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Petrogeochemical Aspects of the Late Cretaceous and Paleogene Ignimbrite Volcanism of East Sikhote-Alin

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Abstract—The chemical and trace-element features of the Late Cretaceous and Early Paleogene ignimbrite complexes of East Sikhote Alin are discussed. The Turonian–Campanian volcanic rocks of the Primorsky Complex compose linear structure of the Eastern Sikhote Alin volcanic belt. They are represented by crystal-rich rhyolitic, rhyodacitic, and dacitic S-type plateau ignimbrites produced by fissure eruptions of acid magmas. The Maastrichtian–Paleocene volcanic rocks occur as isolated volcanic depression and caldera structures, which have no structural and spatial relations with the volcanic belt. This period is characterized by bimodal volcanism. The Samarginsky, Dorofeevsky, and Severyansky volcanic complexes are made up of basalt–andesite–dacite lavas and pyroclastic rocks, while the Levosobolevsky and Siyanovsky complexes are comprised of rhyolitic and dacitic tuffs and ignimbrites. Petrogeochemically, the felsic volcanic rocks are close to the S-type plateau ignimbrites of the Primorsky Complex. The Paleocene–Early Eocene silicic volcanics of the Bogopolsky Complex are represented by S- and A-type dacitic and rhyolitic tuffs and ignimbrites filling collapsed calderas. The eruption of A-type ferroan hyaloignimbrites occurred at the final stage of the Paleogene volcanism (Bogopolsky Complex). The magmatic rocks show well expressed mineralogical and geochemical evidence for the interaction between the crustal magmas and enriched sublithospheric mantle. It was shown that the revealed differences in the mineralogical and geochemical composition of the ignimbrite complexes are indicative of a change in the geodynamic regime of the Asian active continental margin at the Mesozoic–Cenozoic transition.

Keywords: plateau ignimbrites, hyaloignimbrites, geochemistry, S- and A-type granitoids, geodynamic settings of volcanic manifestations, Sikhote-Alin

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INTRODUCTION

Explosive eruptions of acid magmas leading to the formation of peculiar lava and pyroclastic rocks—ignimbrites and associated variably welded tuffs—provide insight into the manifestations of ancient and modern volcanism of island arcs, active continental margins, and intracontinental zones. Two types of ignimbrites are presently distinguished. The first type is represented by voluminous plateau-ignimbrites filling large volcanic depression (VD). These provinces are abbreviated as SLIP (Silicic Large Igneous Province) by analogy with LIP (Large Igneous Provinces)—within-plate large basaltic provinces. However, unlike the latters, they are related to Andean-type subduction geodynamic settings [34]. The second type comprises small-scale caldera-type ignimbrites, which were formed by the collapse of their roof into the magma generation zone of a subsurface magmatic chamber [50]. They were found in different geodynamic settings: island arcs, active continental margins, continental rifts, and oceanic islands.

The Andean-type East Asian volcanic belt, unique in the world in its length, was formed on the Asian continental margin in the Late Cretaceous (Turonian–Campanian). The voluminous fissure eruptions of acid magmas produced a giant plateau-ignimbrite pile corresponding to the SLIP type of magmatic provinces. The younger (Maastrichtian–Paleocene) "caldera" ignimbrites of active continental margins have not been related to the volcanic belt but are reflected the stage of areal volcanism extending far beyond the area of the linear volcanogenic structure. Similar types of ignimbrites were also found in East Sikhote-Alin (Fig. 1). The Late Cretaceous (Turonian–Campanian) ignimbrites of the Primorsky Complex compose the main volume of the volcanic rocks of the East Sikhote-Alin volcanic belt (ESAVB), the central chain of the East Sikhote-Alin lineament. The rocks of the complex are homogenous in composition. They compose thick sequences (up to 1500 m) dominated by rhyolitic crystal-rich welded tuffs and ignimbrites with vague signs of stratification. The Maastrichtian–Paleocene volcanic rocks fill volcanic

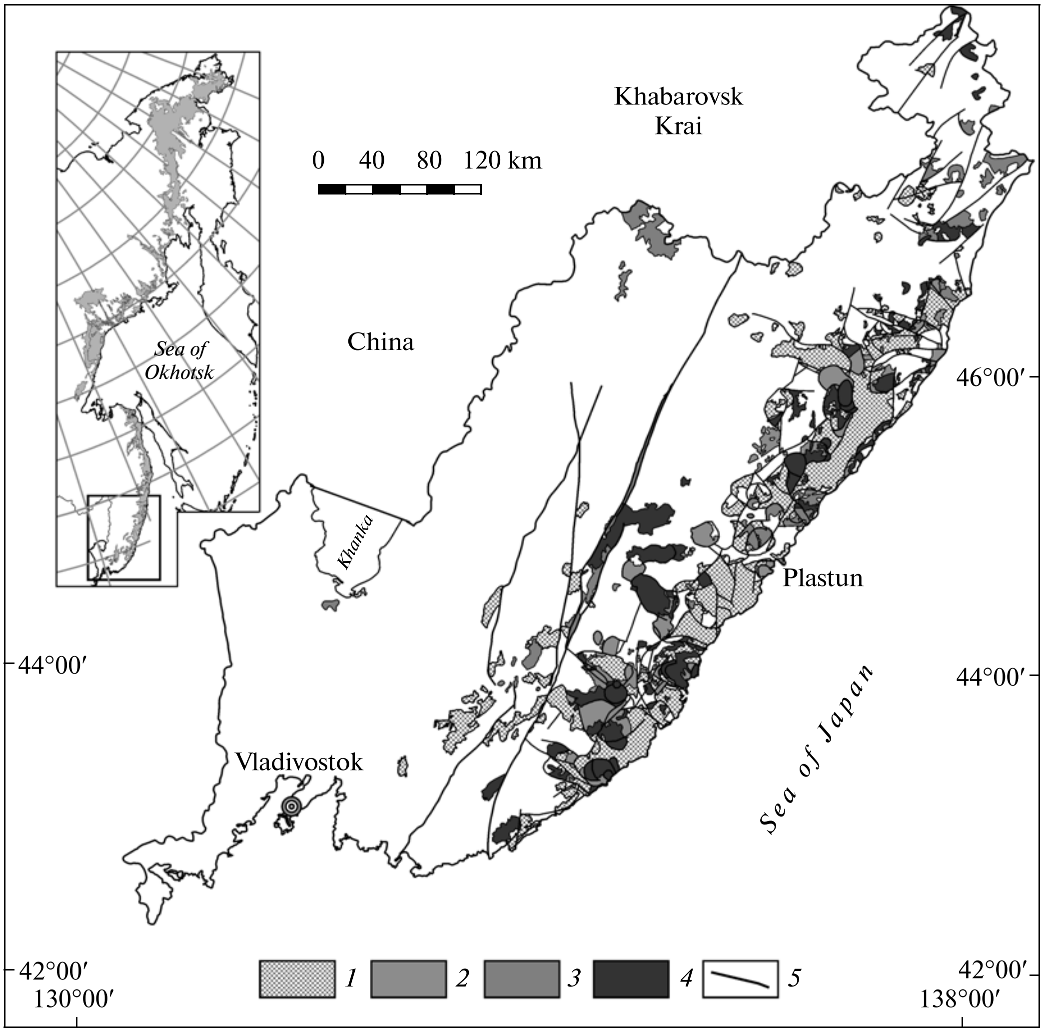

Fig. 1. Distribution scheme of the Late Cretaceous and Early Paleogene ignimbrites in Primorye (Russian Far East).
(*1–2*) main fields of the Turonian–Campanian plateau-ignimbrites of the Primorsky Complex (*1*) and the Campanian–Maastrichtian caldera ignimbrites of the Siyanovsky and Levosobolevsky complexes (*2*); (*3*) development areas of the Campanian–Maastrichtian basalt-dacite series of the Samarginsky, Dorofeevsky, and Severyansky complexes; (*4*) fields of the Early Paleogene ignimbrites of the Bogopolsky Complex; (*5*) main faults. The inset compiled after [12] shows the areas of the manifestation of the Cretaceous–Paleogene ignimbrite volcanism in the Russian Far East.

depressions and compose individual volcanic edifices both among fields of plateau ignimbrites of the volcanic belt and beyond its limits. This period was responsible for the formation of bimodal volcanism. The products of explosive acid volcanism distinguished in the Levosobolevsky and Siyanovsky complexes are represented by dacite–rhyolite tuffs and ignimbrites, while the Samarginsky and Dorofeevsky complexes comprise lavas and pyroclastic rocks of basalt–andesite–dacite composition.

