled with rare horizons of sandstones, siltstones, mixtites, and submarine slumps.

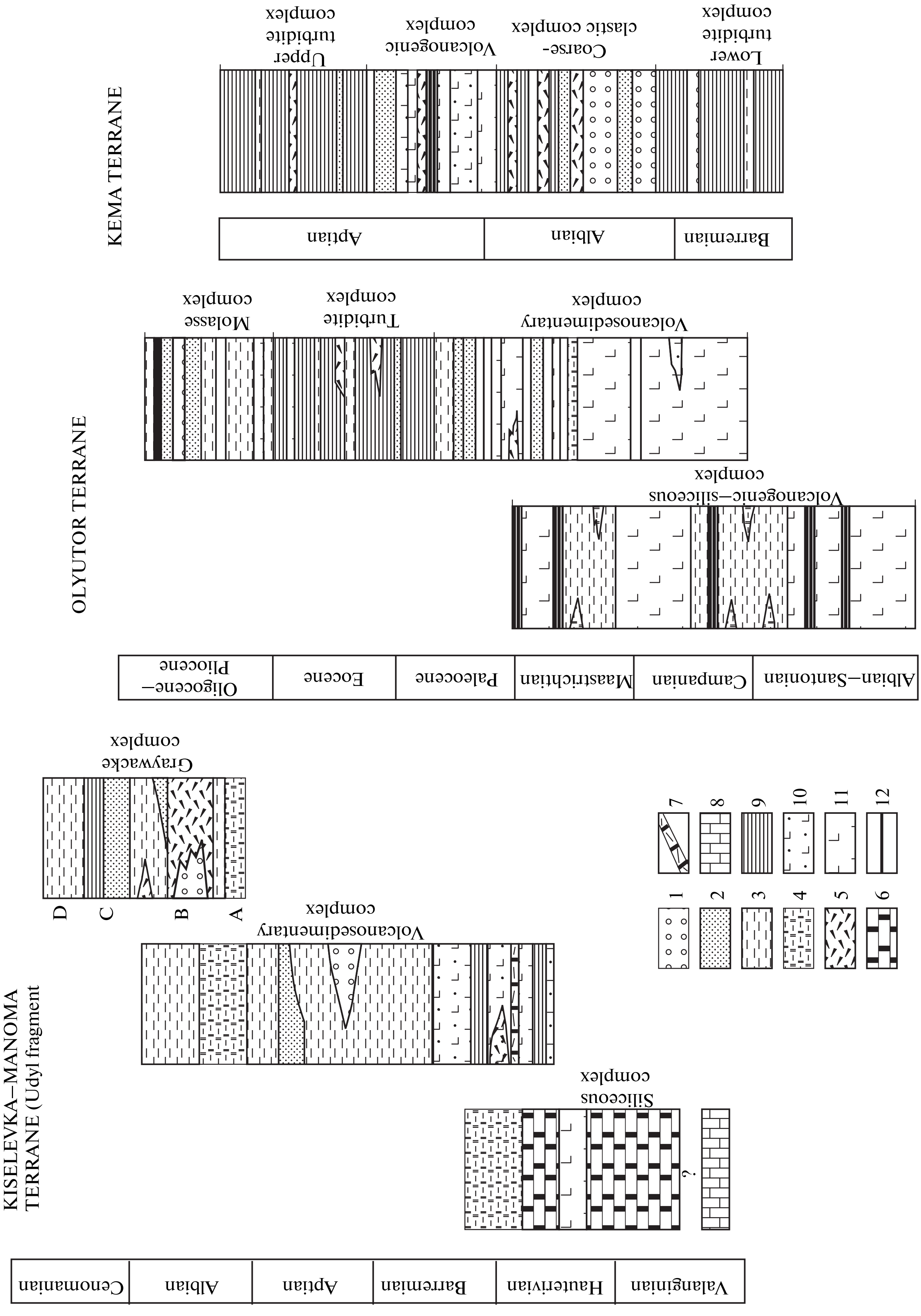
COMPOSITION AND GEOCHEMISTRY OF TERRIGENOUS ROCKS

A brief petrographic description of the petrography of terrigenous rocks from each object studied is given below, because the petrographic composition governs their geochemical features.

The geochemical characteristics of sandy and sandy–silty rocks is usually described based on average contents of the major oxides and some petrochemical coefficients (modules) presented in the table. All data on the objects studied are grouped in accordance with the identified lithostructural complexes.

Based on the lithological composition of terrigenous rocks (Malinovsky, 1993; Markevich et al., 1987), the *Olyutor terrane* can be divided into the Northern and Southern provinces (Fig. 1).

In terms of the rock-forming components, sandstones of the terrane match the typical graywackes. The clastic portion (60–90 vol %) includes fragments of the terrigenous, siliceous, and effusive rocks, feldspars, quartz, chlorite, pyroxenes, and ore minerals. According to classification in (Shutov, 1967), the rocks fit graywackes and their quartz–feldspar and feldspar varieties. Provinces of the terrane show the following differences. The Southern Province is marked by higher contents of quartz (up to 23%), clasts of siliceous and terrigenous rocks (up to 65%), acid plagioclases (up to 50%), and K-feldspars (up to 20%). In contrast, the Northern Province is enriched in effusives (up to 60%) and basic and intermediate plagioclases (up to 60%). Volcanomictic sandstones of the volcanogenic–siliceous and volcanosedimentary complexes are characterized by the lowest quartz content (up to 8%), but higher contents of plagioclases (up to 60%) and effusive fragments (up to 60%). Basic and intermediate effusives prevail in the clasts, while pyroclastic, terrigenous, and siliceous rocks are subordi-


KEMA TERRANE
Upper turbidite complex
Volcanogenic complex
Coarse-clastic complex
Lower turbidite complex
Aptian
Albian
Barremian
OLYUTOR TERRANE
Molasse complex
Turbidite complex
Volcanosedimentary complex
Volcanogenic–siliceous complex
Oligocene–Pliocene
Eocene
Paleocene
Maastrichtian
Campanian
Albian–Santonian
KISELEVKA–MANOMA TERRANE (Udyl fragment
Graywacke complex
A
B
C
D
Volcanosedimentary complex
Siliceous complex
?
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
1
2
3
4
5
6
7
8
9
10
11
12

←

Fig. 2. Summary lithostratigraphic columns of island-arc rocks in the studied objects.(1) Conglomerates and gritstones; (2) sandstones; (3) siltstones and mudstones; (4) siliceous–clayey rocks; (5) mixtites; (6) cherts; (7) tuffosilicites; (8) limestones; (9) turbidites; (10) tuffs and tephroids; (11) basalts and basaltic andesites; (12) coal. Sequences in the Udyl fragment of the Kiselevka–Manoma terrane: (A) mudstones; (B) mixtites; (C) sandstones; (D) siltstones.

nate. Intrusive and metamorphic rocks are rare and found only in the Southern Province.

