The Composition, Source, and Depositional Environment of Lower Cretaceous Sediments in Northern Sikhote-Alin

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Abstract—The structure, composition, and source areas of Lower Cretaceous terrigenous sediments and geodynamic conditions for their deposition in the Northern Sikhote-Alin are considered. The study established that in terms of mineralogical and geochemical parameters the sandstones, being either petrogenic or first cycle deposits formed by the products of the breakdown of bedrock from the source areas, correspond to graywackes. They are characterized by low maturity, weak lithodynamic reworking of parental rocks, and high rates of deposition. The paleogeodynamic interpretation of the data suggests sedimentation in the Early Cretaceous along the continent–ocean boundary in the basin related to large-scale strike-slip motions along the transform faults. The source area combined sialic land formed by granite-metamorphic and sedimentary rocks, a mature and deeply eroded continental-margin arc, and fragments of Jurassic–Early Cretaceous accretion prisms of the Sikhote-Alin with ophiolites incorporated into their structure. All this allows the studied deposits to be considered as a part of the Early Cretaceous Zhuravlevka pull-apart terrane.

INTRODUCTION

Widespread Lower Cretaceous deposits are characteristic of the Sikhote-Alin Ridge geological structure; they occupy more than half of its area and have a total thickness of about 12 000 m [13]. The Early Cretaceous stage in the eastern margin of Eurasia largely determined the modern appearance of the geological structures of this region. The formation of different types of terranes, e.g., oceanic, island-arc, as well as related to the regime of lithospheric plate transform sliding corresponds to this time period [1, 2, 7, 13, etc.]. Ores, coal, and other mineral deposits are also localized in the Lower Cretaceous sediments. They are also promising in terms of hydrocarbon reserves.

Due to many years of research, the stratigraphy of the Lower Cretaceous sediments of Sikhote-Alin is well studied; however, the lithological information is extremely uneven. The composition of the Early Cretaceous terranes of the Southern and Western Sikhote-Alin (Kema, Zhuravlevka, Taukhin, and Nadanhada-Bikin) has been studied in the most detail [7, 9, 10, 21]. A comprehensive study of the composition of the terrigenous sediments of these terranes allowed the paleogeodynamic conditions of sedimentation basins formation to be reconstructed, and the tectonic types and rock composition of the sources of the clastic material for these basins to be established.

Such studies are still scarce in the Northern Sikhote-Alin. Composition of the sediments was only studied in the Kiselevka-Manoma terrane (Udyl Lake area) [12] and the Komsomolsk (Pivan) section, the northern fragment of the Zhuravlevka (Zhuravlevka – Amur) terrane [16]. It is obvious that such a level of lithological information about the Lower Cretaceous deposits of such a vast territory is utterly insufficient and does not allow drawing any conclusions about their geodynamic nature and, accordingly, about the type of their terrane. In order to fill this gap and obtain new data on the material composition of sediments of the Northern Sikhote-Alin, we studied two sections: the Berriasian–Barremian (Vysokogornyi settlement area) and the Hauterivian-Aptian (Buta River basin) (Fig. 1). The article presents the results of detailed lithological studies of the Lower Cretaceous deposits in these areas. The structure of deposits, petrographic and geochemical composition of rocks, and the content and ratios of rock-forming components and heavy clastic minerals in them are considered. The interpretation of the obtained data made it possible to determine the type and composition of source rocks of these sediments, as well as the geodynamic setting of its formation.
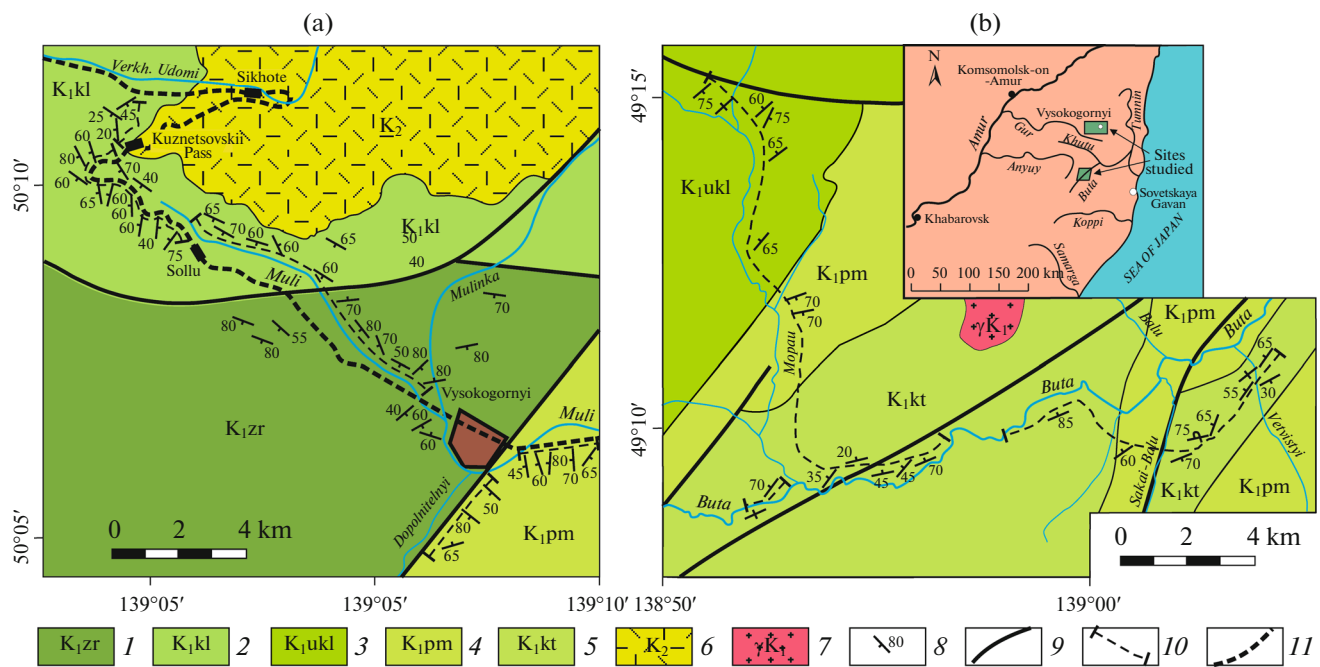
Fig. 1. Location and geological maps of the objects studied within the Lower Cretaceous deposits of the Northern Sikhote-Alin, modified after [3]. a, area of the Vysokogornyi settlement; b, Buta River basin. *1−5*, formations; *1*, Zhuravlevka (K_1zr); *2*, Klyuchevskaya (K_1kl); *3*, Ust-Kolumbe (K_1ukl); *4*, Primanka (K_1pm); *5*, Katalevka (K_1kt) *6*, Late Cretaceous volcanics (K_2); *7*, Early Cretaceous granites (γK_1); *8*, strike and dip; *9*, faults; *10*, studied sections; *11*, railroad.

THE GEOLOGICAL SETTING

On the map of Sikhote-Alin terranes, the considered areas of Lower Cretaceous deposits are confined to the junction zone of the coeval (Early Cretaceous) terranes: the synsedimentary turbidite Zhuravlevka and island-arc Kema terranes [1, 2, 23]. There were many attempts to associate the deposits to some terrane [4, 18, 23], but it was difficult to do so based on geological data alone, because all terrane rocks here have a similar lithological composition (siltstones, mudstones, less frequently sandstones, rhytmic lamination) as well as similar dislocation types.

The studied Lower Cretaceous sites are located in the Northern Sikhote-Alin (Fig. 1). The first site, occupying the area between the Muli and Udomi rivers, is located in the vicinity of the Vysokogornyi settlement and the second is in the basin of the Buta River and its left tributary, the Mopau Creek. Berriasian−Aptian sediments of these sections, with a total thickness of more than 6500 m, are represented by marine terrigenous rocks (sandstones, siltstones, mudstones, numerous sequences of their rhythmic interbedding, less frequently horizons and lenses of conglomerates, gravel conglomerates and mixtites). The peculiarity of the structure of the sections is the almost complete absence of products of synsedimentary volcanic activity. The rocks are intensely dislocated, disturbed by numerous zones of faulting, schistosity, and boudinage [23].

On the State Geological Map of sheet M-54 at a scale of 1 : 1 000 000 (third generation) [3] the Lower Cretaceous deposits of the studied areas are subdivided into five formations, according to the stratigraphic sequence: Zhuravlevka, Kluchevskaya, Ust-Kolumbe, Primanka, and Katalevka. Their structure and composition are as follows.

The more than 1000 m-thick Zhuravlevka Formation (Berriasian − Valanginian) located in the vicinity of the Vysokogornyi settlement (Fig. 2a), which lies at the base of the visible section, is composed mainly of siltstones and mudstones containing interlayers of fine-grained sandstones and interbedded sandstones and siltstones. The units have different thicknesses of elementary rhythms (from 1−10 cm to 20−30 cm) and ratio of sandstones and siltstones (Sand/Silt). The rhythms are dominated by siltstones, the thickness of which reaches 30 cm. The Sand/Silt ratio ranges from one-half to one-fifth. Unity or inverse ratios of rocks are rare. The overlying Valanginian Kluchevskaya Formation, which is more than 1600-m thick, is composed mainly by rhythmic interbedding of sandstones and siltstones. The rather monotonous interbedded sequence is sometimes interrupted by horizons of siltstones and sandstones. The rhythms have different thicknesses and ratios of constituent rocks. Amounts of sandstones and siltstones in the sequences with rhythms from 1−6 cm to 10−15 cm thick are usually equal. Sandstone layers, whose thickness in some cases reaches 40 cm, prevail in the sequences with 20−

50 cm-thick rhythms. The Sand/Silt ratio here is 2 : 1—5 : 1. Massive and layered siltstones and mudstones predominate in the Hauterivian—Barremian Primanka Formation. In addition, there are horizons of uneven-grained sandstones and thin, rhythmic interbedding of fine-grained sandstones, siltstones, and mudstones with rhythm thicknesses from 1—7 cm to 10—20 cm and various component ratios. The thickness of the formation in the vicinity of Vysokogornyi settlement exceeds 1600 m.

The section of Lower Cretaceous sediments in the Buta River basin (Fig. 2b), starts with the Hauterivian Ust-Kolumbe Formation, that is 800 m thick in the area studied. The Formation is composed of uneven-grained sandstones containing siltstones, interlayers and lenses of pebble and gravel conglomerates, mixtites, as well as fairly rare rhythmic interbedding of sandstones and siltstones. The interbedded piles consist of rhythms of varying thickness: from 3—7 cm to 25—35 cm, rhythms of 10—15 cm being most common. The Sand/Silt ratio ranges from 2 : 1 to 10 : 1, in places reaching 1. The overlying Hauterivian — Barremian Primanka Formation has a lithologic composition similar to that observed in the vicinity of Vysokogornyi. It is composed primarily of siltstones and mudstones and contains rhythmic interbedding of sandstones and siltstones with varying thicknesses of rhythms, and scarce thin sandstone and mixtite beds. The thickness of elementary rhythms in the interbedding units ranges from 7—15 cm to 30—50 cm. Sandstones usually sharply predominate: the Sand/Silt ratio reaches 10 : 1—20 : 1. The formation thickness is estimated at 1600 m. The Katalevka Formation (Aptian) is characterized by alternation of thick sandstone beds (up to 300 m) and beds of rhythmic interbedding of sandstones and siltstones (20—150 m). Siltstones and lenses of gravel conglomerates occur much less frequently. The thickness of rhythms is usually 5—10 cm, sometimes up to 40—50 cm. The amounts of sandstones and siltstones are approximately equal, although in places one or another component may prevail. The thickness of the formation in the Buta River basin was assessed as 1500 m. Thus, the structure and composition of the Berriasian—Aptian deposits, both in the Vysokogornyi settlement area and in the Buta River basin (Northern Sikhote-Alin), have the following features: (1) a sediment section consisting exclusively of terrigenous rocks without any noticeable influence of coeval volcanic processes; (2) the presence in the section of a large number of rhythmically interbedded sandstones and siltstones; and (3) a considerable (up to 6500 m) thickness.