The Paleocene–Eocene ignimbrites of the Bogopolsky volcanic complex also fill collapsed calderas and individual shear-related volcanic depressions. The initial stage of the volcanism (Danian) produced a stratified succession consisting of rhyolitic and rhyodacitic tuffs, ignimbrites, and lava flows, while volcanic final stages (Paleocene–Eocene) were responsible for the formation of dacite–rhyolite "variegated" tuffs, hyaloignimbrites, and extrusive lava bodies. The latters are often made up of volcanic glass.

The more than half-century history of studies of the East Sikhote-Alin ignimbrites takes its origin from the works of M.A. Favorskaya, V.O. Solov'eva, E.V. Bykovskaya, N.S. Podgornaya, M.G. Rub, G.P. Volarovich, I.I. Bersenev, and others, who studied for the first time the geological structure and composition of the Late Cretaceous tuffs and ignimbrites of the Ol'ginsky (presently Primorsky) Complex and the Siyanovsky and Bogopolsky formations in the first half of the 20th century. Their investigations highlighted the main tendencies of the Far East Mesozoic–Cenozoic volcanism and revealed the position and chemical features of the ignimbrites from different volcanic zones [28, 32, 35, 36, etc.]. In this period, the East Sikhote-Alin volcanic belt was distinguished by Shatskii [33] and studied in detail by Bykovskii [5].

The detailed geological-survey and topical works carried out in 1970 to the 1980s in East Sikhote-Alin (V.V. Vetrennikov, F.I. Rostovskii, V.A. Mikhailov, V.I. Rybalko, A.V. Oleinikov, G.L. Amel'chenko, A.P. Matyunin, I.N. Govorov, F.G. Fedchin, G.M. Fremd, V.G. Sakhno, V.A. Baskina, A.M. Kurchavov, V.P. Simanenko, L.G. Filimonova, G.B. Levashev, and others) provided significant breakthroughs in studying the composition of the volcanic rocks. The results of the volcanological research were generalized and published in several monographs [3, 9, 10, 24, 37, 38].

At the end of the 1980s to the beginning of the 1990s, Levashov et al. [18] launched a geochemical study of the volcanic rocks of Primorye, including the Late Cretaceous and Early Paleogene ignimbrites of East Sikhote-Alin, and attempted to interpret the magmatism of the Sikhote-Alin fold system from the view point of plate tectonics. This direction gained further evolution in the investigations of Khanchuk et al. [12, 39] aimed at studying the geodynamic settings of the manifestation of the Mesozoic–Cenozoic magmatism of East Sikhote-Alin.

The isotope-geochemical studies performed in recent decade provided new geochronological data on the volcanic rocks, which have allowed one to specify the time boundaries of the volcanic manifestations in this region [1, 27, 30, 31, 56, and others]. The geochemical study of the Mesozoic–Cenozoic volcanic complexes of East Sikhote Alin started at that time was used in paleotectonic reconstructions of the Asian continental margin [21, 23, 31, 39, 40, and others]. The main attention was given to basalts as indicators of deep (mantle) processes. We attempted to carry out a similar study of acid volcanic rocks [12, 15]. The results obtained showed that the acid volcanic rocks formed in different geodynamic settings (previously distinguished on the basis of paleotectonic reconstructions and the results of the geochemical study of basalts) also have definite chemical differences [12].

Based on our data and the materials of other researchers, this work reports the results of the comparative analysis of the composition of the Late Cretaceous and Paleogene ignimbrites of East Sikhote-Alin, considers the petrochemical criteria to discriminate between the distinguished types of ignimbrites as well as the petrogenetic features of the ignimbrite-forming felsic melts, and discusses the correlation of the chemical composition of the ignimbrites with their geodynamic regime and style of felsic eruptions at the Mesozoic–Cenozoic boundary. In this work, the geological term "ignimbrite" refers to a complex geological body consisting of welded pyroclasic flows, since type sections of ignimbrite flows in modern volcanic areas (for instance, in Kamchatka) are made up of loose pumice material in the bottom and roof and lava-like tuffs in their central part (tuffolava). The transitional zone between them comprises variably welded rocks often containing lens-like fragments of volcanic glass with splintered edges (fiamme) corresponding to the petrographic meaning of this term [42].

METHODS

The study of the chemical composition (silicate chemical analysis) was carried out at the Far East Geological Institute of the Far East Branch of the Russian Academy of Sciences using conventional techniques. The trace-element composition was determined by inductively coupled plasma mass spectrometry (ICP-MS) at the Institute of Geochemistry of the Siberian Branch of the Russian Academy of Sciences and by instrumental neutron activation analysis (INNA) at the Reactor Center of Missouri University in Columbia, USA using technique [48].

Diagrams were plotted using the chemical and trace-element data on volcanic rocks obtained by the authors during the study of the Late Cretaceous and Paleogene ignimbrite complexes from type sections of the Ternei-Kema and Zevsk-Sobolevsky volcanic fields, as well as from the Martelevsky (Solontsovsky), Uglovsky, Yakutinskaya, Bogopolsky, and Brusilovskaya volcanic depression. Our petrochemical considerations were additionally underlain by the data of Vetrennikov [9], Kurchavov [17], Baskina [3], Mikhailov [24], Sakhno [29], and others (amounting in total to more than 200 chemical analyses). The data set included only unaltered acid magmatic rocks. The compositions were recalculated to 100% water free. The molecular amounts were calculated using standard techniques [41].

The choice of the petrochemical parameters as criteria was not random. It should be admitted that the existing geochemical classifications of granitic rocks based on the differences in the trace and rare element concentrations cannot provide the unambiguous determination of the magmatic source or tectonic setting [45]. This is related to the fact that the trace elements in felsic melts, unlike basic lavas, behave as incompatible elements [43]. Such elements as REE, U, Th, and Zr are usually incorporated in accessory minerals: apatite, zircon, titanite, allanite, and monazite. Other elements, including Nb and Y, are accumulated in magnetite, ilmenite, and amphibole. Thus, the contents of the aforementioned elements are determined by the conditions and extensive parameters (oxygen and water fugacity) of the magma crystallization. Crustal contamination also exerts a stronger effect on the concentrations of trace elements than on the petrogenic oxides. Therefore, we believe that the application of petrochemical parameters provides for the more reliable determination of the steady distinctive compositional (petrochemical) features of rocks of magmatic complexes.

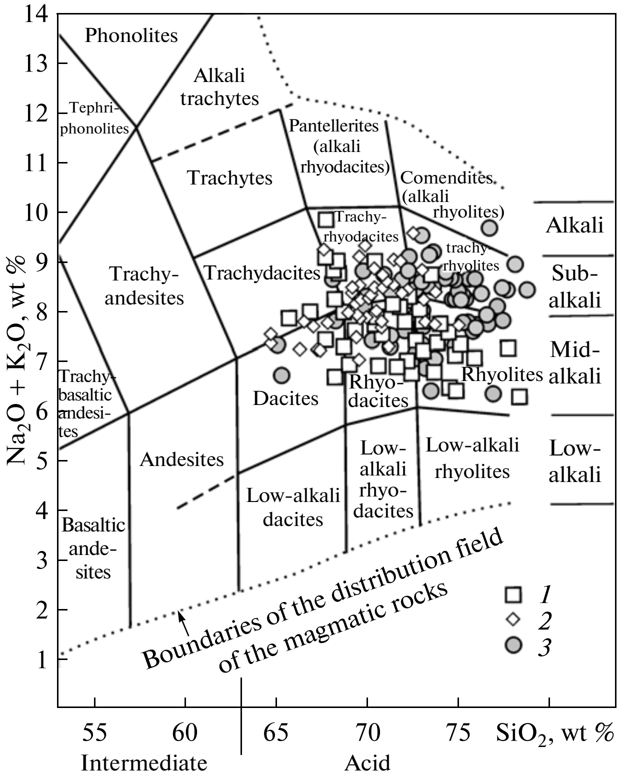

Fig. 2. $Na_2O + K_2O–SiO_2$ (wt %) diagram for the chemical classification of the magmatic (volcanic) rocks.
(*1*) crystal ignimbrites of the Primorsky Complex; (*2*) tuffs and ignimbrites of the Siyanovsky and Levosobolevsky complexes; (3) ignimbrites and volcanic glasses of the Bogopolsky complex.