In general, the clastic portion of silty–clayey rocks (up to 70 vol %) is similar to sandstones in composition. The sandstones are only distinguished by a higher content of rock clasts and comparatively lower content of feldspars and quartz. The clayey portion of rocks in the Northern Province is mainly composed of aggregates of fine-flaky clay minerals (primarily smectite, chlorite, and mixed-layer smectite-chlorite). Hydromica prevails in the Southern Province.

The greatest difference in the chemical composition of these provinces is related to sandstones. Variation in the silica content is most contrasting: from 55.12 to 61.53% in the Northern Province and from 58.56 to 65.11% in the Southern Province. Notable discrepancies are also observed in the contents ofFe_2O_3 (2.88–4.06 and 1.63–3.22%, respectively), MgO (2.57–4.16 and 2.08–2.40%), and CaO (2.67–5.23 and 1.23–1.75%). All these facts testify to a greater femic module of rocks in the Northern Province relative to the Southern Province. In general, with respect to the chemical composition, sandstones of both provinces belong to typical graywackes close to the average graywackes in (Pettijohn, 1978), graywackes and tuffaceous sandstones of the Franciscan Formation in California, and Jurassic graywackes in the Greater Caucasus (Shutov, 1975). However, the studied rocks are distinguished from counterparts in the regions listed above by depletion in SiO_2, FeO, and K_2O, but enrichment in Al_2O_3, Fe_2O_3, and MgO.

In terms of the chemical composition, the silty–clayey rocks are usually close to sandstones (see the table). However, the former rocks are enriched in clay minerals and depleted in clastic components. Therefore, they are enriched in Al_2O_3 (14.85–16.76%), TiO_2 (0.65–0.78%), and K_2O (1.13–2.33%), but depleted in SiO_2 (56.16–63.12%) and Na_2O (2.03–4.04%). The provinces show different compositions of the silty–clayey rocks. Relative to the Southern Province, the Northern Province is marked by lower contents of SiO_2 and K_2O, but higher contents of Al_2O_3, MgO, CaO, and total Fe.

In the Udyl fragment of the Kiselevka–Manoma terrane, sandstones occur only in the volcanosedimentary and graywacke complexes. They represent polymictic, often volcaniclastic rocks that fit feldspar–quartz, quartz–feldspar, and proper graywacke rocks in the classification of Shutov (1967). Of particular interest are feldspar graywackes of the volcanosedimentary complex primarily composed of the pyroclastic eruption products and volcanomictic materials. Differences between the complexes are observed in the contents of major components and the differences are most prominent in the content of quartz: the quartz content is no more than 7% in the volcanosedimentary complex and 10–40% in the graywacke complex. The content of feldspars in them is 60–80 and 10–50%, respectively. Among the feldspars, albite and oligoclase make up as much 95%, while the K-feldspars (primarily orthoclase) account for no more than 5%. Among rock fragments that account for 15–30% of the volcanosedimentary complex, the dominant portion is composed of basic and intermediate volcanics (as much as 70%), whereas the subordinate portion consists of sedimentary rocks (up to 30%) and altered volcanic glass (up to 15%). In the graywacke complex, the clastic portion (40–55%) is composed of the dominant fine-grained sedimentary (30–50%) and siliceous (20–40%) rocks, the subordinate effusive rocks (5–15%), and the rare felsic intrusive and metamorphic rocks.

The clastic portion (5–80 vol %) of silty–clayey rocks is composed of the silty and rare psammitic grains of plagioclase, quartz, basic volcanics, and glass. Fragments of cherts, volcanics, pyroxenes, and ore minerals are found in some places. Clayey minerals of all complexes are very homogeneous and mainly represented by two minerals (hydromica and chlorite). Smectite and smectite-chlorite occur sometimes in the volcanosedimentary complex.

Contents of the major oxides differ appreciably in different complexes of the terrane (Markevich et al., 1997). Relative to the graywacke complex, sandstones of the volcanosedimentary complex are primarily marked by substantially lesser contents of SiO_2 (58.56 and 66.90–67.05%, respectively), FeO (1.56 and 2.40–2.87%), and K_2O (0.96 and 1.93–2.00%), but higher contents of Al_2O_3 (19.16 and 12.99–13.26%), Na_2O (6.87 and 2.61–3.15%), Fe_2O_3 (4.32 and 2.82–3.04%), MgO (2.71 and 2.29–2.55%), and CaO (2.41 and 1.56–1.92%). Such discrepancies are caused by the appreciable higher contents of clasts of basic volcanics and feldspars in sandstones of the volcanosedimentary complex. In terms of composition, sandstones of the graywacke complex match the medium graywacke in Pettijohn's classification (1978), as well as graywacke and tuffaceous sandstones of the Franciscan Formation.

Silty–clayey rocks of different complexes are also marked by different compositions. The discrepancy is most contrasting for the average silica content in the volcaniclastic and graywacke complexes (62.54 and 65.42–66.50%, respectively) and less contrasting for Fe_2O_3 (4.56 and 2.46–3.73%), MnO (0.27 and

1 Average chemical composition (wt %) of terrigenous rocks of the island-arc complexes in 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																			
Olyutor terrane																			
Northern Province																			
Volcanogenic–siliceou	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
Volcanosedimentary	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
Molasse	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																			
Volcanosedimentary	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
Molasse	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)																			
Volcanosedimentary	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:																			
mixtites	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
sandstones	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
Sandy rocks																			
Olyutor terrane																			
Northern Province																			
Volcanogenic–siliceou	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
Volcanosedimentary	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
Molasse	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																			
Volcanosedimentary	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
Molasse	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)																			
Volcanosedimentary	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:																			
mudstones	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
mixtites	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
sandstones	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
siltstones	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	0.62	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. Analyses were carried out at the Far East Geological Institute, Far East Division, Russian Academy of Sciences (V.N. Kamenskaya, G.I. Makarova, L.A. Avdenina, and L.A. Vrzhosek, analysts).