MATERIALS AND METHODS

The objects of the study were mainly sandy rocks from the Lower Cretaceous sediments of the Northern Sikhote-Alin. Geochemical compositions of siltstones were used as additional data. Rock samples were taken
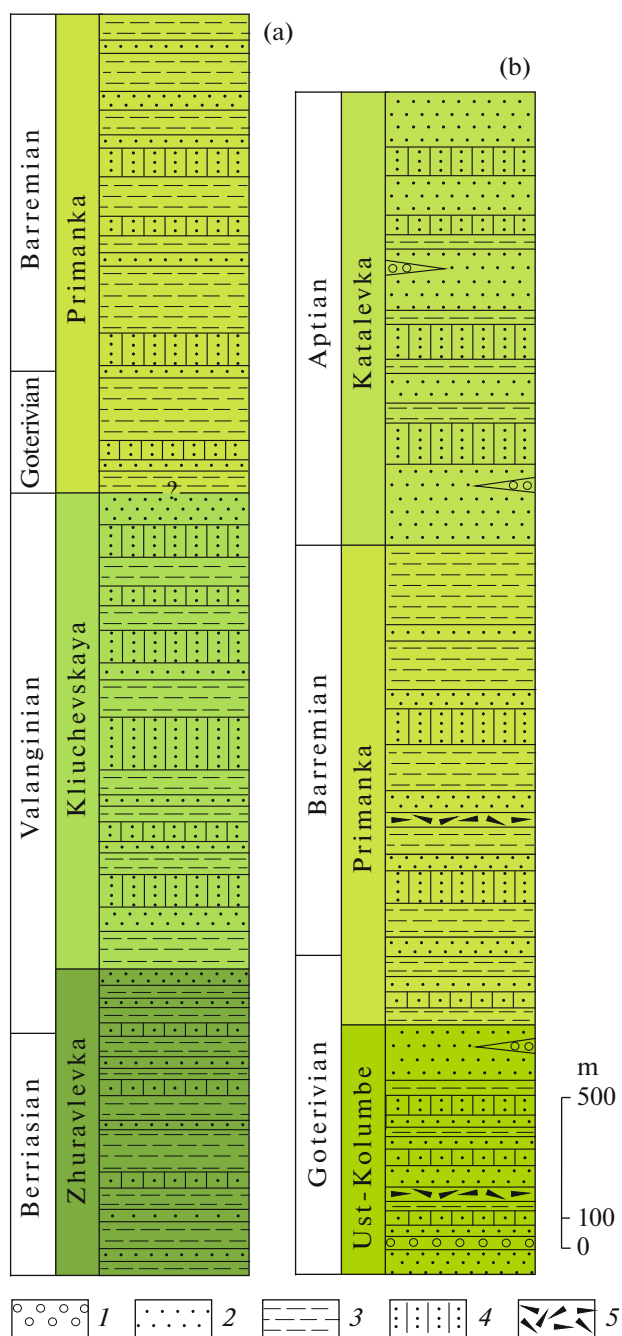
Fig. 2. Lithologic and stratigraphic columns of the Lower Cretaceous deposits of the Northern Sikhote-Alin: a, area of the Vysokogornyi settlement; b, Buta River basin. *1*, conglomerates and gravel conglomerates; *2*, sandstones; *3*, siltstones and mudstones; *4*, rhythmic interbedding of sandstones and siltstones; *5*, mixtites.

in the coastal outcrops of the Buta, Muli, and Mulinka rivers, the Mopau, Dopolnitel'nyi, Sakai-Bapu, and Vetvistyi brooks, and in quarries and excavations along railroads and highways.

Rock samples that, according to the study of thin sections, were least affected by secondary transforma-

tions were used for analyses. A total of about 250 samples of terrigenous rocks were subject to various analyses, rock-forming components were counted in 88 thin sections, associations of heavy clastic minerals were studied in 85 sections, 178 grains of different minerals were examined with microprobe, content of petrogenic elements was determined in 85 samples, and concentration of rare and rare-earth elements was determined in 77 samples.

The petrographic composition of rocks and the contents of the main rock-forming components and heavy clastic minerals in the sandstones were studied using conventional and repeatedly approved methods, the details of which are given in a number of publications [7–9, 11, etc.]. The chemical composition of heavy minerals was studied on a JXA-8100 XRD microanalyzer (analyst N.I. Ekimova). The contents of petrogenic elements were determined by atomic emission spectrometry with iCAP 6500 Duo, SRM-25, and VRA-30 inductively coupled plasma using spectrometers in the analytical chemistry and X-ray methods laboratories of the Analytical Center of Far East Geological Institute, FEB RAS (Vladivostok) and the laboratory of X-ray spectral analysis of the Northeastern Interdisciplinary Research Institute FEB RAS (Magadan). Concentrations of rare and rare-earth elements were determined by inductively coupled plasma mass-spectrometry (ICP-MS) using a quadrupole Agilent 7500c instrument of the Analytical Center of Far East Geological Institute, FEB RAS and Elan DRC II PerkinElmer at the Khabarovsk Innovation Analytical Center (KhAC) FEB RAS. Analysts were D.V. Avdeev, L.S. Bokovenko, T.D. Borkhodoeva, E.V. Volkova, G.A. Gorbach, E.V. Elovsky, V.E. Zazulina, V.N. Kaminskaya, V.I. Manuilova, E.A. Tkalina, and N.V. Khurkalo.

THE COMPOSITIONS OF TERRIGENOUS ROCKS

Since sandstones provide the most objective information about the type and composition of the parent rocks of the sediments and about the geodynamic conditions of sedimentation basin formation, let us dwell on their material composition.

The sandstones of both studied areas are generally fine- and medium-grained, rarely coarse-grained. They are medium- to well-sorted, except for the coarse-grained varieties; the latter also often contain small (up to 2 cm) sharply angular fragments of siltstones and mudstones scattered throughout the rock volume. Sand grains are usually sub-rounded, less often angular or rounded, isometric and elongated.

In terms of the ratio of rock-forming components, all the studied Early Cretaceous sandstones are homogeneous and may be termed as polymictic. The clastic material, which makes up 70–90% of the rock volume, consists of quartz, feldspars, biotite, quartzite

fragments, effusive, terrigenous, and siliceous rocks, and ore minerals. In the classification diagram by Shutov [24] (Fig. 3a), the sandstones of both sections form a single field, falling into the quartz-feldspar and feldspar-quartz graywackes. The quartz content in the sandstones ranges from 28 to 41%. Quartz is mostly monocrystalline, sharp-angled, isometric, or weakly elongated, often with undulating extinguishment. Polycrystalline quartz is rare. Elongated, tabular, less frequently isometric grains of acidic plagioclases, albite and oligoclase, predominate (up to 90%) among feldspars, the content of which varies from 24 to 43%. The content of potassium feldspars, as represented by isometric grains of pelitized orthoclase and, more rarely, lattice microcline, is 3–8% sometimes reaching 10–13%. Basic and medium plagioclases are very scarce. Rock fragments, amounting to 25% to 45% of all grains, are siliceous (up to 25% of the total number of grains), terrigenous (up to 23%), and volcanic (up to 16%) rocks. Fragments of quartzite and quartz-sericite schists are rare.

Thus, the petrographic composition of sandy rocks suggests that the sediment source area was composed of a complex of siliceous, terrigenous, granite-metamorphic, and volcanic rocks. The sufficiently high contents of quartz and plagioclase in the sandstones indicate a significant participation of erosion products of acid intrusive rocks in the sedimentation process. The presence of a significant number of fragments of siliceous and terrigenous rocks suggests that they were derived from fragments of the Jurassic accretionary prism of the Samarka Terrane, presently located in the vicinity of the investigated sections of the Northern Sikhote-Alin.

The composition, content, and relationship between individual heavy clastic minerals and their associations were studied in the sandstones. Heavy minerals account for 0.01–0.7% of the total rock volume, very rarely reaching 2%. Figure 4 shows their average content and distribution in different formations of the studied sites. Two associations of heavy minerals were established in the sandstones. The most common is the sialic association of minerals associated with the destruction of acidic igneous or metamorphic rocks: zircon, garnet, tourmaline, sphene, rutile, apatite, anatase, corundum, as well as ilmenite and leucoxene that may also occur in basic volcanics. The sum of the contents of these minerals averages between 75% and 96% of the total heavy fraction, sometimes reaching 100%. Zircon predominates among the minerals of this association; its average content in different formations varies from 67% to 83% (the Katalevka Formation), while in some samples it reaches 93–98%. The average contents of other minerals in the association are markedly lower: 0.5–8% garnet, 0.2–3% tourmaline, 0.5–5% apatite, 2–10% ilmenite, and associated leucoxene. The remaining minerals make up the first percent or trace amounts. The second, subordinate, femic association
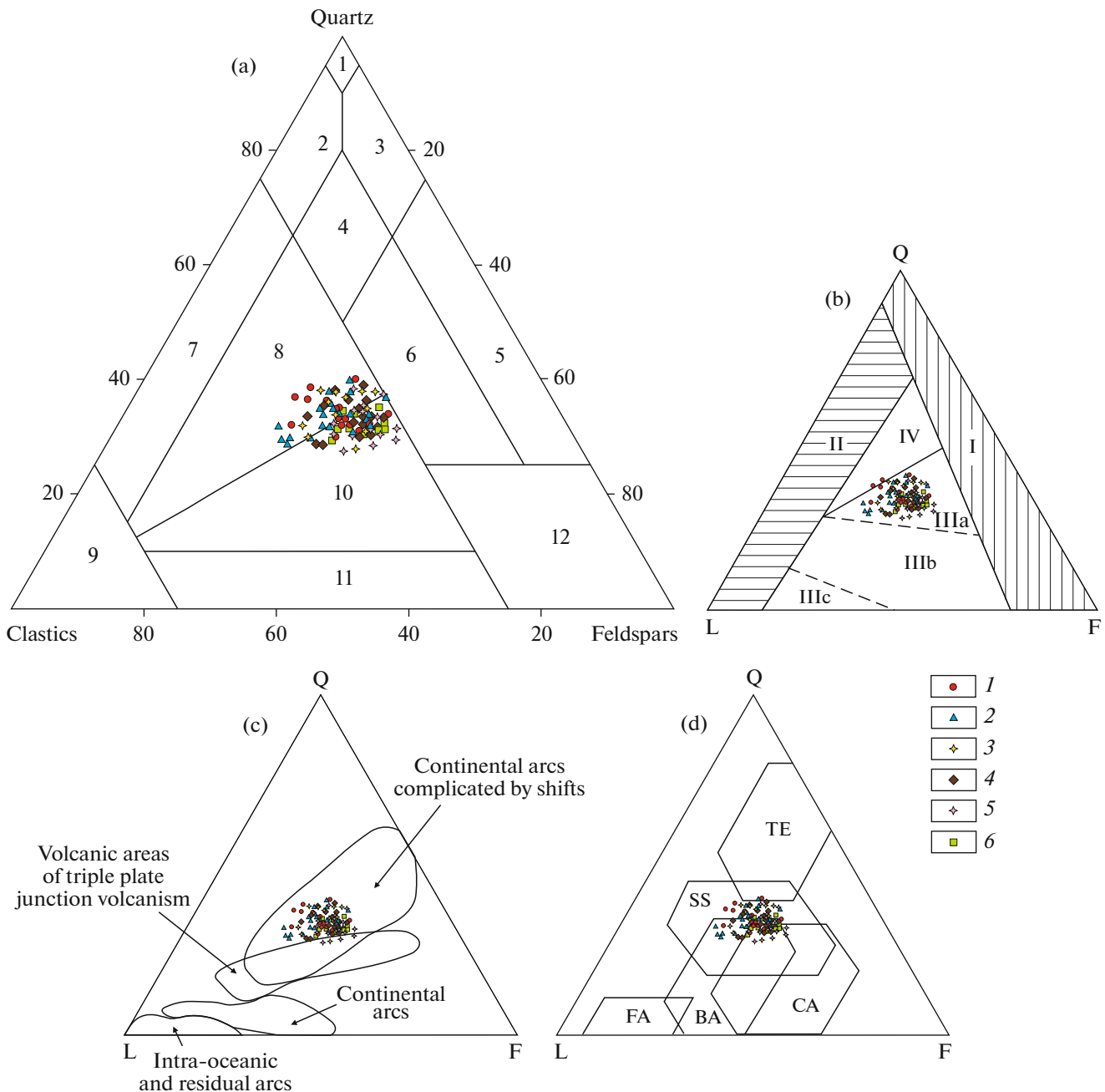
Fig. 3. Rock-forming components of sandstones from Lower Cretaceous deposits of the Northern Sikhote-Alin and their paleogeodynamic interpretation. a, Classification diagram of rock types [24]. Fields of rock types: 1−4, quartz sandstones: 1, monomictic quartz; 2, siliciclastic-quartz; 3, feldspar-quartz; 4, mesomictic quartz; 5-6, arkose sandstones: 5, arkoses; 6, graywacke arkose; 7−11, graywacke sandstones: 7, quartz graywackes; 8, feldspar-quartz graywackes; 9, graywackes; 10, quartz-feldspar graywackes; 11, feldspar graywackes; 12, crystalline tuffs; b; c, possible types of the sources: Qb, [34]; c, [38]. I, stable cratons and raised basement blocks; II, remobilized orogens; III, magmatic arcs (IIIa, deeply eroded; IIIb, transitional; IIIc, slightly eroded); IV, mixed sources. d, possible types of basin settings [39]. Basins: passive continental margins (TE); active continental margins complicated by shear dislocations along transform fractures (SS); merges with: the continental marginal magmatic arc (CA); the oceanic volcanic arc (FA, forearc basins and BA, back-arc basins). L, rock clasts; Q, quartz; F, feldspars. Formations: 1−3, Vysokogornyi settlement area: 1, Zhuravlevka; 2, Klyuchevskaya; 3, Primanka; 4−6, Buta River basin: 4, Ust-Kolumbe; 5, Primanka; 6, Katalevka.