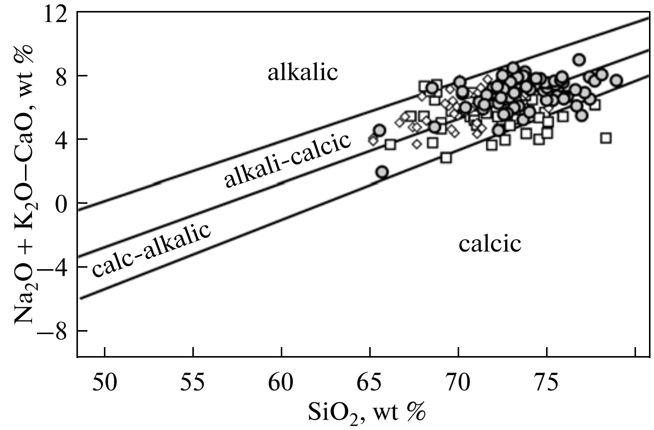

Fig. 3. $(Na_2O + K_2O–CaO)–SiO_2$ (wt %) diagram with the fields of the alkalic, alkali-calcic, calc-alkalic, and calcic series according to [45].

PEROGRAPHY AND CHEMISTRY OF THE EAST SIKHOTE-ALIN IGNIMBRITE COMPLEXES

Volcanic Rocks of the Primorsky Complex (Turonian–Campanian)

The ignimbrites of the Primorsky Complex mainly consist of tuffs and ignimbrites, with less common lavas of rhyodacite and rhyolite composition. The detailed description of sections and the petrographic composition of the rocks are reported in [9, 10, 24, etc.]. The age of the complex is determined as the Turonian–Campanian based on numerous paleofloral finds [26] and geochronological datings (90–82 Ma) [17, 24]. Distinctive features are the gray with greenish tint color of the rocks; the high degree of welding; the massive structure; the presence of fiamme-like lithic clasts; and the high content (40–60%) of crystal clasts of quartz, plagioclase, and chloritized (sometimes epidotized) mafic minerals (biotite and amphibole). Accessory minerals are represented by magnetite, apatite, more rare zircon, and allanite. The rocks are characterized by their felsic and moderately felsic composition (SiO_2 = 64–75 wt %), normal and elevated K–Na alkalinity (Table 1, Fig. 2), and correspond to plumasite and peraluminous (K_{agp} = 0.41–0.75, ASI = 1.08–1.86) varieties with low and high Fe mole fractions (f = 0.54–0.90). It is seen in the $(Na_2O + K_2O–CaO)–SiO_2$ diagram after [45] that the data points of the volcanic rocks are not ascribed to a single petrochemical series, while varying from calcic to calc-alkalic series (Fig. 3). According to the FeO^{tot}/FeO^{tot} + MgO)–SiO_2 diagram developed by Myashiro [55] for island arc and continental margin volcanic rocks, the ignimbrites of the Primorsky Complex are ascribed to the tholeiitic and calc-alkaline series (Fig. 4a) and to the ferroan and magnesian types of magmatic rocks according to Frost classification [45] (Fig. 4b). According to the modified Maeda diagram $(Na_2O + K_2O)/Al_2O_3–Al_2O_3/(CaO + Na_2O + K_2O)$ [53], the ignimbrites of the Primorsky Complex are ascribed to S-type granitoids (Fig. 5). In the diagrams of Pearce and Velikoslavinskii [8] (Fig. 6), the ignimbrites of the complex are plotted in the fields of island arc and orogenic (collisional) rocks. Petrochemically, the volcanic rocks of the Primorsky Complex are close to the Late Cretaceous granitoids of the coastal zone [4, 6, 7].

The upper crust-normalized trace and rare-earth element variations for the ignimbrites of the Primorsky Complex (Table 2) show a weakly fractionated pattern (Fig. 7). Their La_N/Yb_N ratio varies from 5.7 to 6.7, while the Eu/Eu*, from 0.5 to 1.0. The upper crust-normalized multielement patterns exhibit distinct negative Ba, Nb–Ta, Sr, and Ti anomalies, while the REE pattern has a negative Eu anomaly (Fig. 7).

The volcanic rocks of the Siyanovsky and Levosobolevsky complexes (Maastrichtian–Paleocene) are welded tuffs and ignimbrites of dacites and rhyodacites. The volcanic sequences contain individual horizons of andesite, dacite, and rhyolite lavas. Acid lavas are often represented by fluidal and spherulitic varieties with scarce phenocrysts of quartz and

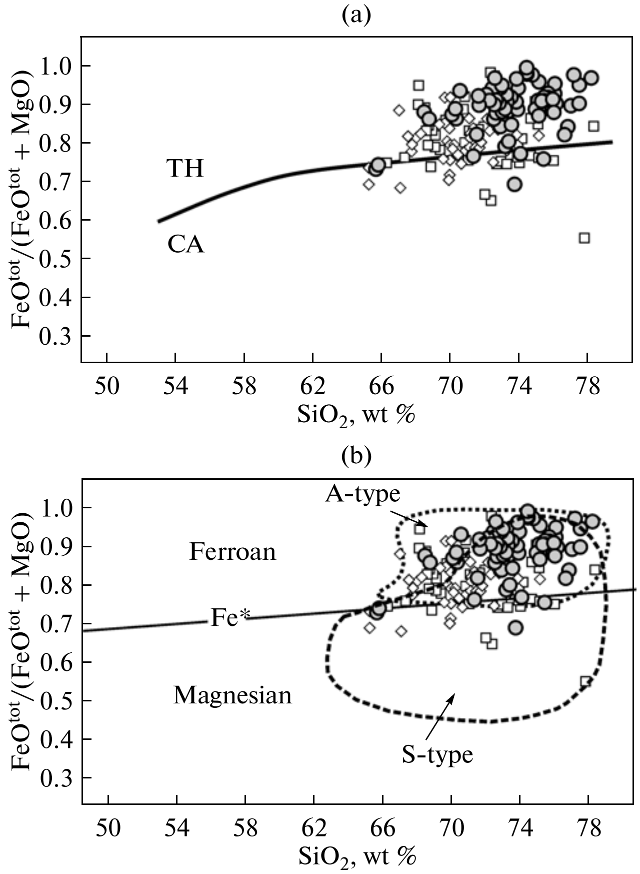

Fig. 4. $FeO^{tot}(FeO^{tot} + MgO)–SiO_2$ (wt %) diagram with the fields of the A- and S-type granites [45].

(a) the solid line shows the boundary between the calc-alkaline (CA) and tholeiitic (TH) series after [55]; (b) the solid line shows the boundary between the ferroan and magnesian types of granitoids. The symbols are shown in Fig. 2.

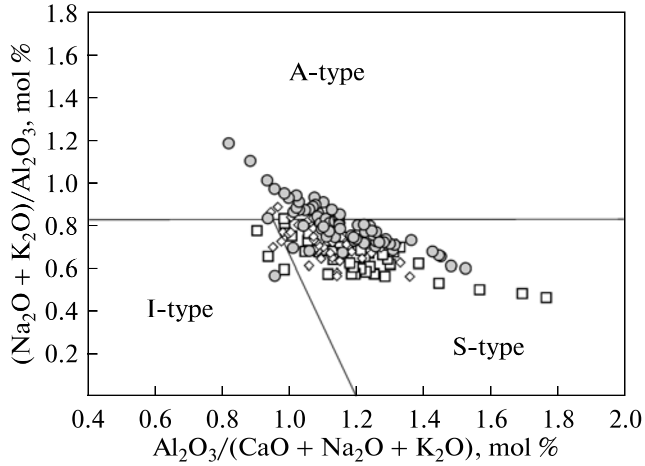

Fig. 5. A/(C + N + K)–(N + K)/A (mol %) diagram [53]. The symbols are shown in Fig. 2.

sodic plagioclase. Tuffs contain an insignificant amount (10–15%) of crystal clasts of quartz, K-feldspar, plagioclase, biotite, and hornblende. Accessory minerals are represented by ilmenite, zircon, anatase, titanite, and moissanite [24]. The rocks have a moderately acid composition (SiO_2 = 67–71 wt %); mid- and elevated K–Na alkalinity (Table 1, Fig. 2); and correspond to plumasite, metaluminous, and (more rarely) peraluminous varieties (K_{agp} = 0.56–0.84, ASI = 0.96–1.33) with low and high Fe numbers (f = 0.67–0.91). In the ($Na_2O + K_2O–CaO$)–SiO_2 diagram, the data points of the volcanic rocks fall in the fields of calc-alkalic; alkali-calcic; and, partly, calcic series (Fig. 3). The ignimbrites of the Levosobolevsky and Siyanovsky complexes are ascribed to the tholeiitic and, more rarely, to the calc-alkaline series according to Myashiro [44] (Fig. 4a) or, correspondingly, to the ferroan and magnesian series according to the classification of Frost [45] (Fig. 4b). In the Maeda diagram, the ignimbrites of the Siyanovsky and Levosobolevsky complexes are also ascribed to the S-type granitoids (Fig. 5) and only individual samples correspond to I- and A-type.