0.08–0.13%), MgO (3.41 and 1.78–2.13%), and K_2O (1.74 and 2.21–2.47%).

Sandstones of the *Kema terrane* show a rather homogeneous composition of the rock-forming components and generally correspond to polymictic rocks. The clastic portion (60–80 vol %) includes quartz,
1 feldspars, rock clasts (terrigenous, siliceous, and effusive), volcanic glass, and ore minerals. According to Shutov's classification (1967), the sandstones primarily correspond to the feldspar–quartz and quartz–feldspar graywackes and to the feldspar arkoses in some places. The major component of sandstones is represented by quartz (30–52%). Its content is highest in the lower turbidite complex (35–52%) and slightly lower in the volcanogenic complex (31–42%). The content of feldspars in the sandstones is 22–41%. The feldspars occur as plagioclases (60–95%) mainly represented by albite and oligoclase. Potassic feldspars (up to 20%) are dominated by orthoclase, and microcline is rare. Rock clasts (17–42 vol %) are represented by the siliceous (30–45%, on the average) and sedimentary (25–35%) rocks coupled with the subordinate basic effusives (15–30%). The effusive rock clasts are most abundant in sandstones of the volcanogenic complex (up to 70%). Clasts of intrusive and metamorphic rocks are rare.

Depending on the grain size composition of the silty–clayey rocks (siltstones, mudstones, and silty mudstones), the content of clastic particles in them varies from 5 to 70–80%. The silty grains are commonly represented by quartz and feldspars. Cherts, effusives, fine-clastic rocks, biotite, volcanic glass, and ore minerals are rare. The clayey component is represented by hydromica coupled with the less common smectite and chlorite, which prevail in the volcanogenic complex.

The sandstones have a rather homogeneous chemical composition (Malinovsky et al., 2005a, 2005b). However, rocks of the volcanogenic complex, relative to other complexes, are slightly depleted in SiO_2 (73.26 and 74.34–77.30%, respectively), but enriched in TiO_2 (0.38 and 0.25–0.35%) and Al_2O_3 (10.76 and 8.18–10.24%). In general, with respect to the composition of major oxides, the Kema sandstones are transitional between arkoses and graywackes. Relative to the average arkoses, the Kema sandstones are marked by a slightly lower SiO_2 content; higher Al_2O_3, MgO, and total Fe contents; and prevalence of Na_2O over K_2O, a typical feature of graywackes (Pettijohn, 1978). In general, the silty–clayey rocks show a similar chemical composition in all complexes. Relative to the sandstones, they are marked by lower contents of SiO_2 (64.75–67.23%) and CaO (1.26–2.16), but higher contents of TiO_2 (0.54–0.62%), Al_2O_3 (13.89–14.52%), and (FeO + Fe_2O_3), i.e., total Fe (4.36–5.03%). Moreover, K_2O prevails over Na_2O.

Subdivision of aluminosilicate clastic sedimentary rocks based on the aluminosilicate (A) and femic (F) modules proposed by A.A. Predovsky (1980) is shown

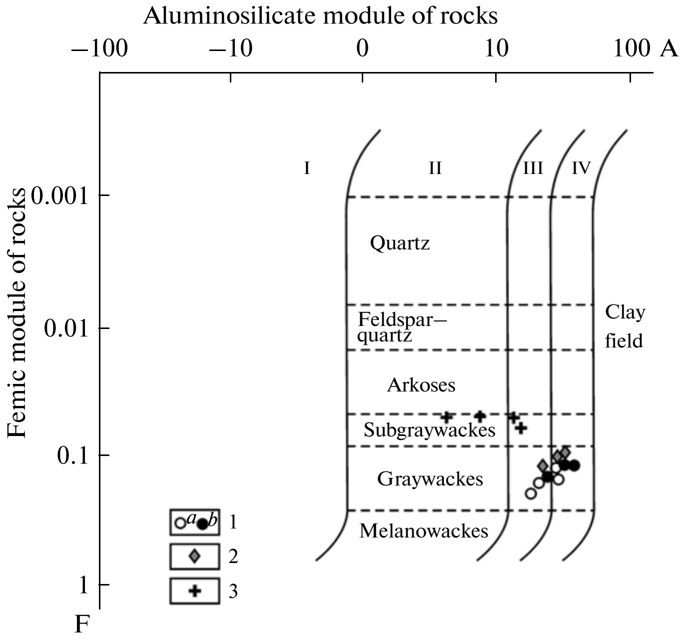


Fig. 3. The A–F diagram for sandy rocks of the studied objects (Predovskii, 1980). A = Al_2O_3 – (K_2O + Na_2O + CaO); F = (Fe_2O_3 + FeO + MgO)/SiO_2 (molecular weights). (I–IV) Rocks: (I) transitional to tuffite and proper tuffite rocks; (II) low-aluminous; (III) clayey; (IV) high-aluminous. (1–3) Terranes: (1) Olyutor (provinces: (*a*) Northern, (*b*) Southern); (2) Kiselevka–Manoma terrane (Udyl fragment); (3) Kema terrane.

in Fig. 3. With respect to these parameters, sandstones from island-arc complexes of the Russian Far East show certain similarities and dissimilarities. In terms of the aluminosilicate module, all sandstones of the Olyutor and Kiselevka–Manoma terranes are located in the domains of aluminous and high-aluminous rocks. In terms of the femic module, they fall into the graywacke domain. At the same time, sandstones of the Southern Province are closer to the graywacke domain than their counterparts from the Northern Province with respect to the femic module. Sandstones from the Udyl fragment of the Kiselevka–Manoma terrane are located even closer to the graywacke domain. Rocks of the Kema terrane exhibit the greatest distinctions in terms of these parameters. With respect to the femic index, they fall into the graywacke domain and even approach the arkose domain. With respect to the aluminosilicate module, they fall into the aluminous and low-aluminous domains. In general, scatter of averaged data points of sandstones with respect to the aluminosilicate module can be explained by different contents of the aluminous matrix or pyroclastic admixture in the rocks.