of minerals is formed by chromite, magnetite, ortho- and clinopyroxene, hornblende, epidote, and olivine, that apparently derived from basic and ultrabasic igneous rocks. The total content of these minerals is low, varying on average across the formations from 4−11% in the Buta River basin to 22-25% in the vicinity of Vysokogornyi. The main mineral in this association is chromite; its average content is highest in the lower
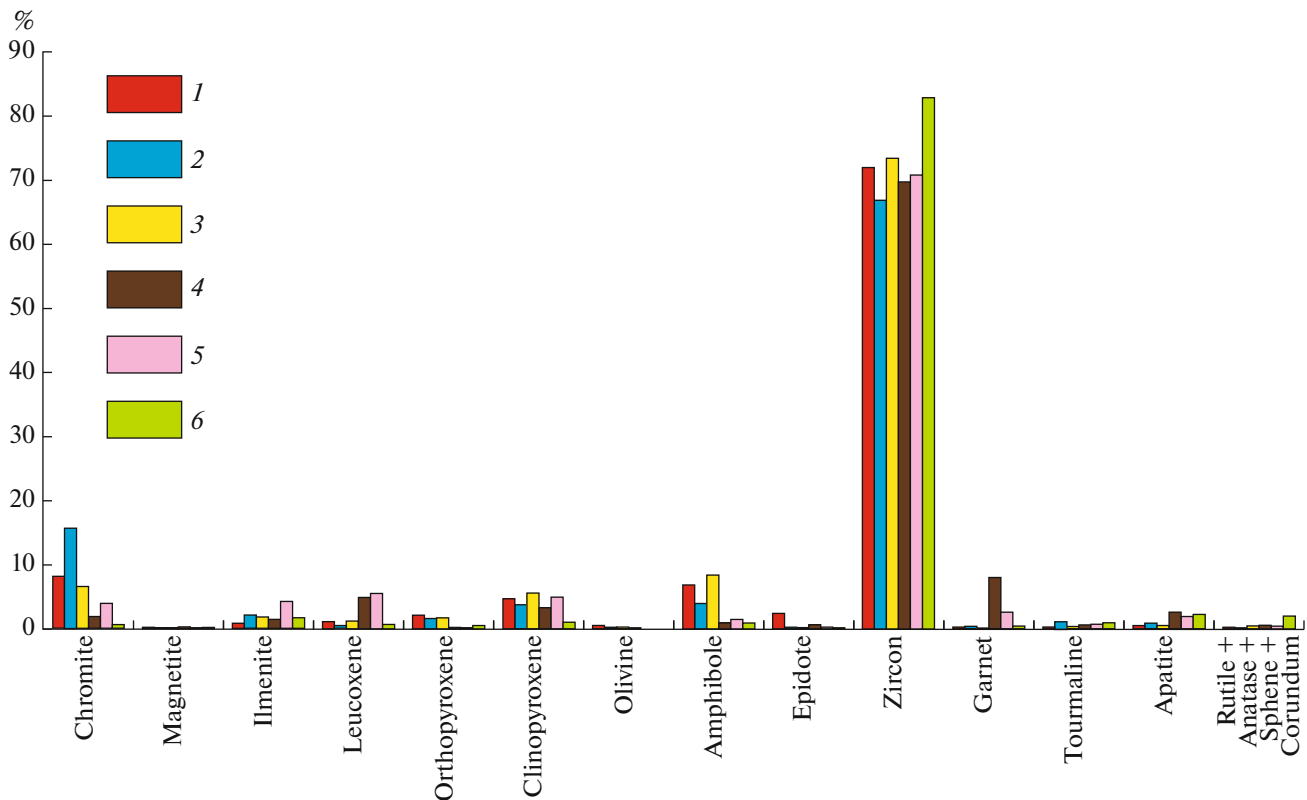
Fig. 4. The distribution pattern of heavy clastic minerals in sandy rocks from Lower Cretaceous deposits of the Northern Sikhote-Alin (average content). The following formations: *1–3*, Vysokogornyi settlement area: *1*, Zhuravlevka; *2*, Klyuchevskaya; *3*, Primanka; *4–6*, Buta River basin: *4*, Ust-Kolumbe; *5*, Primanka; *6*, Katalevka.

part of the section in the Zhuravlevka and Klyuchevskaya Formations (8 and 16%), decreasing to 4% and 0.7% in the Primanka and Katalevka Formations. The content of clinopyroxene (1% to 6% on average for the different formations) and amphibole (2% to 8%) is even lower; the other minerals are scarce.

In terms of the chemical composition, the sandstones of the objects studied are sufficiently similar (Table 1). Only a slightly elevated silica content in the rocks of the Vysokogornyi settlement area, varying on average for formations from 74.71% to 76.43%, was detected. The SiO_2 content in the sandstones of the Buta River basin is lower and varies on average from 70.34% to 72.65%. In addition, rocks of the Vysokogornyi settlement area have slightly lower contents of TiO_2 (0.38−0.40% and 0.41−0.46%, respectively), Al_2O_3 (9.95−11.86% and 13.66−14.64%), MgO (0.87−0.96% and 0.69−1.05%) and CaO (0.80−0.91% and 1.00−1.14%), but higher $FeO + Fe_2O_3$ (3.44−4.15% and 2.53−3.02%). Despite some minor differences that are probably explained by the influence of local sources of clastics, all the studied sandstones are characterized by the characteristic prevalence of Na_2O (2.85−3.13% and 3.50−3.86%) over K_2O (1.81−2.12% and 2.73−2.95%) in graywacke. At the classification diagram of the Na_2O/K_2O and SiO_2/Al_2O_3 values [17]

(Fig. 5), the data points of the sandstones are predominantly grouped in the graywacke domain and only their insignificant part (mainly rocks of the Klyuchevskaya and Primanka formations of the settlement of Vysokogornyi area) fall in the field of lithic arenites, the transitional varieties between graywackes and arkoses.

In terms of the lithochemical indicators (Table 1) used to obtain reliable information on the composition of host rocks, their maturity, lithogenic or petrogenic nature of sediments, and for correct paleoreconstructions of sedimentation environments [5, 6, 9, 14, 16, 26, 27, 44, etc.], the studied sandstones are rather similar. The hydrolyzate module (HM = $(Al_2O_3 + TiO_2 + Fe_2O_3 + FeO + MnO)/SiO_2$) is typical of the sandstones; its average value for different formations varies from 0.18 to 0.26, which suggests a low maturity and, thus, formation due to mechanical destruction of parental rocks with a subordinate role of chemical weathering. In terms of the HM value, the sandstones are very close to the rocks of the Early Cretaceous Zhuravlevka Terrane (0.14−0.26) [9]. The low degree of weathering of the source rocks is also confirmed by the low values of the chemical index of alteration (CIA = $[Al_2O_3/(Al_2O_3 + CaO + Na_2O)] \times 100$) [44], varying on average from 53 to 58. According to the

Table 1. Average concentrations of petrogenic (wt%) elements in Lower Cretaceous sandy rocks of the Northern Sikhote-Alin

Component	Area of the Vysokogornyi settlement			Buta River basin		
	1	2	3	4	5	6
n	12	21	9	14	13	16
SiO_2	74.77	75.63	76.43	72.38	72.65	70.34
TiO_2	0.39	0.41	0.40	0.41	0.43	0.46
Al_2O_3	11.74	10.51	9.95	13.70	13.66	14.64
Fe_2O_3	1.63	3.11	1.60	1.72	1.25	2.27
FeO	2.00	0.81	1.84	0.80	1.58	0.75
MnO	0.06	0.06	0.06	0.04	0.06	0.08
MgO	1.01	1.15	0.94	1.05	0.69	0.95
CaO	0.90	0.83	0.83	1.02	1.00	1.14
Na_2O	2.85	3.03	3.13	3.86	3.50	3.83
K_2O	2.11	1.98	2.12	2.81	2.73	2.95
P_2O_5	0.20	0.15	0.13	0.13	0.18	0.16
LOI	0.13	0.15	0.12	0.05	0.13	0.21
H_2O	1.97	1.96	2.04	1.80	1.98	2.04
Total	99.77	99.79	99.74	99.77	99.83	99.82
HM	0.21	0.20	0.18	0.23	0.23	0.26
TM	0.032	0.039	0.040	0.030	0.032	0.031
FM	0.06	0.07	0.06	0.05	0.05	0.06
IM	0.30	0.39	0.39	0.18	0.21	0.21
MNA	0.42	0.45	0.53	0.49	0.46	0.46
CIA	58	55	53	55	56	56

Note. n, number of analyses. Formations: 1–3, region of Vysokogornyi settlement: 1, Zhuravlevka; 2, Klyuchevskaya; 3, Primankinskaya; 4–6, Buta River basin: 4, Ust-Kolumbe; 5, Primanka; 6, Katalevka.

femic modulus (FM = $(Fe_2O_3$ + FeO + MnO + MgO)/SiO_2), which allows graywackes and arkoses to be distinguished [27], the sandstones mainly correspond to graywackes or occupy an intermediate position between them and arkoses (0.05−0.07). Such FM values are in the good agreement with the low content of basic volcanic clasts and the high content of quartz, siliceous, and other quartz-bearing rocks. In terms of FM, the sandstones are close to the sandstones of both Zhuravlevka (0.03-0.06) and island-arc Kema (0.04−0.07) terranes of the Sikhote-Alin [7, 9]. The TM values (TM = TiO_2/Al_2O_3), which allow the parent rocks composition to be estimated, are low (from 0.030 to 0.040), because of the domination of acid volcanics in the source areas, which, in turn, are characterized by low TM values. In terms of this parameter, the sandstones are similar to the sandstones of both the Kema (0.031−0.035) and the Zhuravlevka (0.017−0.030) terranes. The modulus of normalized alkalinity (MNA = $(Na_2O$ + $K_2O)$/Al_2O_3) reveals an admixture of volcanic material in sedimentary rocks and, accordingly, helps distinguish between arkoses and graywackes [26, 27]. Relatively high MNA values (from 0.42 to 0.53)

generally correspond to intermediate rocks between graywackes and arkoses and are explained by the abundance of micas, feldspars, and fragments of acid eruptive rocks. In terms of MNA, the sandstones are comparable to the sandstones of the Zhuravlevka Terrane (0.33−0.53) [9]. Another lithochemical parameter, the iron module (IM = $(Fe_2O_3$ + FeO + MnO)/$(TiO_2$ + $Al_2O_3)$ [27] distinguishes the composition of parental source rocks. Its relatively low values in the studied sandstones (0.18−0.39) suggest a predominant influence of erosion products of acidic rocks on their formation. The sandstones of the Zhuravlevka (0.21−0.40) and Kema (0.27−0.37) terranes have similar IM values [7, 9].