The volcanic rocks of the Bogopolsky Complex (Paleocene–Early Eocence) are characterized by a set of distinctive features manifested in their facies and petrographic composition. These features are used as markers in studying “silent” successions. Among them are the presence of unaltered volcanic glasses (perlites), hyaloignimbrites with classic fiamme, peculiar variegated (from light green to ash brown tints) ash tuffs, and lithic-crystal tuffs of biotite rhyolites. Two type sections of the Bogopolsky Formation are distinguished in southern Sikhote-Alin [22]. The first type is made up of horizons of rhyolitic biotite-bearing tuffs and ignimbrites and ash deposits of the caldera–lacustrine type, often fluorine-bearing ones. They fill small collapsed calderas, for instance, the South Yakutinskaya volcanic structure [22]. The second type is represented by sections described in large volcanotectonic graben calderas (Yakutinskaya, Brusilovskaya, Berezovskaya, Kedrovskaya, and other structures) with the predominant extrusive-subvolcanic complex of the Bogopolsky volcanic rocks, which contain abundant sanidine phenocrysts. In the summarized section of the stratified rocks of the Bogopolsky Complex (upper dellenite–liparite formations according to the terminology of the cited work), V.A. Baskina distinguished the leucocratic or biotite-bearing varieties in the lower part and biotite–amphibole and pyroxene-bearing varieties in the upper part [3].

The isochron (Rb/Sr) datings of flows and extrusive rocks of the Bogopolsky Complex yield 59.7–52.9 Ma [27, 49]. The K–Ar data also confirm the Early Paleogene age of the Bogopolsky volcanic rocks [2, 56, etc.].

The study of the mineralogical composition of the ignimbrites of the Yakutinskaya VD made it possible to

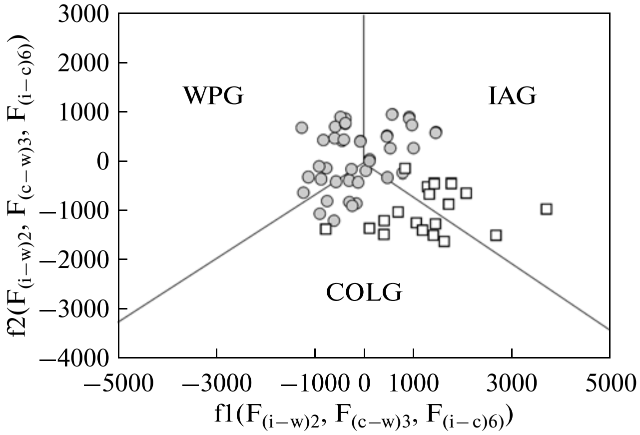

Fig. 6. f1F($_{(i-w)2}$, $F_{(c-w)3}$, $F_{(i-c)3}$, $F_{(i-c)6}$)–f2($F_{(i-w)2}$, $F_{(c-w)3}$, $F_{(i-c)3}$) diagram with the fields of the within-plate (WPG), collisional (COLG), and subduction (IAG) granitoids [8].

distinguish a set of individual features for the upper part of the section of the Bogopolsky Complex. The hyaloignimbrites and voluminous bodies of volcanic glasses show a wide abundance of sanidine and ultra-Fe silicates: ferrohedenbergite ($Ca_{44}Mg_2Fe_{54}$), ferrohypersthene ($Ca_3Mg_{27}Fe_{70}$), fayalite (Fa_{89-99}), high-Fe hornblende (Hb_{70-80}), and biotite (Bi_{70-88}), as well as "spherules" of native iron and cohenite [14, 51].

The rocks have high silicity (SiO_2 = 70–77 wt %), mid- and elevated K–Na alkalinity (Table 1, Fig. 2), and more often are represented by metaluminous and agpaitic (K_{agp} = 0.74–1.11, ASI > 1) varieties with a high Fe mole fraction (f = 0.82–0.99). In the (Na_2O + K_2O–CaO)–SiO2 diagram, the data points of the volcanic rocks are plotted in the fields of calc-alkalic and alkali-calcic series and, rarely, in the calcic and alkalic series (Fig. 3). According to the criterion of Myashiro [55], the ignimbrites of the Bogopolsky Complex are ascribed to the tholeiitic series (Fig. 4a) and correspond to the ferroan series according to the Frost clas-

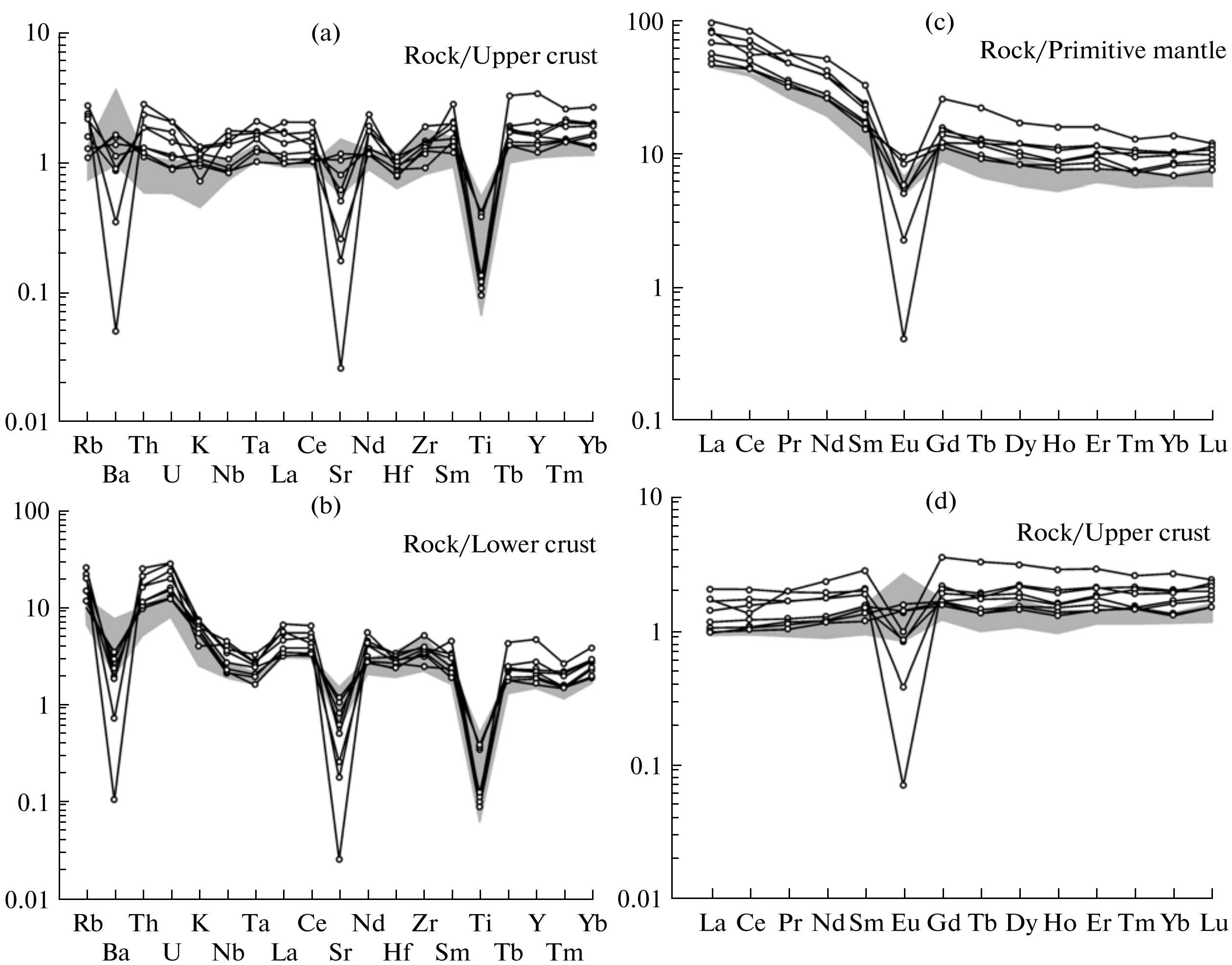

Fig. 7. Trace element patterns normalized to the average composition of the upper (a, d) and lower (b) continental crust and primitive mantle (c) [57] for the volcanic rocks of the Primorsky Complex (shaded field) and the Bogopolsky Complex (symbols).