In the Si–Al–Fe diagram based on (Moor and Dennen, 1970), data points of sandstones from the studied objects make up a line coinciding with or nearly parallel to the granite–basalt line. According to this classification, sandstones of the Olyutor and

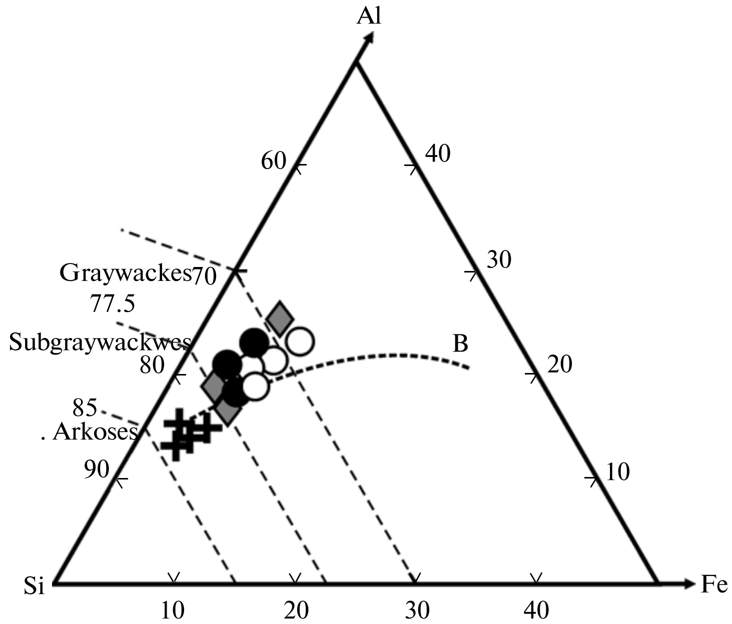


Fig. 4. The Si–Al–Fe diagram for sandy rocks in the studied objects (at. wt.) (Moor and Dennen, 1970). The G–B line shows the granite–basalt trend. See Fig. 3 for legend.

Kiselevka–Manoma terranes match graywackes. At the same time, sandstones from two provinces of the Olyutor Province are clearly separated from each other, while volcanosedimentary rocks are isolated in the Kiselevka–Manoma terrane. Sandstones of the Kema terrane make up a prominent group with the granite-type composition in the subgraywacke domain.

Since absolute contents of the major oxides reflect
1 the composition of not only the clastic portion of terrigenous rocks, but also their matrix, one can make more substantiated conclusions about similarities and dissimilarities of the studied objects based on the most informative ratios of oxides and their sums (petrochemical modules) presented in the table, as well as module diagrams (Fig. 5) proposed in (Yudovich, 1981; Yudovich and Ketris, 2000).

The hydrolyzate module (HM), which represents the ($Al_2O_3 + TiO_2 + Fe_2O_3 + FeO + MnO/SiO_2$ ratio, is used for the quantitative assessment of the chemical weathering of rocks, i.e., maturity of rocks. Value of this parameter depends on the amount of clastic quartz or silica-rich rock clasts, on the one hand, and the share (and composition) of feldspars and clayey components in the matrix, on the other hand.

Ion terms of the hydrolyzate module, sandstones of all objects studied are characterized by low maturity, suggesting that their formation was primarily related to mechanical destruction of parental rocks rather than chemical weathering. Values of the HM module vary from 0.47–0.35 for the least mature rocks of the Northern Province (Olyutor terrane) to 0.14–0.19 for the most mature rocks (Kema terrane). The comparatively higher maturity of the Kema sandstone is likely caused by the higher content of clastic quartz and siliceous rocks in them and the lower content of feldspars and clayey matrix. In the clayey rocks, the HM module value is usually higher than in the sandstones because of the lower content of quartz and feldspars and the higher content of clayey matter. Exception is provided by rocks of the volcanogenic–siliceous and volcanosedimentary complexes of the Olyutor and Kiselevka–Manoma terranes, because sandstones of these complexes are strongly depleted in quartz. At the same time, they are enriched in basic effusives and clayey matter of cement and matrix.

The femic module (FM), which represents the ($Fe_2O_3 + FeO + MnO + MgO/SiO_2$ ratio, is very convenient for the identification of graywackes and arkoses (Pettijohn, 1978). Its values are maximal in the volcaniclastic graywackes (Yudovich and Ketris, 2000) because of abundance of the Fe- and Mg-rich fragments of volcanic rocks and glass, as well as clayey cement and matrix, in them. In general, the femic module reflects intensity and rate of the weathering and burial of material: the amount of femic elements transferred to solution due to weathering has a negative correlation with the FM value. Consequently, the sandstones show a greater difference from the typical graywackes.

In terms of the femic module, the typical graywackes include sandstones of the Kiselevka–Manoma (0.12–0.15) and Olyutor (0.12–0.25) terranes. At the same time, one can clearly see distinctions between rocks of the Northern Province (0.12–0.18) and its marginal areas (0.15–0.25). In addition,