The values and ratios of the lithochemical parameters, as well as the position of their figurative points on a number of diagrams (positive correlation between the pairs of FM−TM and FM−IM modules and negative or no correlation between other pairs) (Fig. 6) [26, 27], indicate that the studied rocks have passed only one sedimentation cycle and were formed without any significant lithodynamic sorting of clastic material.
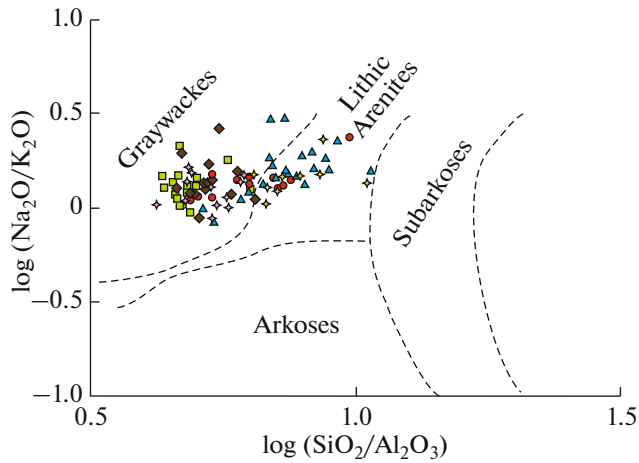
Fig. 5. Classification diagram log (Na_2O/K_2O)–log(SiO_2/Al_2O_3) for sandy rocks from Lower Cretaceous deposits of the Northern Sikhote-Alin [17]. See Fig. 3.

The contents and distribution pattern of rare and rare-earth (REE) elements were studied in the sandy rocks of the Northern Sikhote-Alin. Their contents in siltstones were regarded as additional information. In general, the total REE concentrations in the rocks are relatively low and vary on average across the formations from 123 to 149 ppm in the vicinity of Vysokogornyi settlement, and from 137 to 145 ppm in the Buta River basin (Table 2). The REE spectra normalized to the chondrite composition [30] for all studied formations are similar and characterized by normal distribution trends with a moderate fractionation and a relatively low ratio of light lanthanides to heavy $(La_N/Yb_N \sim 7.70–9.14)$ in the area of Vysokogornyi and slightly increased $(La_N/Yb_N \sim 9.12–12.03)$ in Buta River basin (Fig. 7). The REE spectra are characterized by a distinct negative Europium anomaly $(Eu/Eu^* \ 0.54–0.58$ and $0.57–0.60$, respectively). Compared to the post-Archean Australian middle
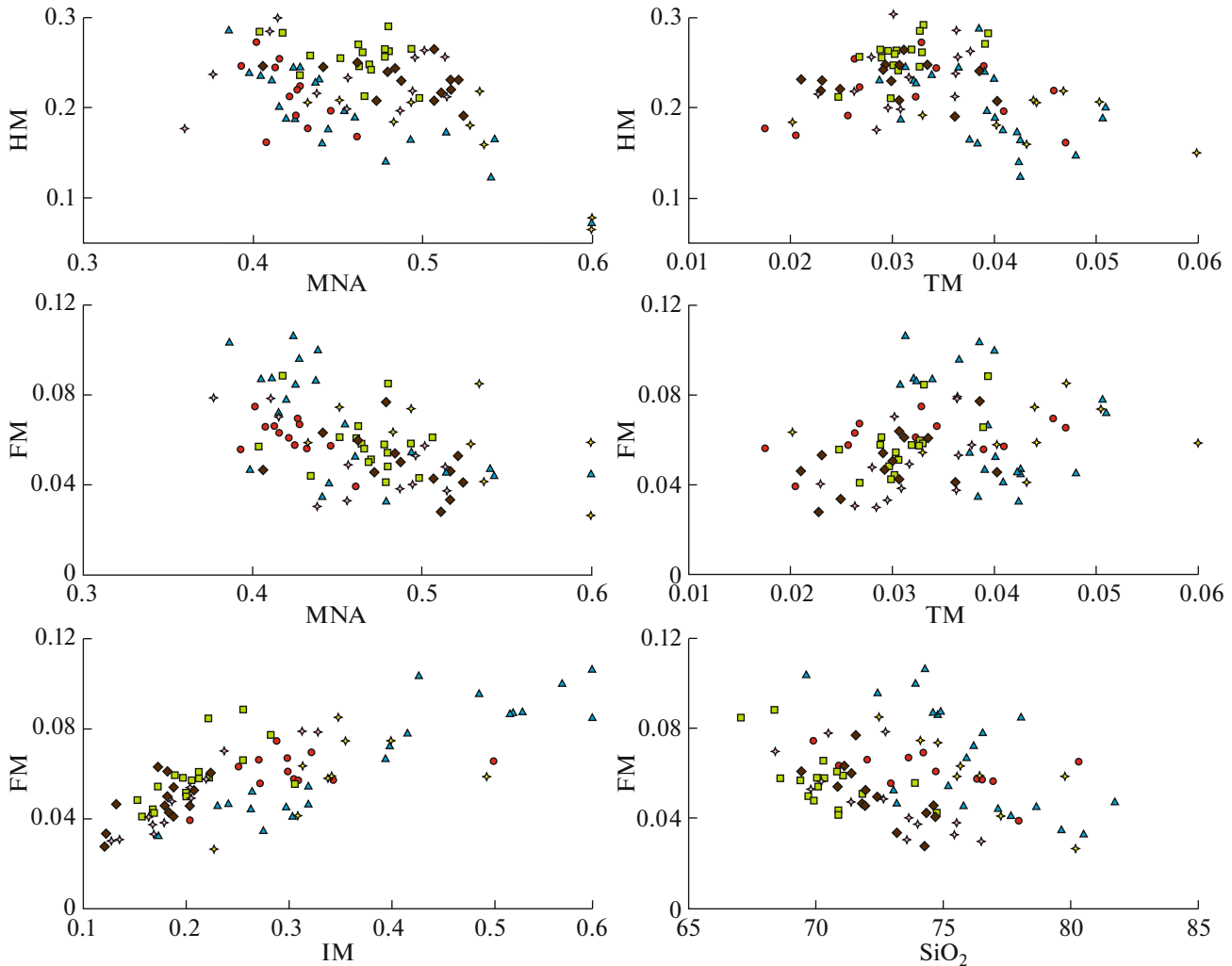
Fig. 6. Modulus diagrams for sandy rocks from the Lower Cretaceous sediments of the Northern Sikhote-Alin [26, 27]. See Fig. 3 for legend.

clayey shale (PAAS) assumed to be the average composition of the upper continental crust [19], all of the studied terrigenous rocks are slightly depleted in both light and heavy elements (1.1−2.1 times), apart from Gd that has equal or slightly higher concentrations.

THE SEDIMENT SOURCES AND A PALEOGEODYNAMIC INTERPRETATION OF THE RESULTS

The results of study of the material composition of the sandstones of the Northern Sikhote-Alin suggest that they are petrogenic graywackes and, only partly, lithic arenites characterized by a low degree of the clastic material maturity and formed from the parental rocks that practically did not undergo chemical weathering. The position of the data points of sandstones on the Q−F−L diagram [34] (Fig. 3b), which is designed to reconstruct the tectonic types of sources based on the composition of rock-forming components of sandstones, indicates that apart from the main continental source composed of granite-metamorphic and sedimentary rocks, the source area included a dissected, deeply eroded marginal continental magmatic arc, where erosion uncovered granitoid intrusions at the root of this arc. As a consequence, it was the products of erosion of the sialic basement of the arc that mainly entered the sedimentation basin, while the basic-medium volcanics remained as accessories. The source of sands and sandstones uncovered by the deep-water drilling in the Pacific Ocean and marginal seas [38] (Fig. 3c) apparently correspond to the continental arcs under the action of transform faults. Modern examples of such areas are the convergent margins of North America: Cascadia, Mexico, Guatemala, etc.

A reliable indicator of the tectonic type of the source area, as well as the composition of the parental rocks, is the composition, content, and certain ratios of heavy clastic minerals in sandstones [8, 11, 20, 36, 41, 43, etc.]. The contents and ratios of the individual heavy minerals and their associations in the studied sandstones, as well as the locations of data points on the MF−MT−GM, Opx−Hb−Cpx, and A-&-POS diagrams [36, 42, 43] (Figs. 4, 8), suggest that the source area included two contrasting sources of clastic material. The main source, which formed the sialic association of minerals, was the granite and metamorphic blocks of mature continental crust (cratons and marginal parts of rifts) participating in the structure of the eastern Eurasian margin [1], as well as the basement of the marginal continental magmatic arc. The second, subordinate source of clastics, which supplied minerals for the femic association, was the erosion products of the basic and intermediate arc volcanics, as well as ultrabasic magmatites of the ophiolites, which participated in the structure of the Jurassic accretionary prisms widely spread in Sikhote-Alin.

The chemical composition of heavy clastic minerals sheds light on the geological nature and petro-
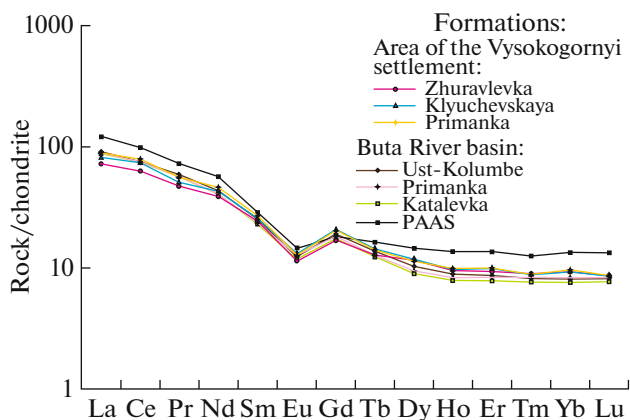
Fig. 7. REE distribution spectra normalized to chondrite [30] in the sandy-silty rocks of the formations studied and their comparison with PAAS [19].

graphic composition of the rocks of the source areas [8, 10, 41-43, 45, etc.]. The compositions of some of them (clinopyroxenes, hornblende, garnets, and chromites) are shown in Table 3. The clinopyroxene composition corresponds mainly to diopside and augite, less often to salite. Most clinopyroxenes on the $F_1−F_2$ discriminant diagram [45] (Fig. 9a), which allows determining their magmatic source, correspond to oceanic floor basalts and, to a lesser degree, to intraplate and island-arc basalts. The position of clastic amphibole on the Fe−Al−10Ti diagram [42] (Fig. 9b), reflecting low total chromium and titanium contents, confirms the presence of island-arc volcanics among sources and testifies to the presence of metamorphic and ultrabasic intrusive ophiolite rocks, which are part of both the arc base and Jurassic−Early Cretaceous accretionary complexes of Sikhote-Alin. Presence of ultrabasic and basic intrusive and volcanic rocks in the source area is also indicated by the presence of a fairly significant amount of chromites in the heavy sandstone fraction. The chromites are of two types [25] (Fig. 9c): low-Ti (less than 1.5% TiO_2), originating from basic and ultrabasic igneous ophiolite rocks, and high-Ti (over 1.5% TiO_2) from alkaline basalts of intraplate uplifts. Most garnets of the sandstones belong to the almandine group (Al_2O_3 − 17.66-23.33%, $FeO + Fe_2O_3$ − 16.13-34.51%) with the occasional addition of a grossular or spessartite component. The location of garnets compositions on the Mg−Mn−Ca diagram [50] (Fig. 9d) indicates that their source was granitoids and metamorphic rocks of different degrees of metamorphism, composing the mature continental Earth crust, and, probably, in the basement of an ensialic arc.