Table 1. Chemical composition (wt %) of representative volcanic rocks of the Primorsky Complex

	P-241/1	P-241/4	P-241/5	P-29/1	P-318/5	P-321/3	P-326/14	P-326/11	P-326/8	P-326/2	P-324/4	P-324/5	P-325/3	P-302/1	Mikh-4	Mikh-5	Mikh-7
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*
SiO_2	69.30	75.00	73.80	76.16	78.30	77.70	70.83	72.29	73.20	72.90	71.96	68.66	68.55	75.89	73.20	70.65	68.43
TiO_2	0.41	0.05	0.12	0.25	0.23	0.44	0.22	0.49	0.25	0.27	0.25	0.34	0.65	0.18	0.23	0.25	0.66
Al_2O_3	17.61	14.07	14.60	12.93	12.03	11.10	14.87	14.35	14.03	14.18	14.25	15.85	14.83	12.35	13.65	14.15	15.54
Fe_2O_3	0.96	0.77	1.02	1.21	0.43	0.54	1.43	1.15	1.45	1.47	1.77	1.66	4.28	1.09	1.34	1.47	1.81
FeO	1.20	0.86	0.90	1.27	0.65	0.71	0.54	0.55	0.68	0.61	0.12	0.31	0.64	1.13	1.79	2.36	1.38
MnO	0.06	0.05	0.07	0.06	0.02	0.02	0.04	0.07	0.07	0.07	0.03	0.05	0.15	0.08	0.08	0.08	0.06
MgO	0.40	0.30	0.60	0.81	0.21	1.02	0.50	0.93	0.75	0.70	0.97	0.53	1.00	0.73	0.35	0.51	0.41
CaO	3.21	1.26	1.77	0.28	1.38	0.34	1.81	1.86	1.33	1.97	0.60	1.04	2.25	0.87	1.32	1.70	1.36
Na_2O	3.40	2.60	3.06	2.03	2.54	1.42	4.22	3.50	3.75	4.00	3.92	2.49	3.70	2.46	3.00	3.34	3.80
K_2O	1.52	2.97	2.98	2.87	2.86	5.07	3.02	2.80	2.75	2.75	3.57	7.24	2.25	3.81	4.14	3.76	4.52
P_2O_5	0.24	0.05	0.10	0.13	0.08	0.00	0.08	0.08	0.08	0.08	0.04	0.05	0.20	0.05	0.02	0.06	0.04
H_2O^-	0.26	0.40	0.17	0.12	0.30	0.17	0.21	–	0.79	0.75	0.76	0.50	0.89	0.53	–	–	–
L.O.I.	0.74	1.40	0.43	1.66	0.63	1.10	1.83	1.87	0.65	0.40	1.37	1.01	1.00	0.46	1.14	1.24	1.66
Total	99.31	99.78	99.62	99.78	99.66	99.63	99.60	99.94	99.78	100.15	99.61	99.73	100.39	99.63	100.26	99.57	99.67
ASI	1.35	1.44	1.27	1.86	1.23	1.32	1.10	1.18	1.21	1.08	1.25	1.15	1.18	1.27	1.16	1.12	1.14
K_{Agp}	0.41	0.53	0.57	0.50	0.60	0.70	0.69	0.61	0.65	0.67	0.72	0.75	0.57	0.66	0.69	0.68	0.72
f'	0.84	0.84	0.75	0.74	0.83	0.54	0.79	0.63	0.73	0.73	0.64	0.77	0.82	0.74	0.90	0.88	0.88
Na_2O/K_2O	2.24	0.88	1.03	0.71	0.89	0.28	1.40	1.25	1.36	1.45	1.10	0.34	1.64	0.65	0.72	0.89	0.84

Table 1. (Contd.). Chemical composition (wt %) of representative samples of the volcanic rocks of the Siyanovsky, Kamensky, and Levosobolevsky complexes

	AV-26/1	AV-15/2	M-11	M-22	Mikh-19	Mikh-20	Mikh-21	Mikh-22	Mikh-23	Mikh-24	Mikh-25	Mikh-26	Ls-1	Ls-2	Ls-3	Ls-4	Ls-5
	18	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*34*
SiO_2	71.67	69.64	69.25	67.42	66.66	67.01	68.19	72.13	67.65	69.75	73.36	69.92	73.19	70.36	69.71	65.16	70.79
TiO_2	0.25	0.22	0.50	0.36	0.61	0.50	0.43	0.31	0.45	0.40	0.32	0.37	0.39	0.29	0.39	0.62	0.31
Al_2O_3	13.88	12.74	15.73	15.03	15.60	15.20	15.10	13.73	16.45	14.20	13.40	13.87	12.48	14.71	15.79	15.67	14.95
Fe_2O_3	2.55	1.23	1.76	2.01	4.99	2.10	2.03	0.91	1.52	1.96	2.27	1.16	1.19	1.54	1.70	2.01	1.23
FeO	0.77	1.22	1.78	1.52	2.37	1.33	1.44	1.62	2.65	2.10	1.32	2.33	1.13	1.28	1.13	2.01	1.32
MnO	0.06	0.03	0.10	0.09	0.17	0.13	0.11	0.09	0.10	0.04	0.07	0.07	0.08	0.07	0.11	0.09	0.08
MgO	0.89	0.23	0.64	0.81	1.00	1.61	0.77	0.52	1.10	1.33	0.50	0.92	0.67	0.87	0.71	1.81	0.74
CaO	0.79	2.20	1.16	2.30	1.54	1.79	2.04	1.13	2.94	1.75	0.36	1.72	0.90	1.95	1.21	2.99	1.42
Na_2O	4.36	3.38	3.27	3.75	3.11	3.92	3.87	3.41	3.82	3.92	3.30	3.31	3.62	3.49	4.27	3.85	3.85
K_2O	4.18	3.40	4.07	3.26	3.37	3.25	3.26	4.39	2.71	3.37	3.84	3.87	3.98	4.16	3.30	2.99	3.51
P_2O_5	0.07	0.10	0.09	0.15	0.47	0.15	0.12	0.07	0.09	0.06	0.02	0.86	0.05	0.13	0.10	0.18	0.09
H_2O^-	0.50	1.09	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
L.O.I.	0.21	4.32	1.36	2.98	1.08	2.45	2.42	1.56	1.30	0.94	1.36	2.65	–	–	–	–	–
Total	100.18	99.80	99.71	99.68	100.97	99.44	99.78	99.87	100.78	99.82	100.12	101.05	97.68	98.85	98.42	97.38	98.29
ASI	1.06	0.96	1.32	1.08	1.35	1.15	1.11	1.11	1.13	1.07	1.31	1.09	1.05	1.07	1.23	1.04	1.18
K_{Agp}	0.84	0.73	0.62	0.64	0.56	0.66	0.66	0.75	0.56	0.71	0.72	0.69	0.82	0.70	0.67	0.61	0.68
f'	0.77	0.91	0.84	0.80	0.87	0.67	0.81	0.82	0.79	0.74	0.87	0.79	0.77	0.75	0.79	0.68	0.77
Na_2O/K_2O	1.04	0.99	0.80	1.15	0.92	1.21	1.19	0.78	1.41	1,16	0.86	0.86	0.91	0.84	1.29	1.29	1.10

Table 1. (Contd.). Chemical composition (wt %) of the representative volcanic rocks of the Bogopolsky Complex