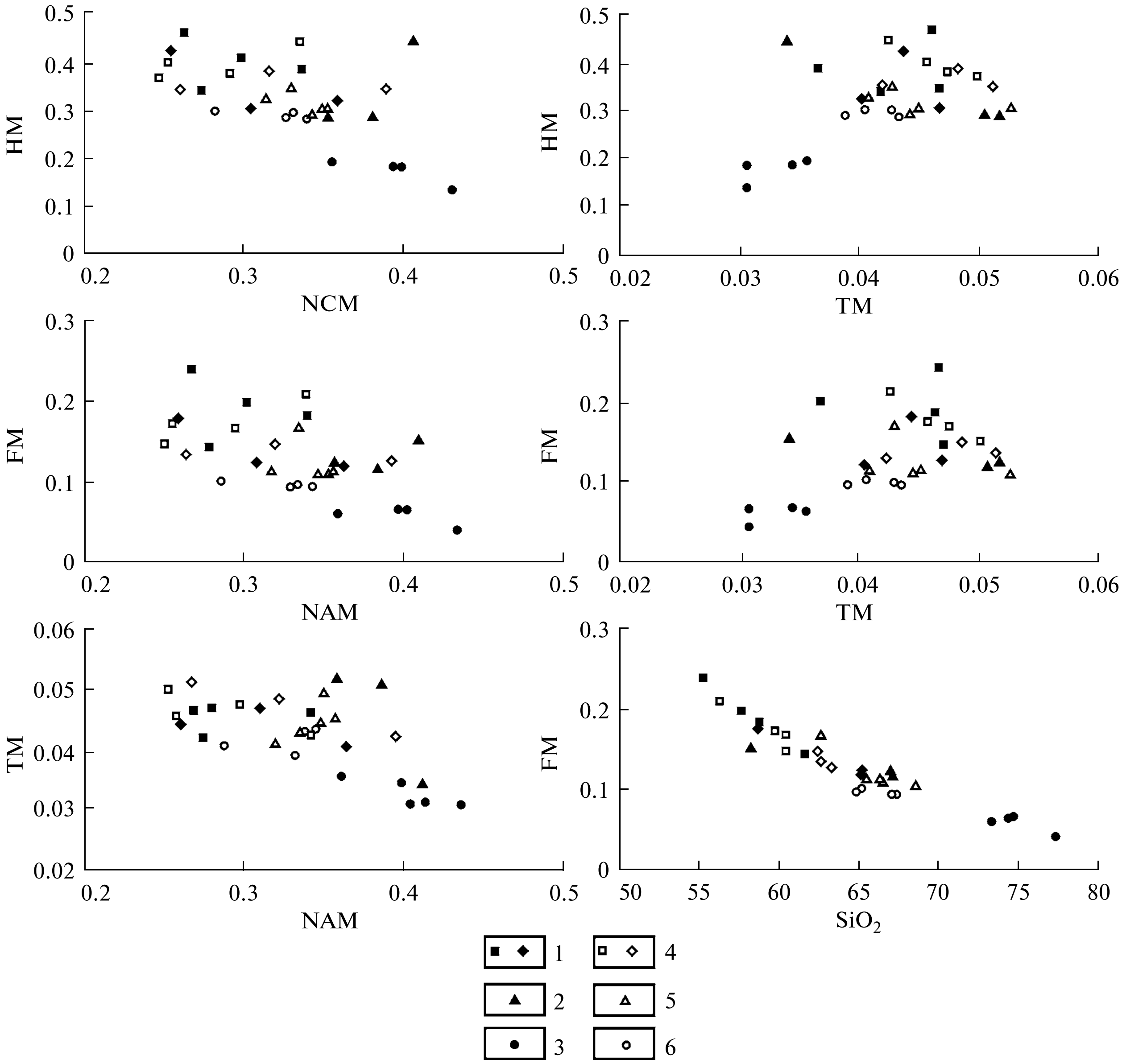


Fig. 5. Module diagrams for sandy and silty–clayey rocks in the studied objects (Yudovich and Ketris, 2000). (1–3) Sandy rocks; (4–6) silty–clayey rocks. Terranes: (1, 4) Olyutor (provinces: (*a*) Northern, (*b*) Southern); (2–5) Kiselevka–Manoma terrane (Udyl fragment); (3, 6) Kema.

sandstones in the volcanogenic–siliceous and volcanosedimentary complexes have high FM values, suggesting their affiliation to volcaniclastic graywackes. The femic module is significantly lower in sandstones of the Kema terrane (0.04–0.07), which is consistent with the lower content of basic volcanic clasts and the higher content of quartz, siliceous rocks, and granitoids in them. In terms of this parameter, the Kema sandstone occupies an intermediate position between graywackes and arkoses. According to (Yudovich and Ketris, 2000), relative to sandy rocks, clayey rocks are typically marked by higher FM values. In our case, this rule is confirmed for rocks of the Kema terrane. In silty–clayey rocks of the Olyutor and Kiselevka–Manoma terranes, the FM value is lower or equal to that in sandstones. Similar results were obtained by Markevich (1985) for flysch sediments from the Il'pin Peninsula of East Kamchatka.

The normalized alkalinity module (NAM), which represents the (Na_2O + K_2O/Al_2O_3 ratio proposed in (Middleton, 1960), allows one to identify the volcanic admixture in sedimentary rocks (Yudovich and Ketris, 2000). Values of this module are usually higher in arkoses because of the abundance of micas and feldspars (potassic varieties included) in them and lower in graywackes because of the abundance of clayey matter and clasts of basic volcanics and clayey-silty matrix.

In terms of the NAM value, the closest analogues of arkoses are represented by sandstones of the Kema terrane (0.36–0.43), in which the volcanomictic material likely contains a small amount of the sialic clastic admixture. The NAM value is slightly lower in sandstones of the Kiselevka–Manoma terrane (0.35–0.41). This parameter shows the lowest value in typical graywackes of the Olyutor terrane (0.26–0.36), in which the high-aluminous volcanics make up the major clastic component and the clayey material (mainly chlorite and smectite) is abundant. In silty-clayey rocks of the objects studied, the NAM value is commonly lower than in sandstones, probably, due to their depletion in feldspars and enrichment in clays. Exception is provided by the volcanogenic–siliceous and volcanosedimentary complexes of the Olyutor terrane. According to (Malinovsky, 1993), clayey rocks in the latter complexes are often composed of only smectite (up to 90%).

The titanium module (TM), i.e., the TiO_2/Al_2O3 ratio introduced by Migdisov (1960), allows one to assess the composition of rocks (in particular, their titanium potential) in the provenance and the sedimentation zone dynamics, which promotes the sorting of Ti-bearing minerals and clayey matter (Yudovich and Ketris, 2000).