The geochemical features of the studied rocks, such as moderate values of the lithochemical moduli FM, IM, MNA and TM, relatively low concentrations of REE, with a minor enrichment of light elements compared to heavy ones, as well as a clearly expressed

Table 2. The average contents of rare and rare-earth elements (g/t) in Lower Cretaceous terrigenous rocks of the Northern Sikhote-Alin

Component	Area of the Vysokogornyi settlement			Buta River basin		
	1	2	3	4	5	6
n	10	30	13	14	2	8
Li	13.96	32.48	33.38	33.41	40.02	54.54
Be	1.26	1.44	1.36	−	−	−
Sc	7.78	10.02	10.40	7.47	7.33	7.78
V	61.30	70.93	66.02	55.83	54.67	63.65
Cr	53.84	67.86	53.58	52.49	54.83	55.25
Co	9.81	9.45	6.44	10.40	16.81	17.15
Ni	24.83	19.46	18.12	19.45	14.37	18.82
Cu	22.15	25.05	20.31	19.89	85.55	21.89
Zn	69.05	139.52	89.89	86.42	73.55	71.40
Ga	14.54	15.93	15.80	16.43	17.79	17.65
Rb	76.16	116.22	106.48	103.11	106.32	99.35
Sr	124.93	130.15	116.71	159.20	191.50	170.77
Y	16.21	17.36	16.60	15.71	13.38	13.32
Zr	165.24	114.44	156.46	77.55	82.84	68.16
Nb	9.10	9.69	9.48	9.54	8.92	9.11
Mo	0.94	0.74	0.59	1.14	0.69	0.67
Sn	2.85	5.92	2.69	−	−	−
Cs	5.25	14.74	6.21	12.86	11.37	14.60
Ba	430.30	519.68	455.14	424.19	634.16	514.04
La	22.85	25.73	28.21	27.71	27.72	28.10
Ce	51.65	60.57	64.85	58.95	61.42	61.06
Pr	5.79	6.22	6.87	6.88	6.97	7.00
Nd	23.55	25.67	27.83	24.96	24.48	24.34
Sm	4.73	4.95	5.25	4.68	4.56	4.45
Eu	0.85	0.96	0.95	0.89	0.96	0.88
Gd	4.42	5.35	5.32	4.70	4.72	4.57
Tb	0.61	0.67	0.67	0.62	0.60	0.59
Dy	3.76	3.82	3.70	3.15	3.04	2.91
Ho	0.69	0.70	0.71	0.61	0.60	0.57
Er	1.97	2.09	2.10	1.73	1.77	1.66
Tm	0.29	0.28	0.29	0.25	0.27	0.25
Yb	1.96	1.95	2.03	1.62	1.74	1.60
Lu	0.28	0.28	0.28	0.25	0.27	0.25
Hf	2.47	3.70	3.70	−	−	−
Ta	0.47	0.66	0.63	−	−	−
W	1.37	1.76	1.53	−	−	−
Pb	21.88	18.78	15.37	28.07	17.48	17.22
Th	7.64	9.48	10.36	10.54	10.68	9.99
U	1.86	1.77	1.98	2.15	2.23	2.06
Eu/Eu*	0.56	0.58	0.54	0.57	0.60	0.58
La_N/Yb_N	7.70	8.65	9.14	11.76	9.12	12.03

n, the number of analyses. Formations: 1−3, region of the settlement of Vysokogornyi: 1, Zhuravlevka; 2, Klyuchevskaya; 3, Primanka; 4−6, Buta River basin: 4, Ust-Kolumbe; 5, Primanka; 6, Katalevka. Dash, not determined.
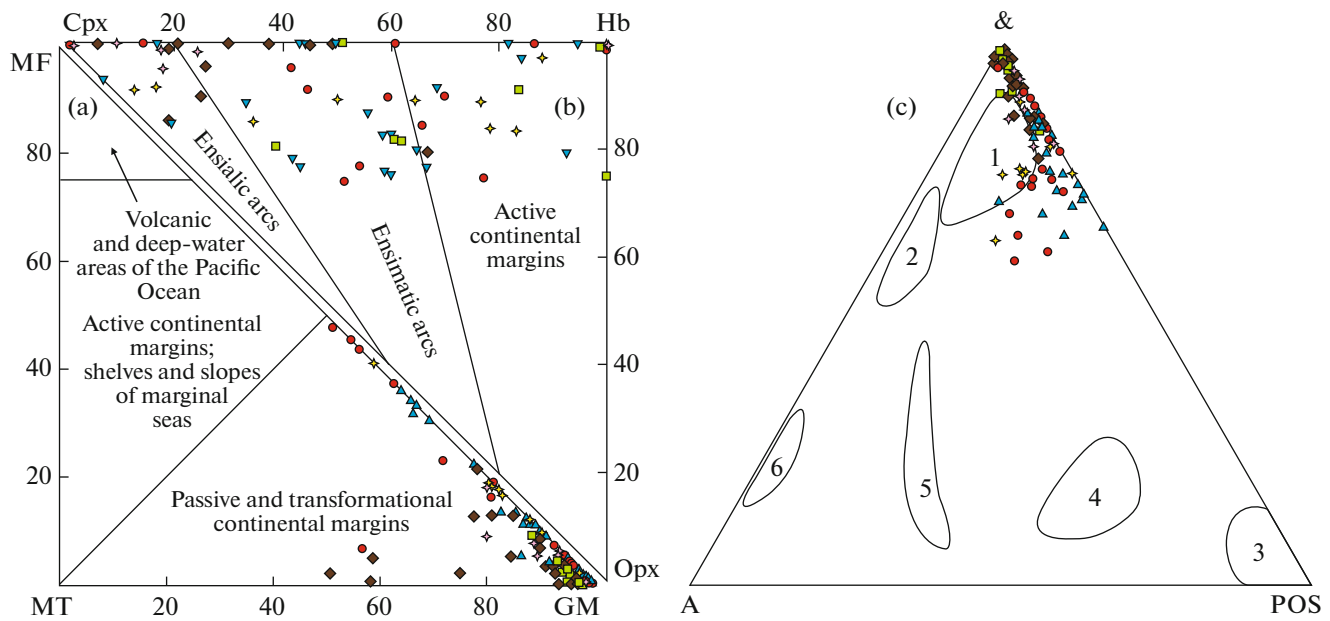
Fig. 8. Possible types of source areas for sandy rocks of the Early Cretaceous of the Northern Sikhote-Alin according to the distribution of heavy clastic minerals. a, MF−MT−GM and b, Opx−Hb−Cpx [42, 43]. Sums of contents: MF, olivine; pyroxenes; green hornblende; MT, epidote; garnet; blue-green amphiboles; GM, zircon; tourmaline; staurolite; disthene; sillimanite and andalusite. Opx, orthopyroxene; Hb, amphibole; Cpx, clinopyroxene; c, &-A-POS [36]. A, amphiboles and epidotes; POS, clinopyroxenes; orthopyroxenes; olivines and chromites; &, other transparent minerals. Types of source areas: 1, continental blocks (cratons and marginal parts of rifts); 2, collisional orogens; 3−6, magmatic arcs: 3, not eroded; 4, transitional slightly eroded; 5, transitional eroded; 6, strongly eroded. See Fig. 3 for legend.

negative Eu anomaly, suggest that the source area included both acidic igneous and, to a much smaller extent, basic and intermediate volcanic rocks. Geodynamic interpretation of the geochemical composition of rocks carried out using discriminant diagrams allowed additional information about the tectonic type and composition of the parent rocks to be obtained. Most of data points in the diagram designed to distinguish the different types and development stages of source island arcs [37] (Fig. 10a) indicate that the source of clastics was either a marginal continental arc or a deeply eroded island arc where only the basement was available for further erosion. The data points of the geochemical composition of rocks in the F_1−F_2, Hf−La/Th, La/Sc−Th/Co, and Zr/Sc−Th/Sc diagrams [33, 35, 40, 47] (Figs. 10b−10d), which are designed to recognize the composition of the parent rocks, indicate that the main source of material was acid magmatic rocks, with a rather insignificant contribution of intermediate and, possibly, basic volcanic, as well as sedimentary rocks enriched in ancient clastic components. The share of the basic and intermediate components, estimated from the Cr/Th−Th/Sc diagram [32] (Fig. 10e) did not exceed 20−30%, being less than 15% on average.

Thus, the sediment source area combined an ancient sialic land and a deeply dissected marginal continental (ensialic) arc, in which erosion uncovered batholiths of granitoids underlain by volcanics. The deposits were formed mainly due to the destruction of granite-metamorphic complexes and the basement of the arc and the strongly reduced volcanics of the arc as such played a secondary role. In addition, the presence of fragments of Jurassic−Early Cretaceous accretionary prisms with ophiolites can be also assumed.

A U−Pb isotope geochronological study of detrital zircon from Lower Cretaceous sediments of the Northern Sikhote-Alin, including those discussed in the present work, carried out by Didenko et al. [4], revealed that the sources of sialic clastics included granitoids of several age groups located within the North China craton.

The paleogeodynamic setting of the Lower Cretaceous deposits of the Northern Sikhote-Alin was reconstructed from the rock-forming sandstone components using the diagram of Maynard et al. [39] (Fig. 3d) The data points correspond mostly to the settings of active continental margin basins complicated by shear dislocations along transform faults similar to the Gulf of California and, partly, to the basins associated with continental marginal magmatic arcs. The correlation between the heavy clastic mineral associations in the sandstones, as well as the location of their points on the MF−MT−GM and Cpx−Hb−Opx diagrams [42, 43] (Fig. 8a) also indicate that the sediment accumulation occurred in the lithospheric plate transformation setting.

Table 3. The chemical composition (wt%) of heavy clastic minerals from Lower Cretaceous sandstones of the Northern Sikhote-Alin

Sample #	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	Total
					Clinopyroxenes						
MP-52/1	50.65	0.53	3.45	—	7.42	0.19	14.83	22.00	0.37	—	99.45
MP-52/2	51.75	0.31	2.77	0.36	5.31	0.17	16.81	21.30	0.32	—	99.10
MP-52/3	50.99	0.74	3.87	0.46	7.71	0.23	14.65	22.13	0.35	—	101.14
MP-62/1	48.61	0.58	4.86	0.08	7.68	0.20	15.12	21.93	0.36	—	99.41
MP-62/2	49.35	0.71	4.28	—	9.93	0.30	15.36	19.28	0.34	—	99.55
MP-24/1	51.45	0.34	3.00	0.30	5.76	0.14	15.90	22.33	0.25	—	99.46
MP-24/2	49.30	0.58	4.60	0.07	8.49	0.29	13.96	21.49	0.36	—	99.11
MP-63/1	49.36	0.86	4.20	0.18	8.20	0.17	14.69	22.74	0.31	—	100.72
MP-63/2	48.36	0.91	5.72	0.07	8.40	0.27	13.87	21.62	0.32	0.01	99.55
MP-63/3	49.71	0.57	4.55	0.07	8.35	0.36	15.23	20.32	0.42	—	99.58
MP-42	49.43	0.80	4.46	0.93	7.16	0.36	15.74	22.19	0.26	—	101.32
MP-88/1	50.55	0.64	4.41	0.63	5.30	0.10	15.48	22.63	0.29	0.01	100.03
MP-88/2	49.07	0.60	4.57	0.07	8.30	0.14	14.15	22.27	0.36	0.01	99.53
MP-88/3	52.99	0.42	2.29	0.65	5.67	0.12	16.07	21.06	0.31	0.01	99.60
MP-88/4	52.99	0.26	2.38	0.52	5.55	0.21	16.66	22.73	0.32	0.01	101.63
MP-88/5	49.52	0.80	4.80	0.24	7.41	0.24	14.42	21.95	0.32	0.01	99.72
MP-18/1	52.37	0.56	4.13	0.38	5.08	0.18	16.29	18.77	0.20	—	97.97
MP-18/2	52.79	0.61	4.02	0.42	5.15	0.14	16.45	17.78	0.24	0.01	97.62
MP-18/3	51.90	0.52	4.09	0.37	4.85	0.20	15.89	19.42	0.27	0.01	97.51
MP-19/1	51.58	0.76	3.21	0.33	7.29	0.28	15.45	21.06	0.27	—	100.24
MP-19/2	52.22	0.74	2.11	0.05	12.94	0.39	14.40	16.96	0.38	0.01	100.20
MP-19/3	48.84	1.24	5.63	0.09	8.96	0.26	13.47	20.82	0.39	0.02	99.71
MP-19/4	50.40	0.91	2.67	0.06	12.16	0.41	10.24	20.91	2.09	—	99.85
MP-69/1	51.35	0.39	3.38	0.29	6.59	0.22	16.06	21.99	0.32	—	100.60
MP-69/2	51.22	0.66	3.26	0.23	7.44	0.30	15.97	21.47	0.27	—	100.84
MP-69/3	50.98	1.11	3.88	1.25	5.32	0.23	15.87	22.58	0.28	—	101.50
MP-69/4	51.25	0.42	4.14	0.20	6.06	0.18	16.28	22.00	0.36	—	100.90
MP-70/1	50.34	0.61	2.40	0.06	12.82	0.81	14.85	17.38	0.44	—	99.70
MP-70/2	49.38	0.64	2.35	0.03	13.05	0.84	13.87	18.36	0.48	—	99.01
MP-70/3	49.47	1.59	4.79	2.02	6.37	0.17	15.75	19.06	0.43	—	99.67
MP-13/1	51.57	0.44	1.99	0.12	6.39	0.15	15.15	22.38	0.22	0.01	98.41
MP-13/2	51.85	0.65	2.11	0.31	8.99	0.27	15.69	19.80	0.16	—	99.82
MP-14/1	51.89	1.16	2.39	0.01	9.07	0.21	14.90	20.69	0.23	—	100.57
MP-14/2	50.41	1.22	2.63	0.20	9.32	0.19	14.24	20.76	0.34	—	99.32
MP-14/3	51.86	1.25	2.30	0.19	9.01	0.19	14.25	20.82	0.34	—	100.21
MP-14/4	51.61	1.39	3.19	0.61	7.09	0.13	15.47	20.60	0.36	—	100.45
VK-73	51.60	0.50	1.83	0.01	13.66	0.55	13.86	18.27	0.33	—	100.62
VK-27/1	49.74	1.69	6.76	1.59	5.31	0.16	14.55	19.49	1.62	—	100.91
VK-27/2	49.23	1.85	7.02	1.29	5.79	0.08	14.38	19.53	1.59	—	100.76
VK-8/1	49.91	1.06	6.07	—	10.81	0.19	10.82	18.98	1.75	—	99.60
VK-8/2	48.97	2.04	8.59	0.47	7.13	0.24	13.37	19.60	1.14	—	101.55
VK-8/3	51.76	0.40	1.30	0.04	10.98	0.53	11.51	21.77	1.36	—	99.66
VK-8/4	52.76	0.54	2.29	0.23	7.51	0.27	13.82	20.80	1.42	0.83	100.48