	AV-60	AV-23/2	AV-60/1	AV-23/3	AV-23/7	AV-23/10	AV-23/4	AV-25/1	AV-24	AV-24/1	AV-24/5	P-234	P-234/1	P-404/3	P-406/2	P-406/6	P-406/8
	35	*36*	*37*	*38*	*39*	*40*	*41*	*42*	*43*	*44*	*45*	*46*	*47*	*48*	*49*	*50*	*51*
SiO_2	71.76	72.47	74.35	72.47	71.56	72.55	75.83	76.80	71.45	72.55	77.68	72.48	76.63	72.31	73.23	73.13	70.40
TiO_2	0.26	0.08	0.10	0.28	0.18	0.19	0.12	0.05	0.07	0.10	0.09	0.27	0.28	0.10	0.12	0.11	0.17
Al_2O_3	13.72	12.41	12.26	13.87	13.64	14.13	12.63	11.53	12.55	12.24	12.60	14.38	12.29	11.94	12.07	11.98	12.05
Fe_2O_3	0.43	–	0.23	0.29	0.10	1.31	0.54	0.44	0.10	1.01	–	1.00	1.21	0.91	1.16	0.95	1.32
FeO	2.18	1.24	1.17	1.91	1.42	0.64	0.95	0.26	0.48	0.15	0.45	0.62	0.73	0.50	0.10	0.54	0.08
MnO	0.06	0.03	0.02	0.05	0.04	0.02	0.03	0.02	0.02	0.01	0.00	0.06	0.03	0.03	0.02	0.03	0.03
MgO	0.24	0.06	0.03	0.23	0.18	0.21	0.15	0.14	0.05	0.04	0.05	0.27	0.00	0.10	0.14	0.12	0.10
CaO	1.49	0.42	0.57	1.21	0.97	0.84	0.59	0.30	0.66	0.74	0.16	0.88	1.00	0.65	1.19	0.54	0.87
Na_2O	3.94	4.38	4.61	3.47	3.82	3.34	3.30	4.84	4.44	4.05	2.97	4.19	2.66	4.49	3.61	4.07	3.95
K_2O	4.37	3.96	3.60	4.37	3.97	4.53	5.19	4.43	2.33	2.18	4.85	4.42	4.40	2.40	3.37	3.26	2.80
P_2O_5	0.06	0.00	0.00	0.07	0.03	0.02	0.01	0.05	0.00	0.00	0.00	0.06	0.06	0.03	0.05	0.05	0.05
H_2O^-	N.d.	0.33	N.d.	0.30	0.40	0.30	0.00	0.17	1.51	1.83	0.10	0.11	0.11	1.02	0.31	0.57	2.70
L.O.I.	N.d.	4.29	N.d.	2.21	3.29	1.64	0.70	0.48	5.97	4.89	0.72	1.12	0.87	5.50	4.78	4.76	5.94
Total	98.51	99.67	96.94	100.73	99.60	99.72	100.04	99.51	99.63	99.79	99.67	99.86	100.27	99.98	100.15	100.11	100.46
ASI	0.99	1.01	0.98	1.10	1.11	1.19	1.04	0.87	1.14	1.18	1.21	1.08	1.12	1.07	1.03	1.07	1.08
K_{Agp}	0.82	0.93	0.94	0.75	0.78	0.74	0.87	1.11	0.78	0.74	0.80	0.81	0.74	0.84	0.79	0.85	0.79
f'	0.91	0.95	0.98	0.90	0.89	0.90	0.91	0.82	0.92	0.96	0.90	0.85	1.00	0.93	0.89	0.92	0.93
Na_2O/K_2O	0.90	1.11	1.28	0.79	0.96	0.74	0.64	1.09	1.91	1.86	0.61	0.95	0.60	1.87	1.07	1.25	1.41

(*1–17*) Primorsky Complex. (*1–3*) rhyolitic tuff, Terneisky–Kema volcanic field, section on the left bank of the Kema River; (*4*) rhyolitic tuff, Zevsk–Sobolevskoe volcanic field. Pan'kova–Sobolevka rivers watershed: (*5–6*) rhyolitic tuff, Uglovskaya VD; (*7–9*) rhyodacitic and rhyolitic ignimbrites, Shirokopadnenskaya VD, coastal sections south of the Zerkal'naya River's mouth; (*10*) rhyolitic tuff, the same area; (*11*) rhyolitic tuff, Zerkal'naya River's mouth; (*12*) rhyodacitic dike, the same area; (*13*) extrusive rhyodacite, Shirokopadnenskaya VD. Coastal sections south of the Zerkal'naya River's mouth: (*14*) rhyodacitic ignimbrite, Zerkal'naya River's mouth; (*15*) average composition (10 samples) of rhyolitic tuffs and ignimbrites, Sheptunovskaya VD, after [24]; (*16*) average composition (22 samples) of the rhyolitic tuffs and ignimbrites, Kisinskaya VD, after [24]; (*17*) average composition (4 samples) of dacitic tuffs (?), Edinkinskaya VD, after [24]. (*18–25*) Siyanovsky Complex. (*18–19*) rhyodacitic tuffs, Yaktinskaya VD; (*20*) average composition (2 samples) of rhyolitic tuffs, Mt. Brusnichnaya, after [24]; (*21*) average composition (7 samples) of rhyolitic tuffs and ignimbrites, Kyumskaya VD, after [24]; (*22–25*) average composition (7 samples) of dacitic and rhyodacitic tuffs and ignimbrites, Bazovskaya VD after [24]. (*26–29*) Kamensky Complex. (*26*) average composition (4 samples) of rhyodacitic ignimbrites, Ozerkovskaya VD after [24]; (*27–28*) average compositions of rhyodacites (12 samples) and their tuffs (5 samples), Brinerovskaya VD, after [24]; (*29*) average composition (11 samples) of rhyodacitic tuffs, Dal'negorskaya VD after [24]; (*30–34*) Levosobolevsky Complex. Caldera volcanic structure of the Zevsk–Sobolevsky volcanic field—rhyolitic tuffs: (*31*) rhyodacitic lavas; (*32*) rhyodacitic ignimbrites; (*33*) dacitic tuffs; (*34*) extrusive rhyodacites. Data of G.L. Amel'chenko (1978). (*35–51*) Bogopolsky Complex. (*35–41*) ignimbrite, Yakutinskaya VD; (*42*) rhyolitic porphyry, dike, Yakutinskaya VD; (*43–44*) perlite, Mt. Nezhdanka; (*45*) spherulite rhyolite, Mt. Nezhdanka; (*46–47*) rhyolitic tuffs and ignimbrites, the left bank of the Belembe (Taezhnaya) River; (*48*) perlite, Bogopolskoe deposit; (*49*) perlite, Pryamaya creek valley; (*50–51*) perlite, Bogopolskaya Tropa creek valley. A dash denotes not detected. The analyses were performed using the conventional techniques at the Far East Geological Institute of the Far East Branch of the Russian Academy of Science. ASI = Al/(Ca–1.67 × P + Na + K), mol. %; $K_{agp.}$ = $(Na_2O + K_2O)/(Al_2O_3)$, mol %; f' = Fe_{tot}/Fe_{tot} + MgO, wt %; Na_2O/K_2O, wt %.

Table 2. Trace element composition (ppm) of the volcanic rocks of the Primorsky and Bogopolsky complexes

	P-241/1	P-241/4	P-241-4/2	P-241/5	AB-3/2	AB-3/3	AB-3/5	AB-3/6	AB-3/8	AB-3/13	AB-3/15	AB-23/3	AB-24/3	AB-5/2	AB-23/6b	AB-59
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
Cr	6.34	5.64	9.86	13.55	5.09	9.46	6.31	7.69	5.20	5.87	9.49	3.59	5.57	5.02	3.35	10.17
Co	3.04	2.15	2.42	4.50	1.45	6.62	1.44	1.96	3.70	1.15	4.40	1.92	0.95	4.44	0.03	1.80
Zn	14.41	23.10	24.79	44.86	21.20	66.89	93.84	52.14	44.79	20.42	33.45	36.49	23.69	30.38	60.27	60.38
Ga	27.44	18.93	17.30	18.67	15.49	18.28	30.29	18.58	20.37	13.40	17.59	21.00	20.33	17.97	22.94	22.47
Rb	81	151	143	124	203	120	240	62	166	178	121	179	253	142	268	309
Sr	530	200	195	292	127	278	89	90	154	132	364	172	61	409	9	211
Y	27.83	24.33	24.95	23.80	25.13	25.84	36.82	20.09	17.85	19.90	31.22	34.89	34.55	29.58	44.92	75.76
Zr	346	154	176	181	108	276	171	217	187	148	244	361	258	233	266	219
Nb	14.92	11.33	10.24	10.81	21.17	11.54	14.78	12.99	8.83	9.22	12.70	19.16	20.03	11.91	24.60	22.60
Sn	0.95	2.32	1.77	2.20	3.88	1.95	3.84	3.73	1.21	4.31	2.31	2.60	3.66	1.83	4.59	4.64
Cs	12.78	10.66	9.48	5.57	4.52	3.94	16.81	3.82	14.57	4.38	2.09	7.61	7.80	34.63	9.50	178.68
Ba	527.13	1035.37	1038.59	2018.06	186.02	917.95	616.68	282.75	1173.07	1075.25	890.97	472.00	187.89	763.37	27.14	492.83
La	28.86	28.22	28.28	27.55	19.04	34.67	28.61	29.80	15.56	16.83	31.42	61.42	49.71	29.30	42.14	51.14
Ce	62.65	60.56	61.37	59.49	45.11	76.78	66.73	64.88	41.76	37.12	67.93	130.78	109.78	63.73	98.88	85.68
Pr	7.87	6.48	6.75	6.42	5.24	8.68	7.84	7.03	4.84	4.30	8.29	13.84	11.80	7.25	11.69	14.04
Nd	32.42	25.25	24.74	22.73	18.49	33.17	30.87	26.46	19.99	17.63	30.44	49.98	45.20	29.72	45.72	61.16
Sm	6.98	4.56	4.31	4.21	4.80	6.83	6.56	4.24	3.92	3.90	5.97	8.94	8.40	5.27	9.30	12.79
Eu	2.35	0.81	0.73	0.99	0.29	1.23	0.75	0.18	0.95	0.79	1.39	0.73	0.33	1.24	0.06	0.85
Gd	6.59	4.56	4.98	4.81	3.90	5.84	6.30	3.86	3.73	3.91	6.26	8.25	7.21	6.16	7.76	13.52
Tb	0.88	0.76	0.72	0.63	0.73	0.86	1.13	0.55	0.61	0.66	0.92	1.10	1.17	0.86	1.22	2.11
Dy	5.96	4.29	4.18	3.71	4.86	5.32	7.54	3.66	3.65	3.60	5.30	6.11	6.63	5.04	7.67	11.03
Ho	1.14	0.92	0.88	0.76	1.09	1.19	1.53	0.86	0.81	0.78	1.09	1.25	1.27	1.03	1.61	2.30
Er	3.20	2.58	3.07	2.80	3.35	3.61	4.80	2.73	2.42	2.13	3.25	4.06	4.19	3.27	4.87	6.70
Tm	0.47	0.49	0.46	0.37	0.53	0.47	0.70	0.40	0.31	0.31	0.49	0.49	0.67	0.48	0.62	0.85