High TM values in sandstones are usually related to the admixture of basic volcaniclastic material. Despite a significant share of the volcanomictic and pyroclastic admixture in the clastic component, sandstones of all objects studied in our work are marked by low TM values, probably, because the material is related to destruction of the low-Ti (and high-aluminous) island-arc volcanic series. The TM value in sandstones ranges from 0.036 to 0.047 in the Olyutor terrane and from 0.034 to 0.052 in the Kiselevka–Manoma terrane. In both terranes, the value is lowest for rocks of the volcanosedimentary complexes with the highest content of volcaniclastic material. The values are even lower in the arkose-type Kema sandstone (0.031–0.035) due to the admixture of felsic igneous rock clasts, which are characterized by low TM values. All rocks studied are marked by high Ti contents in the silty–clayey rocks (relative to sandstones). This pattern is typical of volcanomictic rocks, the formation of which is not accompanied by any appreciable mechanical differentiation of the pelitic and psammitic fractions (Yudovich and Ketris, 2000).

Variation trends in the average chemical composition of sandy and silty–clayey rocks from all objects, as well as their similarities and dissimilarities, are clearly seen in the module HM–NAM, FM–NAM, TM–NAM, HM–TM, FM–TM, and FM–SiO_2 diagrams (Fig. 5) compiled after (Yudovich and Ketris, 2000). In all diagrams, the rocks make up the following series: Kema terrane – Kiselevka–Manoma terrane – Olyutor terrane (Southern and Northern provinces). One can see positive correlation in FM–TM and HM–TM pairs and negative correlation in HM–NAM, FM–NAM, TM–NAM, and FM–SiO_2 pairs. This fact testifies to the petrogenic (volcanomictic) nature of rocks and, consequently, their affiliation to graywackes.

At the same time, data points of rocks in all diagrams make up two autonomous domains. The first domain includes the arkose-type sandstones of the Kema terrane characterized by high contents of silica, maximal NAM values, and lower HM, FM. and TM values. This specific feature of sandstones of the Kema terrane is likely related to their formation from both the island-arc volcaniclastic material and the decay products of sialic blocks of a continental crust that served as the island-arc basement. The second (larger) domain includes rocks of all remaining objects, although one can see certain discrepancies. However, all these rocks are characterized by affiliation to typical graywackes, close genetic relationship with the island-arc volcanics, and probable input of a small amount of sialic material.

Thus, the geochemical composition of terrigenous rocks from the objects under consideration indicates their low geochemical maturity, weal lithodynamic reworking, and high rate of mechanical weathering and burial of material. In all cases, the clastic material was mainly derived from the island-arc volcaniclastic rocks, which contained a certain amount of sialic material delivered from elevated blocks of the continental crust.

PALEOGEODYNAMIC INTERPRETATION OF THE RESULTS OF INVESTIGATION

The obtained geochemical data were interpreted based on the actualistic approach, i.e., comparison of the results obtained for recent deep-water sediments with ancient terrigenous rocks. The investigations revealed a close relation between the chemical composition of rocks and the geodynamic setting of provenances and sedimentation basins (Bhatia, 1983; Maynard et al., 1982; Roser and Korsch, 1986; and others).

Figure 6a shows diagrams of the genetic interpretation of the chemical composition of sandstones (Bhatia, 1983) used for the discrimination of sandstones form basins of various tectonic settings. We believe that the representative parameters Al_2O_3/SiO_2, K_2O/Na_2O, $Al_2O_3/(CaO + Na_2O)$, TiO_2, (Fe_2O_3(total) + MgO) reflect the mineral composition of rocks in the provenance and the geochemical behavior of several elements in seawater. Values of these parameters suggest that sandstones of the *Olyutor terrane* match or approach counterparts from the Mariana-type oceanic island arcs and, to a lesser extent, continental island arcs. Geotectonic settings of sedimentation basins are reconstructed with diagrams based on (Maynard et al., 1982). Subdivision of the deep-water sands in the diagrams (Fig. 6b) is based on the SiO_2/Al_2O_3 and K_2O/Na_2O values. In this diagram, data points of the Olyutor sandstones are clustered in the fore-arc (FA) and back-arc (BA) basins of