Table 3. (Contd.)

Sample #	SiO$_2$	TiO$_2$	Al$_2$O$_3$	Cr$_2$O$_3$	FeO*	MnO	MgO	CaO	Na$_2$O	K$_2$O	Total
VK-8/5	51.55	0.74	3.75	–	9.59	0.37	13.27	20.38	0.81	0.01	100.48
VK-8/6	51.60	0.78	3.80	–	9.19	0.41	13.42	20.66	0.87	0.01	100.75
VK-27/3	49.15	1.60	7.21	1.42	6.35	0.27	12.78	20.27	0.85	0.03	99.91
VK-104/1	51.33	0.29	1.59	0.08	14.23	0.54	14.13	17.19	0.26	–	99.63
VK-22/1	50.88	0.76	5.59	0.47	6.31	0.15	14.10	22.36	0.23	–	100.86
VK-22/2	53.03	1.08	2.76	1.94	4.88	0.17	15.65	22.11	0.34	0.01	101.96
VK-34/1	52.12	0.43	1.38	–	7.96	0.84	15.41	19.56	0.26	0.02	97.96
VK-34/2	52.10	0.46	1.91	–	9.59	0.51	15.28	19.79	0.23	0.01	99.89
VK-34/3	52.50	0.31	1.72	–	9.55	0.58	16.73	17.89	0.18	0.01	99.48
VK-105/1	51.61	0.32	1.50	0.04	13.66	0.46	14.22	18.13	0.19	–	100.07
VK-105/2	51.75	0.33	1.93	0.02	11.35	0.59	14.37	18.45	0.29	–	99.07
VK-113/1	51.75	0.31	3.36	0.10	9.29	0.29	15.59	19.74	0.21	–	100.65
VK-113/2	51.28	0.26	2.02	0.02	13.49	0.55	14.17	18.35	0.25	–	100.39
VK-118/1	50.48	0.44	2.17	0.07	10.23	0.42	15.65	20.13	0.23	0.01	99.82
VK-120/1	50.64	0.52	3.29	0.16	9.39	0.34	16.02	20.48	0.21	0.02	101.07
VK-120/2	49.93	0.43	1.73	0.12	11.33	0.58	14.76	20.13	0.27	0.01	99.29
VK-115/1	50.76	0.48	1.61	0.14	13.65	0.74	13.81	18.26	0.22	–	99.68
VK-114/1	48.78	0.53	3.42	0.32	10.11	0.60	17.20	18.66	0.21	0.01	99.82
VK-114/2	50.09	0.42	2.58	0.18	9.45	0.47	15.31	19.92	0.21	–	98.63
VK-118/2	52.42	0.49	1.61	–	13.79	0.74	13.43	17.46	0.19	–	100.14
VK-116/1	52.31	0.42	1.96	0.04	11.68	0.59	14.62	19.72	0.22	–	101.57
VK-116/2	52.52	0.33	2.75	0.10	8.71	0.47	16.65	18.95	0.19	0.01	100.67
VK-58/1	50.47	0.56	3.78	0.03	9.43	0.23	14.61	20.82	0.36	0.01	100.31
VK-58/2	51.48	0.50	2.07	0.05	13.70	0.47	13.78	17.64	0.13	0.01	99.83
VK-61	50.51	0.86	4.31	0.29	7.37	0.14	14.53	21.02	0.24	0.01	99.28
VK-71/1	50.26	0.50	3.94	0.18	9.74	0.33	14.83	19.83	0.20	0.01	99.82
VK-71/2	52.76	0.33	2.07	0.14	9.47	0.45	16.12	19.49	0.15	0.001	100.98
VK-75	49.95	0.66	2.63	0.04	10.81	0.69	14.44	19.44	0.30	–	98.96
VK-77	50.78	0.55	2.56	0.04	12.95	0.63	13.37	18.81	0.28	–	99.99
VK-85/1	49.44	0.82	4.32	0.03	8.75	0.40	14.22	20.69	0.33	0.01	99.01
VK-85/2	50.18	0.54	2.05	0.03	12.88	0.67	13.57	18.25	0.24	–	98.42
VK-92/1	51.35	0.45	1.64	0.02	12.94	0.48	13.83	17.90	1.61	0.03	100.25
VK-95/1	52.31	0.56	1.77	0.06	12.21	0.61	13.34	18.07	0.28	0.01	99.21
VK-95/2	52.88	0.58	1.65	0.04	11.08	0.69	13.74	18.89	0.28	–	99.83
VK-96/1	52.61	0.52	1.49	0.01	13.35	0.46	13.80	18.42	0.25	–	100.91
VK-96/2	52.75	0.49	1.77	0.03	12.95	0.65	13.39	17.44	0.26	–	99.75
VK-96/3	53.12	0.52	1.76	0.02	11.28	0.65	13.97	18.35	0.25	0.01	98.91
VK-96/4	52.33	0.48	1.64	0.07	11.70	0.66	14.11	18.00	0.24	0.01	99.23
VK-100	51.48	0.56	3.33	0.13	9.59	0.40	15.19	20.16	0.23	–	101.07
Amphiboles											
MP-18/1	42.49	3.41	11.94	0.04	11.51	0.16	15.96	8.97	2.53	0.61	98.13
MP-18/2	46.10	1.63	8.00	0.05	20.54	0.69	9.98	8.74	1.38	0.82	97.93
MP-19/1	46.51	1.87	7.13	0.02	16.58	0.40	12.31	11.16	1.47	0.77	98.23
MP-19/2	46.54	1.71	6.19	0.09	16.71	0.42	13.18	10.86	1.54	0.68	97.92
MP-19/3	46.41	1.59	6.69	0.05	17.64	0.88	11.78	10.89	1.52	0.41	97.85

Table 3. (Contd.)

Sample #	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	Total
MP-19/4	47.29	1.09	6.46	0.08	18.08	0.86	12.13	11.03	1.25	0.51	98.77
MP-31/1	51.71	0.94	3.80	0.07	16.74	0.70	13.11	12.16	0.51	0.16	99.90
MP-31/2	50.04	0.56	2.94	0.35	18.24	0.63	12.68	10.21	0.69	0.23	96.57
MP-32	47.26	1.17	6.75	0.10	15.15	0.73	13.73	11.68	1.17	0.66	98.39
MP-14/1	48.33	1.20	3.55	0.04	17.84	0.54	11.13	11.03	1.09	0.60	95.35
MP-14/2	49.00	1.10	3.07	0.02	18.40	0.65	11.65	10.84	1.21	0.56	96.50
MP-7	51.39	1.16	2.15	0.16	12.18	0.19	15.30	12.51	0.03	0.01	95.08
VK-22/1	41.73	1.95	12.34	0.08	14.74	0.33	12.46	11.36	2.38	1.10	98.46
VK-22/2	40.45	1.93	13.17	0.16	15.46	0.31	12.16	11.22	2.38	1.20	98.43
VK-73	60.34	0.01	0.02	—	—	0.01	24.24	13.57	0.14	0.04	98.37
VK-77	41.50	2.98	11.57	0.04	10.50	0.17	14.77	11.14	2.49	0.59	95.74
VK-71/1	48.34	1.02	6.77	0.12	16.74	0.47	11.81	11.78	0.93	0.61	98.61
VK-71/2	48.19	0.88	6.39	0.09	16.55	0.56	12.98	11.52	0.65	0.48	98.28
VK-96/1	60.53	0.01	0.10	0.01	—	—	23.62	13.56	0.03	0.01	97.86
VK-96/2	60.14	0.01	0.09	0.03	—	—	24.11	13.46	0.10	—	97.94
Chromites											
MP-31/1	—	0.10	4.36	60.39	27.85	0.53	6.71	—	—	—	99.94
MP-31/2	—	4.73	14.21	39.45	29.26	0.29	12.49	—	—	—	100.45
MP-32/1	—	2.47	7.42	50.63	25.28	0.33	13.01	—	—	—	99.15
MP-32/2	—	2.76	10.39	47.71	28.96	0.31	10.75	—	—	—	100.89
MP-19/1	—	0.06	23.22	38.24	28.24	0.30	10.71	—	—	—	100.78
MP-19/2	—	1.28	16.36	33.29	43.68	0.43	4.52	—	—	—	99.57
MP-19/3	—	1.83	12.42	40.71	33.57	0.32	9.65	—	—	—	100.52
MP-23/1	—	0.41	8.22	55.20	27.69	0.73	8.44	—	—	—	100.70
MP-23/2	—	0.51	18.27	44.73	24.09	0.35	11.27	—	—	—	99.23
MP-52	—	1.82	10.97	48.64	29.3	0.26	11.86	—	—	—	102.87
MP-75	—	0.01	26.16	42.63	18.64	0.25	14.35	—	—	—	102.06
MP-7/1	—	4.54	10.23	40.22	33.18	0.29	12.92	—	—	—	101.39
MP-7/3	—	3.16	8.93	46.31	30.34	0.34	11.54	—	—	—	100.64
MP-14/1	—	0.45	22.48	37.55	29.61	0.27	9.40	—	—	—	99.78
MP-14/2	—	2.02	11.57	47.34	25.54	0.23	12.05	—	—	—	98.76
VK-118	—	2.47	11.06	43.69	30.39	0.28	11.47	—	—	—	99.38
VK-114/1	—	4.00	8.87	41.64	34.32	0.39	11.36	—	—	—	100.49
VK-114/2	—	4.70	8.36	41.23	34.61	0.37	10.86	—	—	—	100.13
VK-113	—	4.10	9.44	43.86	29.48	0.38	12.44	—	—	—	99.70
VK-105/1	—	4.22	9.29	38.54	37.25	0.50	10.81	—	—	—	100.62
VK-105/2	—	2.05	13.35	43.29	29.67	0.59	12.11	—	—	—	101.06
VK-113	—	3.49	9.22	43.18	31.47	0.56	11.86	—	—	—	99.79
VK-27/1	—	2.16	12.29	46.59	29.43	0.33	10.37	—	—	—	101.18
VK-27/2	—	0.08	17.57	48.20	22.72	0.47	9.68	—	—	—	98.75
VK-118/1	—	1.77	13.33	46.58	26.54	0.20	12.48	—	—	—	100.91
VK-118/2	—	4.21	11.14	40.32	36.05	0.40	10.78	—	—	—	99.91
VK-115/1	—	0.20	16.06	47.58	27.23	0.55	7.62	—	—	—	99.26
VK-115/2	—	1.96	12.48	44.25	28.42	0.55	10.97	—	—	—	98.65
VK-120/1	—	2.47	8.74	44.27	28.31	0.39	11.84	—	—	—	96.03