Table 2. (Contd.)

	P-241/1	P-241/4	P-241-4/2	P-241/5	AB-3/2	AB-3/3	AB-3/5	AB-3/6	AB-3/8	AB-3/13	AB-3/15	AB-23/3	AB-24/3	AB-5/2	AB-23/6b	AB-59
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
Hf	6.77	3.64	4.17	4.35	3.80	5.93	5.11	5.07	4.02	3.01	4.47	6.38	5.27	4.58	6.42	5.52
Yb	2.60	2.87	2.98	2.50	3.59	3.51	4.40	2.76	2.10	1.78	2.92	3.66	4.34	2.84	4.21	5.91
Lu	0.49	0.42	0.51	0.37	0.54	0.54	0.69	0.46	0.36	0.30	0.48	0.58	0.63	0.48	0.73	0.77
Ta	1.02	1.29	0.98	1.09	2.49	1.16	1.46	1.29	0.72	1.90	1.23	1.53	2.00	0.96	1.66	1.62
Pb	13.37	18.49	20.61	20.22	24.13	17.12	29.91	12.88	12.37	11.85	16.64	25.31	30.13	18.09	37.13	31.66
Th	6.19	11.73	12.09	10.48	25.57	11.85	13.94	12.58	5.79	14.56	12.71	20.00	30.56	13.92	25.53	20.21
U	1.61	2.74	2.86	2.43	6.22	2.48	3.03	2.70	2.60	2.89	2.52	4.01	5.79	3.20	5.73	4.81
$(La/Sm)_N$	2.27	3.39	3.60	3.59	2.18	2.78	2.39	3.85	2.18	2.37	2.89	3.77	3.25	3.05	2.48	2.19
La/Nb	1.93	2.49	2.76	2.55	0.90	3.00	1.94	2.29	1.76	1.83	2.47	3.21	2.48	2.46	1.71	2.26
Ba/Nb	35.33	91.38	101.42	186.68	8.79	79.55	41.72	21.77	132.85	116.62	70.16	24.63	9.38	64.09	1.10	21.81
Eu/Eu	1.05	0.54	0.48	0.67	0.20	0.58	0.35	0.13	0.75	0.61	0.69	0.26	0.13	0.67	0.02	0.20
$(La/Yb)_N$	6.73	5.96	5.75	6.68	3.21	5.99	3.94	6.54	4.49	5.73	6.52	10.17	6.94	6.25	6.07	5.24
Yb/Ta	2.55	2.24	3.04	2.29	1.44	3.02	3.01	2.14	2.91	0.93	2.37	2.39	2.17	2.96	2.53	3.65
Y/Nb	1.87	2.15	2.44	2.20	1.19	2.24	2.49	1.55	2.02	2.16	2.46	1.82	1.72	2.48	1.83	3.35

(*1–4*) Primorsky volcanic complex, rhyolitic tuff, Terneisky–Kema volcanic field, section on the left bank of the Kema River; (*5–16*) Bogopolsky volcanic complex; (*5–11*) rhyolitic tuff, Martelevskaya VD; (*12*) ignimbrites, Yakutinskaya VD; (*13*) extrusive rhyolite, Mt. Nezhdanka; (*14*) ignimbrite, Martelevskaya VD; (*15*) fiamme from ignimbrite, Yakutinskaya VD; (*16*) extrusive perlite, Mt. Nezhdanka (Yakutinskaya VD); the ICP-MS element composition of the rocks was determined using an Agilent 7500 at the Institute of Geochemistry of the Siberian Branch of the Russian Academy of Sciences (Irkutsk), analysts G.P. Sandimirova and E.V. Smirnova.

sification [45] (Fig. 4b). According to the modified diagram of Maeda, the ignimbrites of the early stage eruptions of the Bogopolsky Complex are ascribed to S-type, while the rocks of the final volcanic stages belong to A-type granitoids (Fig. 5). In the diagram of Velikoslavinskii (Fig. 6), the "early" ignimbrites of the Bogopolsky Complex are plotted in the field of orogenic (collisional) rocks, while the ignimbrites of final stages fall in the field of within-plate granitoids. In the discriminant geochemical diagrams of J.A. Pearce and N.B.W. Harris, the data points of the volcanic rocks of the Bogopolsky Complex occupy an intermediate position between the fields of island-arc and within-plate granitoids.

The ignimbrites of the Bogopolsky Complex are enriched in Cs, Rb, Ba, Sr, Zr, and REE relative to the Late Cretaceous volcanic rocks (Tables 2, 3). The rocks are characterized by the fractionated trace and rare-earth element distribution relative to the upper crust (Fig. 7). The La_N/Yb_N ratios vary from 3.2 to 10.2, while the Eu/Eu*, from 0.1 to 0.7. The upper crust-normalized multilement diagrams show well expressed negative Ba, Nb–Ta, Sr, and Ti anomalies. It should be noted that the ignimbrites of the initial volcanic stages lack an Eu minimum, while the rocks of the final stage reveal a sharply expressed negative anomaly (Fig. 7).

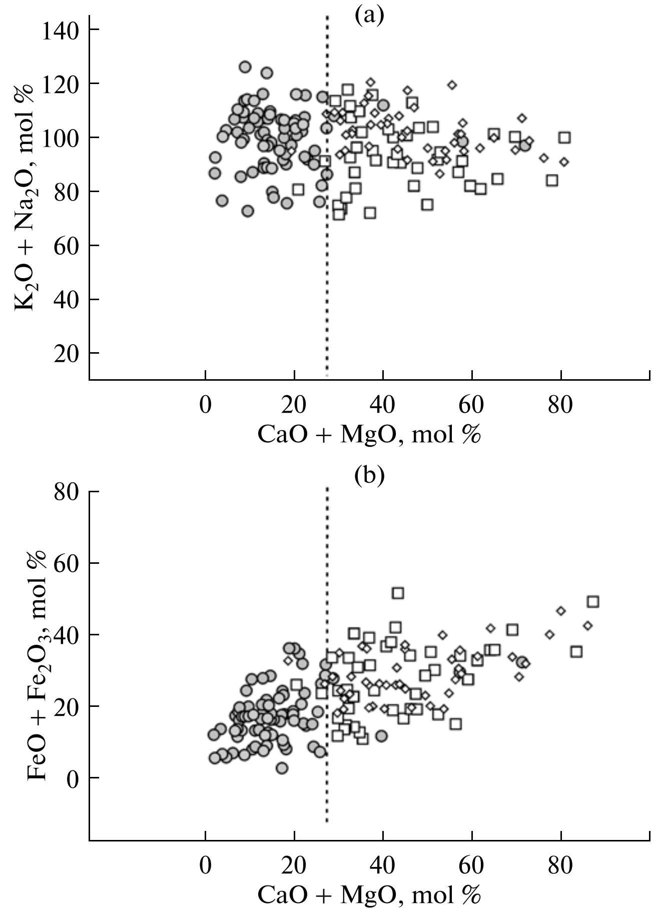

Fig. 8. (a) ($Na_2O + K_2O$)–(CaO + MgO) (mol %) diagram; (b) ($FeO + Fe_2O_3$)–(CaO + MgO) (mol %) diagram.