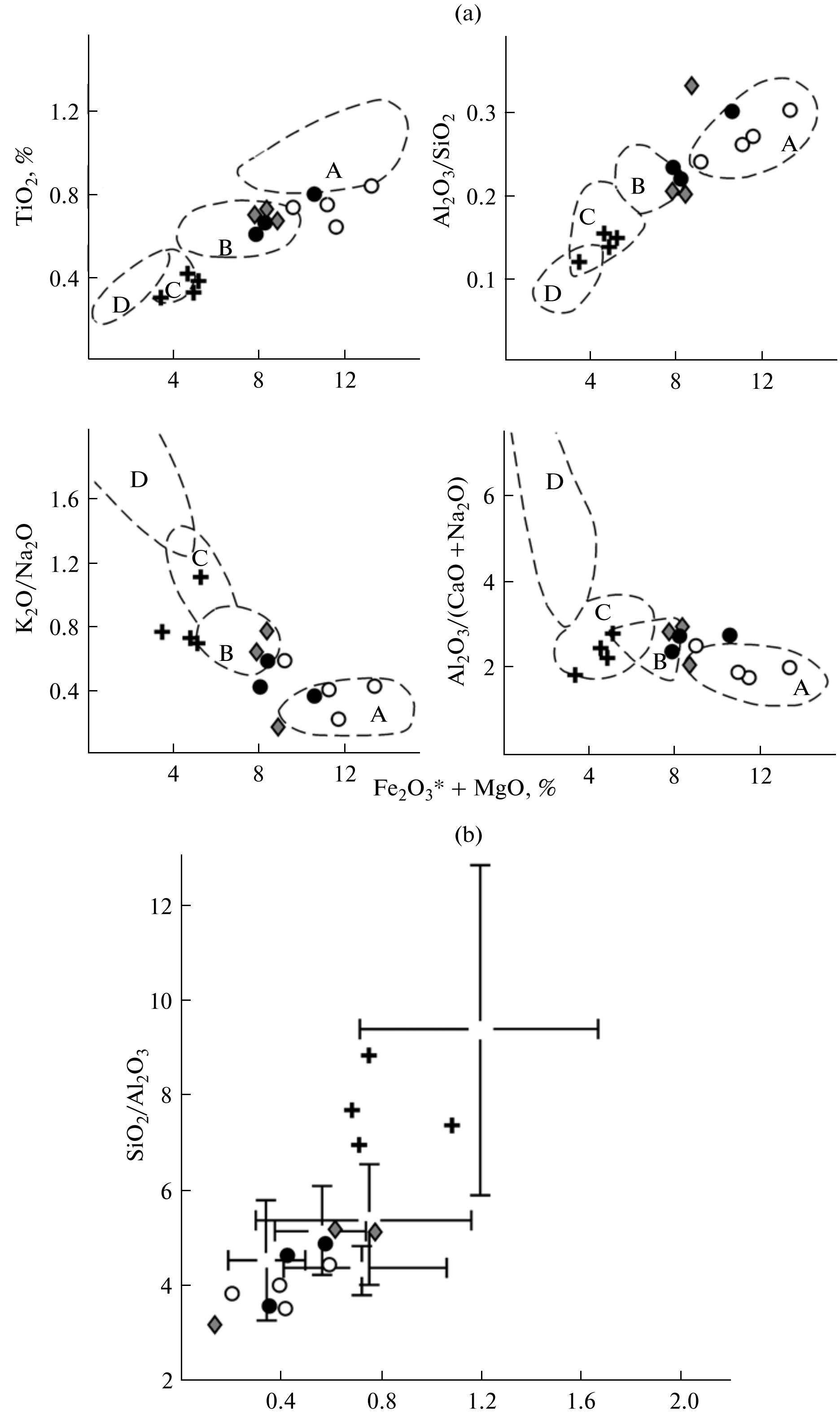


Fig. 6. Diagrams of the chemical composition of sandy rocks from various geodynamic settings. (a) Basin types (Bhatia, 1983). Dotted lines delineate fields with values of the geochemical parameter of ancient sandstones conjugated with (*A*) oceanic island arcs, (*B*) continental island arcs, (*C*) active continental margins, and (*D*) passive continental margins. (Fe_2O_3*) Total Fe. (b) Basin settings (Maynard et al., 1982). Intersecting lines show standard deviations from the average composition of recent deep-water sands from basins in passive continental margins (*TE*); active continental margins conjugated with strike-slip dislocations (*SS*), continental-margin magmatic arcs (*CA*), and oceanic volcanic arcs: (*FA*) fore-arc, (*BA*) back-arc. See Fig. 3 for legend.

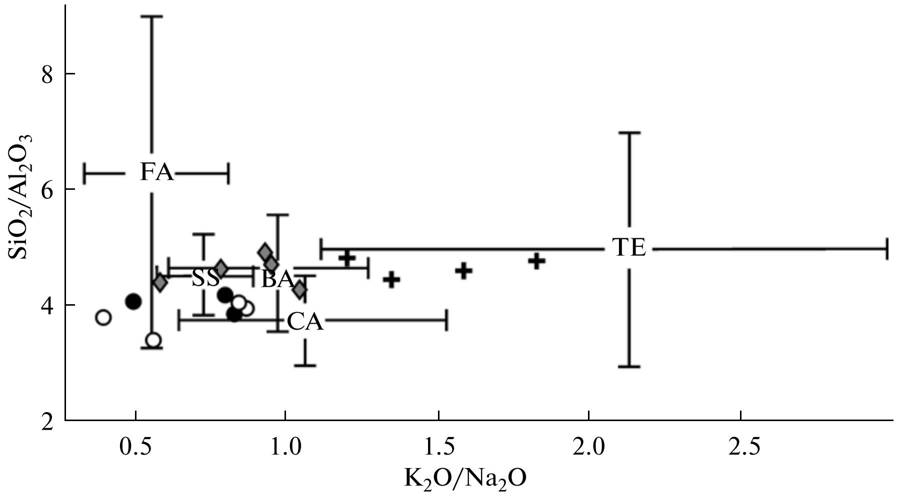


Fig. 7. Diagram of the chemical composition of silty–clayey rocks from various basin settings (Maynard et al., 1982). See Figs. 3 and 6 for legend and abbreviations.

the intraoceanic island arcs. Clastic material for the sandstones was likely derived from the island-arc volcaniclastic rocks. At the same time, the diagrams exhibit certain discrepancies in the composition of sandstones from the two terrane provinces, suggesting the existence of an additional sialic (continental) source of clastic material exerting a constant influence on sedimentation in the Central Province. This source could be represented by blocks of a mature continental crust containing metamorphosed rocks and granitoids (Malinovsky, 1993).

Paleotectonic interpretation of the chemical composition of silty–clayey rocks given in the SiO_2/Al_2O_3–K_2O/Na_2O diagram (Fig. 7) based on (Maynard et al., 1982) does not contradict the interpretation based on the composition of sandstones. All data points of the silty–clayey rocks are clustered in the island-arc domains. At the same time, they approach the back-arc (BA) and fore-arc (FA) settings of basins in the intraoceanic island arcs.

A slightly different tectonic interpretation of the chemical composition of clayey rocks was proposed in (Roser and Korsch, 1986). Their K_2O/Na_2O–SiO_2 diagram (Fig. 8) shows basins of oceanic island arcs (ARC), as well as passive (PM) and active (AM) continental margins. Sandy–clayey rocks of the Olyutor terrane are clustered in the domain of basins related to the oceanic island arcs. This fact is consistent with the data presented above.

1 Interpretation of the chemical composition of terrigenous from the *Udyl fragment of the Kiselevka–Manoma terrane* based on the actualistic principle suggests the existence of several provenances and sedimentation settings. As mentioned above, clastic rocks are virtually missing in the siliceous complex. Therefore, one can infer its geodynamic setting only based on indirect indicators, in particular, heavy minerals extracted from the silty–clayey rocks. Prevalence of minerals like clinopyroxene in the femic association is typical of deep-water basins in marginal seas of the Pacific, where the clastic material was mainly derived from the island-arc volcaniclastic transported from an oceanic arc of the Izu–Bonin type (Malinovsky and Markevich, 2007). In all diagrams (Figs. 6–8), data points of the volcanosedimentary complex fit the oceanic island arc and fall into the domain of fore-arc (FA) basins. In the diagrams proposed by Bhatia (Fig. 6a) and Maynard et al. (Figs. 6b, 7), data points of sandstones of the graywacke complex are shifted toward the domains of continental-margin and volcanic island-arc basins. However, they are shifted toward the domain of active continental margins (ACM) in the diagrams proposed by Roser and Korsch (Fig. 8). Such deviation is caused by the lower femic content and higher maturity of these rocks due to the presence of erosion products of the sialic (continental) rocks therein.