Table 3. (Contd.)

| Sample #	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	Total
VK-120/2	–	4.59	10.06	36.13	38.63	0.45	10.46	–	–	–	100.33
VK-116/1	–	4.62	9.92	40.37	34.41	0.42	10.85	–	–	–	100.59
VK-116/2	–	0.08	4.12	64.38	19.25	0.39	11.87	–	–	–	100.10
VK-8/1	–	2.72	11.07	45.63	29.29	0.41	9.95	–	–	–	99.06
VK-8/2	–	2.66	11.88	45.66	28.18	0.37	11.52	–	–	–	100.29
VK-8/3	–	3.24	10.73	47.11	27.93	0.40	11.00	–	–	–	100.42
VK-8/4	–	0.12	25.56	39.68	23.36	0.42	10.21	–	–	–	99.36
VK-34/1	–	4.92	9.23	40.90	33.78	0.42	10.78	–	–	–	100.06
VK-34/2	–	2.60	11.26	48.29	25.18	0.41	11.89	–	–	–	99.64
VK-34/3	–	3.12	11.15	45.35	27.96	0.37	11.59	–	–	–	99.55
VK-75/1	–	2.97	9.59	43.27	33.74	0.29	11.51	–	–	–	101.37
VK-75/2	–	2.26	13.15	43.72	27.98	0.32	12.31	–	–	–	99.76
VK-75/3	–	3.04	10.46	40.66	34.76	0.34	10.85	–	–	–	100.14
VK-104/1	–	1.11	13.25	48.75	22.78	0.43	13.42	–	–	–	98.88
VK-104/2	–	3.90	7.64	41.35	36.43	0.40	9.26	–	–	–	98.98
VK-100	–	3.51	10.99	41.80	33.24	0.45	10.84	–	–	–	100.84
VK-96/1	–	4.40	6.54	38.01	43.86	0.39	8.26	–	–	–	101.48
VK-96/2	–	0.17	21.09	40.19	30.36	0.40	8.89	–	–	–	101.12
VK-95/1	–	2.40	9.94	48.30	30.58	0.33	13.01	–	–	–	100.57
VK-95/2	–	4.18	8.46	42.30	35.72	0.38	10.46	–	–	–	101.52
VK-95/3	–	4.18	9.54	38.33	39.37	0.38	9.70	–	–	–	101.50
Garnets											
MP-19	38.62	0.05	21.34	0.04	34.27	3.16	2.67	0.84	0.04	–	101.03
MP-24/1	38.04	0.08	20.34	0.07	34.51	1.36	2.47	2.01	–	–	98.90
MP-24/2	38.00	0.05	20.96	0.04	31.11	7.44	2.52	0.76	–	–	100.89
MP-75/1	37.85	0.06	20.81	0.08	22.90	17.94	0.25	1.13	0.06	0.03	101.11
MP-75/2	37.82	0.06	19.81	0.12	29.49	7.93	0.19	1.95	0.04	0.03	97.44
MP-69/1	39.48	0.07	23.33	0.26	26.23	0.51	10.96	0.98	–	–	100.83
MP-69/2	36.06	0.12	21.35	0.16	32.28	5.71	2.70	0.72	0.02	–	99.15
MP-69/3	37.27	0.05	20.51	0.12	27.77	14.72	0.03	0.65	0.03	–	101.15
MP-69/4	38.99	0.03	20.88	0.27	30.00	1.09	6.91	1.84	0.02	–	100.01
MP-69/5	38.17	0.06	21.34	0.10	32.87	1.29	4.41	1.65	–	–	99.89
MP-7	38.42	0.10	21.07	0.07	34.51	0.83	4.58	0.80	0.08	0.01	100.47
MP-62/1	38.51	0.05	20.67	0.06	33.98	1.13	4.61	1.01	0.02	0.01	100.07
MP-62/2	37.47	0.15	18.36	0.01	18.60	23.06	1.11	0.50	0.09	–	99.35
MP-62/3	37.06	0.05	17.66	0.01	22.94	13.44	1.54	4.61	0.05	–	97.35
MP-62/4	36.89	0.11	19.56	0.05	24.18	17.71	0.05	0.59	0.13	0.01	99.28
MP-19	38.62	0.05	21.34	0.04	34.27	3.16	2.67	0.84	0.04	–	101.03
VK-96/1	38.71	0.40	20.39	0.07	31.49	3.64	2.00	4.03	0.02	0.02	100.77
VK-96/2	36.96	0.41	21.13	0.12	31.71	4.29	2.25	4.18	0.03	0.01	101.08
VK-85/1	37.25	0.18	20.90	0.03	16.13	25.72	0.70	0.20	0.01	0.02	101.16
VK-85/2	37.23	0.06	21.51	0.02	29.38	6.05	2.60	2.64	0.02	–	99.53

FeO*, total iron. Dash, not found.
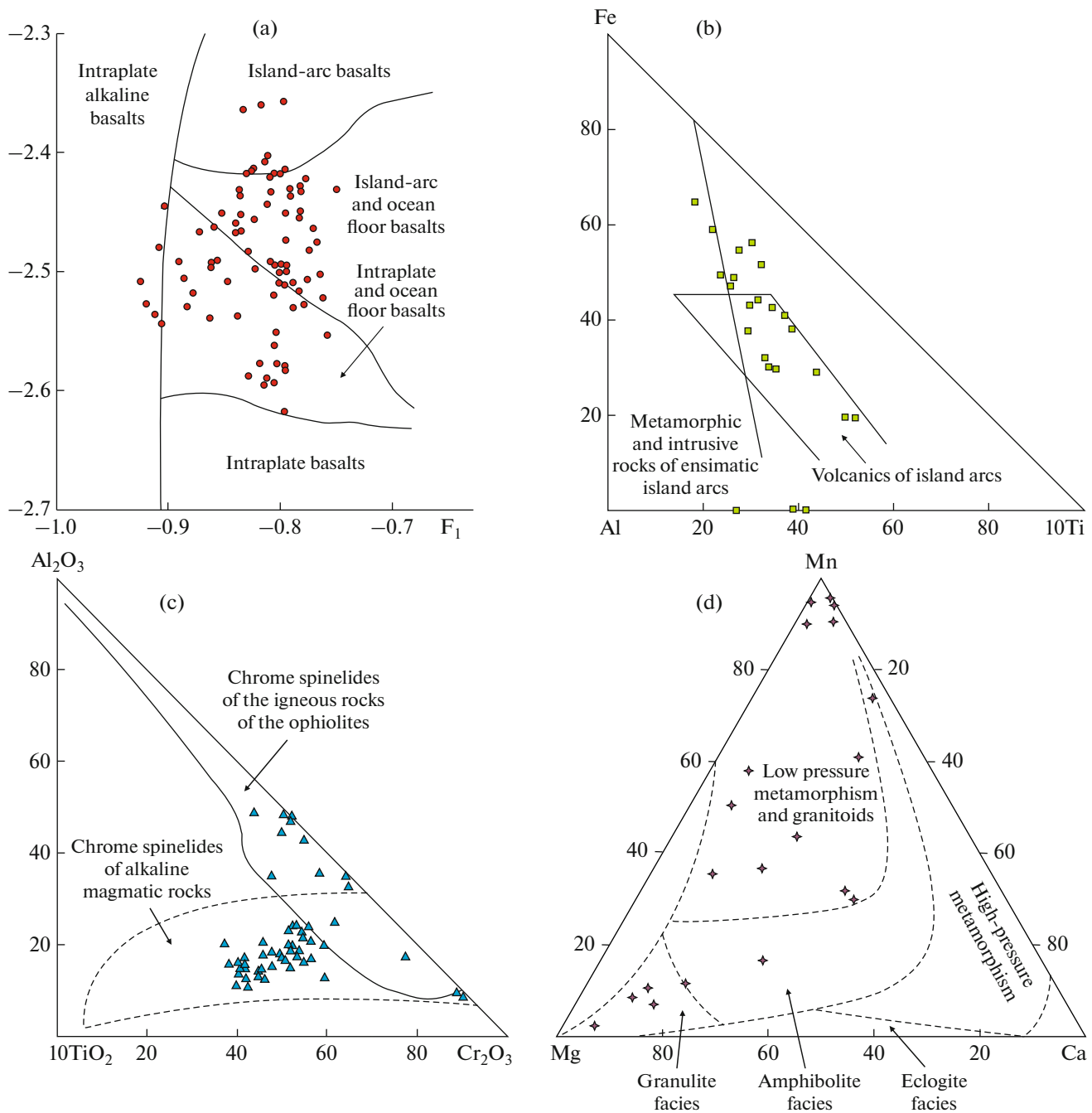
Fig. 9. Composition diagrams for heavy clastic minerals from the sandstones of the Early Cretaceous of the Northern Sikhote-Alin and their probable volcanic sources. a, for clinopyroxenes [45]: F1 = − 0.012SiO$_2$ − 0.0807TiO$_2$ + 0.0026Al$_2$O$_3$ − 0.0012FeO − 0.0026MnO + 0.0087MgO − 0.0128CaO − 0.0419Na$_2$O; F2 = − 0.0496SiO$_2$ − 0.0818TiO$_2$ − 0.02126Al$_2$O$_3$ − 0.0041FeO − 0.1435MnO − 0.0029MgO − 0.0085CaO + 0.0160Na$_2$O; b, for amphiboles [42]; c, for chromites [25]; d, for garnets [50].

The paleogeodynamic interpretation of the geochemical composition of rocks was performed using the discriminant diagrams shown in Fig. 11. In the series of diagrams by Bhatia and Crook [28, 29] (Figs. 11a−11g), which are designed to distinguish sandstones from various tectonic settings, the sandstones mainly fall into or near the fields of sedimentary basins of active continental margins of the Andean