Genetic interpretation of the chemical composition is not always unambiguous for sandstones of the *Kema terrane*. Figure 6a based on (Bhatia, 1983) shows that sandstones from basins of various tectonic settings are clustered in different domains. Data points of the Kema sandstone fall into (or approach) the basins of active continental margins and basins conjugated with island arcs in a mature continental crust (e.g., Japanese Islands). However, the data points do not exactly fall into the domain of continental island arcs due to low contents of the total Fe and Mg (i.e., low femic module in the sandstones), as well as a relatively high maturity of rocks due to the abundance of quartz and siliceous rock fragments therein. In Fig. 6b based on (Maynard et al., 1982), the sandstones occupy an intermediate position between the sands from basins associated with the passive continental margins (TE) and continental-margin arcs (CA). Deviation of data points of sandstones from the basins

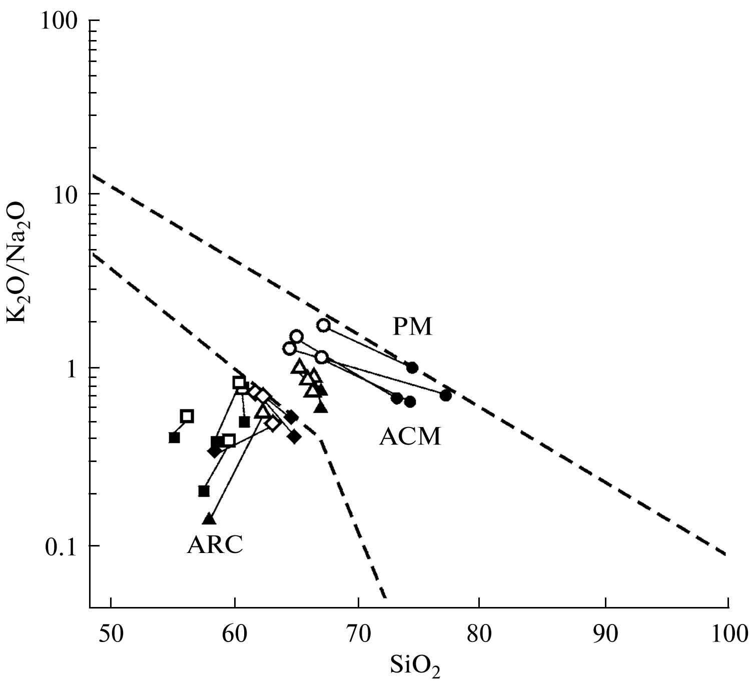


Fig. 8. The (K_2O/Na_2O)–SiO_2 diagram for sandy and silty–clayey rocks in the studied objects (Roser and Korsch, 1986). Basins of tectonic settings: (PM) passive continental margins, (ACM) active continental margins, (ARC) oceanic island arcs. Tie lines join the sandy and silty–clayey rocks from a single complex. See Fig. 5 for legend.

of active continental margins and continental-margin arcs is commonly attributed to the atypical property of these sandstones (prevalence of K over Na) due to the presence of fragments of basalts (shoshonites) of the high-K calc-alkaline series that are typical of the back-arc sectors (Semanenko et al., 2004). Paleotectonic interpretation of the chemical composition of silty–clayey rocks (Figs. 7, 8) does not contradict the interpretation based on the sandstone composition and even shows a higher certainty. Data points of the silty–clayey rocks are primarily confined to domains of basins of active continental margins and island arcs that are developed in the continental crust.

CONCLUSIONS

Examination of the lithological composition of sandy and clayey rocks from various Cretaceous–
1 Paleogene terrigenous complexes of Sikhote Alin and Kamchatka made it possible to unravel the island-arc nature of these objects and make the following conclusions.

1 Based on the lithological composition of terrigenous rocks, the Olyutor terrane can be divided into two mineralogical–geochemical provinces that were formed during the input of material from compositionally different provenances. The sedimentary material was delivered to basins of both provinces mainly from the destructed Cretaceous–Paleogene Achaivayam oceanic island arc (Shapiro, 1995) and synsedimentary volcanic processes. At the same time, sedimentation in the Southern Province was also appreciably affected by another source located beyond the basin. This source was likely represented by continental crust blocks located south of the Olyutor terrane at the site of the present-day Bering Sea (Malinovsky, 1993).

Provenance for sedimentation basins in the Udyl fragment of the Kiselevka–Manoma terrane was represented by volcaniclastic rocks transported from the Cretaceous Udyl oceanic island arc (Markevich et al., 1997). These rocks were mixed with material eroded from the continental margin.

In addition to the typical island-arc volcaniclastic works, continental sialic material also played a great role in rocks of the Kema terrane. The provenance likely included the continental-margin volcanic arc and elevated blocks of the continental crust at the basement. The clastic material was derived from the Early Cretaceous Moneron–Samarga island arc (Malinovsky et al., 2005a, 2005b). The back-arc basin of the latter arc accumulated the volcaniclastic material, as well as decay products of metamorphic and felsic igneous rocks at the arc basement composed of the oceanward-advancing fragments of continental crust.

Thus, the bulk chemical composition of terrige- 1
nous rocks and some geochemical modules make it possible to reliably discriminate the island-arc settings in paleobasins of orogenic regions.

In conclusion, we should mention that the Western Paleopacific in the Paleogene likely included abundant (possibly, to a greater extent than at present) intricate intraoceanic and oceanward-advancing blocks of continental crust, suggesting a complicated pattern of the convergent boundary of lithospheric plates at the eastern margin of Asia.

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SPELL: 1. terrigenous