type, that, according to some authors [28, 39, 46] include margins complicated by shear dislocations along transform faults. Significantly fewer points lie in the field of basins associated with marginal continental magmatic arcs. Even more unambiguously the conditions of accumulation of the studied sediments are established on the diagram of Roser and Korsch [46] (Fig. 11h), where all sandstone data points are closely
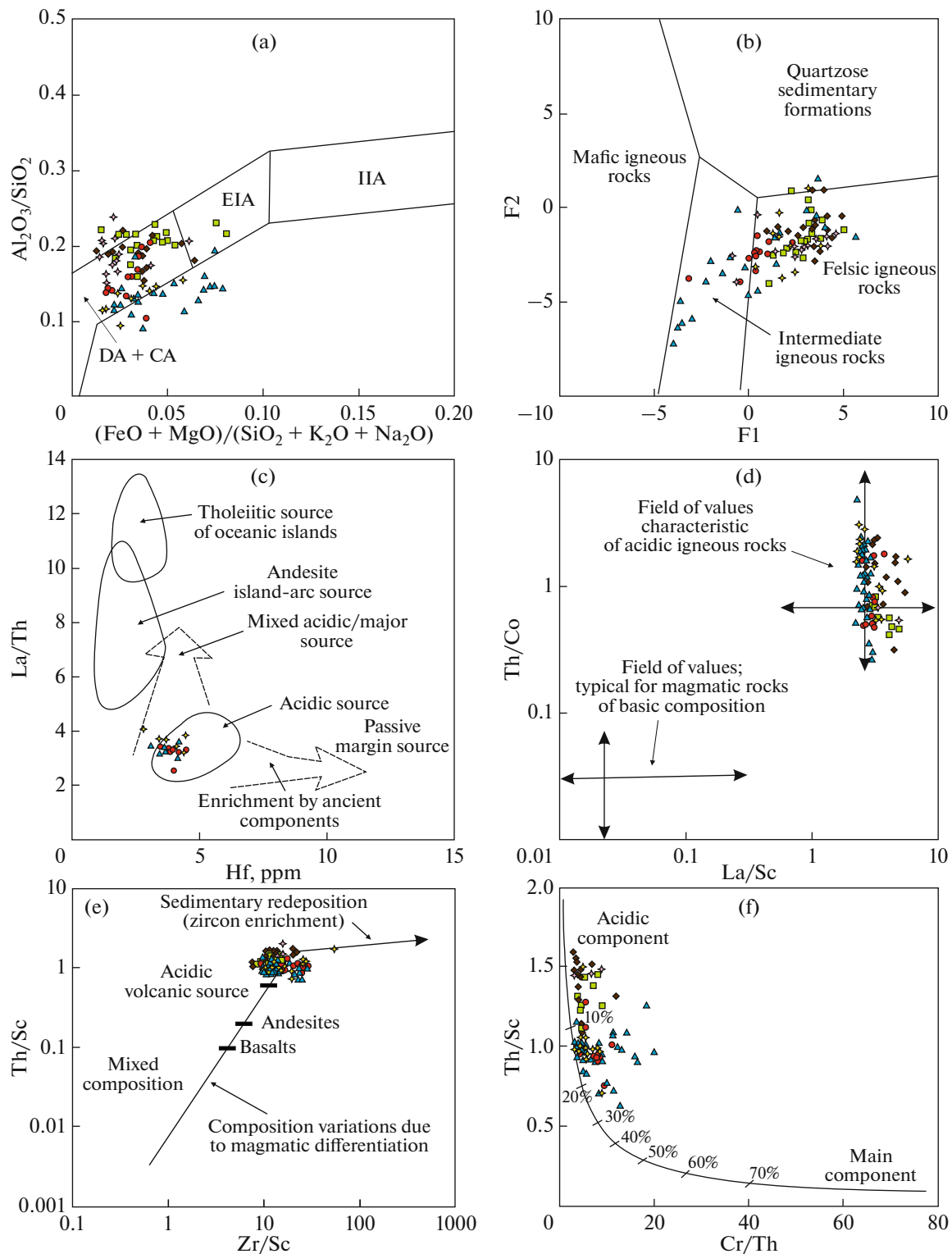
Fig. 10. Possible sources of terrigenous deposits of the Early Cretaceous of the Northern Sikhote-Alin inferred from geochemical data. a, types of feeding provinces of magmatic arcs [37]. Magmatic arcs: IIA, oceanic islands; immature; EAI, weakly eroded insular; DA, islands; deeply eroded; CA, continental margin; b−e, probable compositions of the parent rocks in the diagrams: b, F1−F2 [47]. F1 = 30.638TiO$_2$/Al$_2$O$_3$, 12.541Fe$_2$O$_3^*$/Al$_2$O$_3$ + 7.329MgO/Al$_2$O$_3$ + 12.031Na$_2$O/Al$_2$O$_3$ + 35.402K$_2$O/Al$_2$O$_3$, 6.382; F2 = 56.5TiO$_2$/Al$_2$O$_3$, 10.879Fe$_2$O$_3^*$/Al$_2$O$_3$ + 30.875MgO/Al$_2$O$_3$, 5.404Na$_2$O/Al$_2$O$_3$ + 11.112K$_2$O/Al$_2$O$_3$, 3.89; c, Hf-La/Th [35]; d, La/Sc-Th/Co [33]; e, Zr/Sc−Th/Sc [40]; f, Cr/Th−Th/Sc [32]. For legend; see Fig. 3.
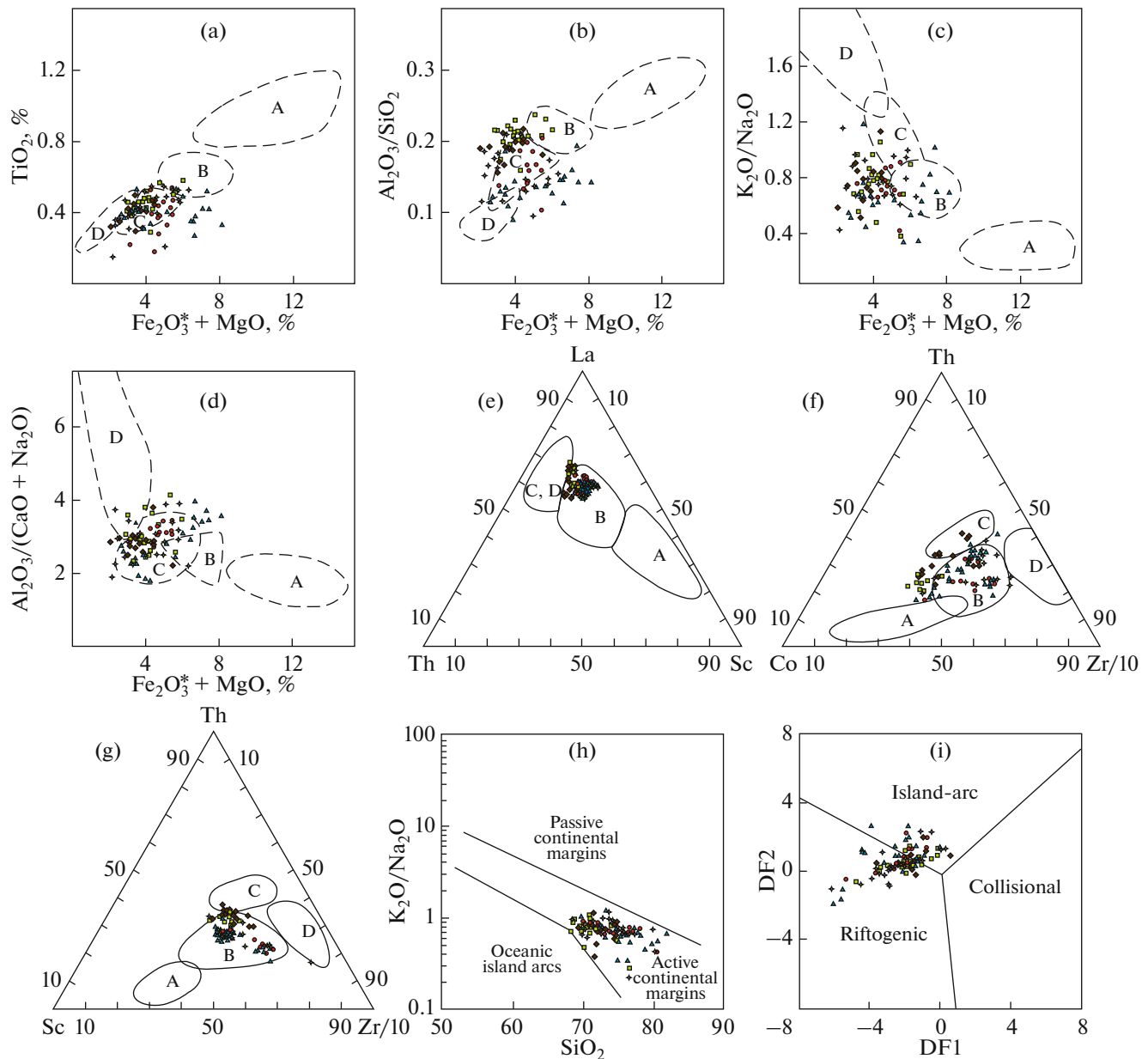
Fig. 11. Paleogeodynamic settings of the formation of Early Cretaceous terrigenous deposits of the Northern Sikhotee-Alin inferred from geochemical data. a−g, types of sedimentation basins [28, 29]. Fields of geochemical parameters of ancient sandstones from basins: A, oceanic arc; B, continental island arcs; C, active continental margin; D, passive margins. $Fe_2O_3^*$, total iron; h, basin settings for sandy-silty rocks [46]; i, possible types of geodynamic settings for high-siliceous rocks [51]. $DF1 = -0.263\ln(TiO_2/SiO_2)adj + 0.604\ln(Al_2O_3/SiO_2)adj + 1.725\ln(Fe_2O_3tot/SiO_2)adj + 0.66\ln(MnO/SiO_2)adj + 2.191\ln(MgO/SiO_2)adj + 0.144\ln(CaO/SiO_2)adj - 1.304\ln(Na_2O/SiO_2)adj + 0.054\ln(K_2O/SiO_2)adj - 0.33\ln(P_2O_5/SiO_2)adj + 1.588; DF2 = -1.196\ln(TiO_2/SiO_2)adj + 1.064\ln(Al_2O_3/SiO_2)adj + 0.303\ln(Fe_2O_3tot/SiO_2)adj + 0.436\ln(MnO/SiO_2)adj + 0.838\ln(MgO/SiO_2)adj + 0.407\ln(CaO/SiO_2)adj + 1.021\ln(Na_2O/SiO_2)adj - 1.706\ln(K_2O/SiO_2)adj - 0.126\ln(P_2O_5/SiO_2)adj - 1.068$. See Fig. 3 for the legend.

grouped in the field of sedimentation basins of active continental margin. Cretaceous sandstones on the DF1-DF2 discriminant diagram [51] (Fig. 11i), which is applicable to rocks with a high silica content (SiO_2 exceeding 63%), occupy an intermediate position between the fields of island arc and rift settings,

including environments associated with transform plate boundaries [15, 48, 49].

In general, since these diagrams were invented quite some time ago, (1980s−1990s), when the fields corresponding to the conditions of transform sliding of lithospheric plates have not yet been distinguished, the

data points were place in fields corresponding to several different geodynamic conditions or sediment sources. Such an "intermediate" position of points in all diagrams is likely to be a characteristic and sufficiently reliable sign of sedimentation in a transform margin setting, when marginal parts of continents, continental margin arcs, and previously accreted fragments of active margins fall into the erosion area [6, 9].

CONCLUSIONS

The petrographic composition, heavy clastic minerals (including the chemical composition of some of them), and geochemical features of sandy rocks were studied to reconstruct the geodynamic conditions of the Lower Cretaceous deposits of the Northern Sikhote-Alin, as well as to determine the type and composition of source rocks. Additionally, data on the geochemistry of silts were involved.

Our study showed that, in terms of their mineralogical and geochemical parameters, they correspond to graywackes and only partly to lithic arenites, being "first cycle" rocks formed mainly due to mechanical destruction of source rocks. They are characterized by weak lithodynamic processing of parent rocks, low maturity of the clastic material, and a relatively high rate of its burial.

The paleogeodynamic interpretation of all the data obtained during the study indicate that the sedimentation in the Early Cretaceous occurred along the continent-ocean border in a basin associated with large-scale shear dislocations along transform faults, one example of which are the basins of the California margin [31].

The source area that supplied clastic material to this sedimentation basin probably combined several settings. The dominant clastic source was sialic landforms composed of granite-metamorphic and ancient sedimentary complexes. This is evidenced, in particular, by rather high contents of quartz and acid plagioclase in the clastic part of sandstones, sharp predominance of their sialic association among heavy minerals, the composition of clastic garnets, and the geochemical features of rocks. The results of U−Pb geochronologic studies of detrital zircons [4] indicate that these sources of sialic clastics, or most of them, were located within the North China Craton.

The next most important source of matter was a mature deeply eroded marginal continental magmatic arc, probably synchronous with the Jurassic accretionary prism of the Samarka terrane and its analogues [22]. The island-arc nature of this source is established by the predominantly graywacke clastics, the presence of the femic association of heavy minerals typical of island-arc volcanics, the composition of clastic clinopyroxenes, amphiboles, and some chromites with island-arc characteristics, as well as a number of geochemical parameters of the rocks. The source of the

material was volcanic arc formations. At the same time, the eroded granite-metamorphic complexes of the arc basement served as another source of sialic clastics.

Another secondary source of femic clastics was fragments of Jurassic-Early Cretaceous accretionary prisms of Sikhote-Alin, whose structures involved ultrabasic and basic ophiolites, as indicated by the presence of chromite, magnetite, pyroxenes, amphibole and olivine with intraplate characteristics among heavy minerals.

Consequently, the source area for Lower Cretaceous deposits of the Northern Sikhote-Alin was heterogeneous. It combined such significantly different sources as continental margins, fragments of island arcs, and sections of the oceanic crust, which is characteristic of sedimentation in basins formed under the conditions of transform sliding of lithospheric plates.

Thus, our studies have shown that the Lower Cretaceous sediments of the Northern Sikhote-Alin accumulated in a sedimentation basin spatially and genetically related to the regime of transformational sliding of lithospheric plates, which allows them to be considered as deposits of the Early Cretaceous Zhuravlevka synsedimentary terrane.

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