The dashed line is conditionally drawn. The symbols are shown in Fig. 2.

DISCUSSION

The comparative analysis of the chemical compositions of the Late Cretaceous and Paleogene ignimbrites revealed a set of distinctive features of these complexes. The plateau ignimbrites of the Primorsky Complex and caldera ignimbrites of the Levosobolevsky and Siyanovsky complexes are characterized by elevated contents of Mg, Mn, Ti, total Fe, and Ca, whereas the tuffs and hyaloignimbrites of the Bogopolsky Complex have higher contents of alkalis and silica (Table 1, Fig. 2). Both types of ignimbrites have a corundum-normative composition. According to the classificaion [58] based on the modified aluminum saturation index (ASI) and representing the Al/(Ca–1.67 × P+Na+K) molecular ratio, the Late Cretaceous ignimbrites are ascribed to peraluminous rocks and the Early Paleogene rocks belong to metaluminous and, more rarely, to peraluminous rocks. The most distinctive difference in the chemical composition between the Late Cretaceous and Early Paleogene acid volcanic rocks are illustrated by the author's binary diagrams: ($K_2O + Na_2O$)–(MgO + CaO) and (Fe_2O_3 + FeO)–(CaO + MgO) expressed in molecular percents (Fig. 8). The ignimbrites of the Primorsky, Siyanovsky and Levosobolevsky complexes show a positive correlation between the concentrations of thermophile cations, their relative crystal saturation, and the degree of fluid saturation of the magmas. For the ignimbrites of the Bogopolsky Complex, this correlation is negative. Note that such a tendency in the distribution of the alkaline and thermophile elements is also typical of similar types of ignimbrites from the Okhotsk–Chukotka volcanic belt and the Badzhal volcanic zone, which contain voluminous crystal ignimbrites of the Dyustachan and Badzhal volcanic complexes and intracaldera ignimbrites of the Belouvalinsky and Nitkansky complexes, respectively [19]. The distribution of large ion lithophile elements in these rocks also shows opposite trends. In particular, the Paleogene hyaloignimbrites have elevated contents of alkali metals (K, Na, Rb), whereas the Upper Cetaceous crystal ignimbrites are enriched in alkali earth elements (Ca, Sr,B, and Mg).

It is known that the excess alumina during feldspar crystallization is incorporated into other Al-bearing phases, in particular, in biotite, while the Ca prevalence over Al in the metaluminous rocks leads to its incorporation in hornblende and Ca pyroxene. In addition, the presence of ortho-, clinopyroxene, and fayalite is determined by the composition of the fluid phase during the melt crystallization [45]. Since

Table 3. Trace element composition (ppm) of the volcanic glasses of the Bogopolsky Complex after [11]

	AV-23/2	AV-23/6a	AV-24	AV-24/2	P-404/2	P-404/3	P-404/4	P-405/3	P-406	P-406/1	P-406/2	P-406/5	P-406/6	P-406/8A	P-406/9	P-406/11
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
Fe	7718	8488	5528	8243	8667	8346	8920	8317	7194	8048	7499	8139	6733	6775	7934	10329
Mn	199	171	115	172	688	438	588	359	592	705	393	517	437	774	654	362
K	32139	29363	16526	35609	20288	22114	21724	25432	26364	26148	35280	32600	30566	25817	31196	23465
Na	29287	32231	33585	26649	32209	31174	30167	31255	28987	28293	28529	8077	28199	29007	25756	33290
Co	0.03	0.02	0.07	0.07	0.10	0.06	0.08	0.14	0.11	0.12	0.47	0.12	0.08	0.11	0.14	0.51
Zn	61.06	78.07	63.34	80.88	70.46	77.71	84.18	73.12	60.64	73.17	30.13	66.39	86.53	58.71	57.46	70.03
Rb	229	228	223	216	144	311	302	235	176	162	91	133	252	300	118	201
Sr	0	0	44	0	49	42	0	85	129	147	196	396	38	104	170	95
Zr	188	181	186	182	196	176	220	196	197	201	102	194	165	177	182	200
Cs	13.65	11.11	98.05	20.04	7.39	205.51	168.55	28.11	9.51	11.46	5.02	12.57	11.20	30.10	4.74	9.27
Ba	0.00	25.70	391.00	86.40	897.40	914.20	921.40	704.00	822.10	806.90	842.70	817.10	814.20	763.20	827.10	930.80
La	38.18	28.83	30.79	21.89	41.56	43.29	42.90	44.15	41.85	40.00	30.88	28.17	44.00	42.16	39.57	31.94
Ce	85.20	71.35	70.17	58.32	84.71	91.40	88.05	88.73	83.27	82.02	58.20	63.41	87.80	87.73	81.22	66.56
Nd	39.82	37.17	33.80	28.94	37.77	37.72	36.51	38.98	37.38	36.41	18.89	28.14	41.66	38.90	35.82	28.26
Sm	8.17	8.57	7.94	8.24	7.43	7.71	7.43	7.65	7.53	7.19	3.43	5.72	8.28	7.61	7.00	6.35
Eu	0.04	0.04	0.52	0.08	1.25	1.28	1.20	1.43	1.55	1.66	0.60	1.22	1.24	1.35	1.22	1.34
Tb	1.11	1.24	1.21	1.30	1.07	1.07	1.04	1.12	1.06	1.01	0.39	0.81	1.19	1.09	0.97	0.93
Dy	7.10	7.36	8.77	8.60	6.70	6.97	5.83	7.59	7.13	6.60	2.09	4.75	7.81	7.78	7.39	5.66
Yb	4.04	4.47	4.17	4.58	3.50	3.73	3.81	3.91	3.82	3.64	1.57	3.19	4.42	3.88	3.65	3.37
Lu	0.62	0.64	0.60	0.68	0.51	0.50	0.52	0.55	0.56	0.53	0.27	0.47	0.59	0.54	0.52	0.50
Sb	0.53	0.56	1.70	0.56	0.42	0.39	0.40	0.42	0.36	0.35	0.17	0.33	0.49	0.42	0.38	0.56
Sc	0.97	0.82	2.18	1.02	6.64	6.62	6.79	5.16	5.50	5.53	2.78	4.82	6.68	4.86	4.83	6.65
Hf	6.47	6.51	5.72	6.72	6.02	5.78	6.54	5.82	5.33	5.71	3.02	5.48	5.36	5.52	5.43	6.03
Ta	1.30	1.32	1.15	1.43	0.98	0.96	1.01	1.00	0.92	0.94	0.75	0.94	1.05	0.99	0.97	0.90
Th	19.11	19.93	15.21	20.26	10.27	9.95	10.17	10.16	9.53	9.50	12.21	9.72	10.80	10.23	9.89	9.76
U	4.61	4.96	3.50	5.03	1.82	3.21	1.58	1.73	1.91	1.99	2.99	1.85	2.18	1.73	1.98	1.81
Cl	792	853	252	923	466	484	431	256	222	289	436	0	526	144	349	435

Rhyolitic perlites from occurrences: (*1–2*) Mt. Yakut-gora (Yakutinskaya VD); (*3–4*) Mt. Nezhdanka (Yakutinskaya VD); (*5–7*) Bogopolsky perlite deposit; (*8–11*) Pryamaya creek valley (Brusilovskaya VD); (*12–15*) Bogopol'skaya Tropa creek valley (Brusilovskaya VD); (*16*) Shmeigedir creek valley (Brusilovskaya VD). The analyses were performed by instrumental neutron-activation at the Department of Geology and Geophysics of the University of California at Berkley, USA (analyst M. Glaskok).

biotite is stable relative to pyroxenes and olivine in Mg-rich melts, the complex of anhydrous silicates is preferentially crystallized in Fe-rich magmas. These factors presumably control the mineral composition of the Late Cretaceous (Bi + Pl + Q + Hb + Mgt) and Paleogene (Snd + Q + Cpx + Opx + Hb + Bi + Ilm + Fa) ignimbrite complexes of Primorye.

In the lower crust-normalized multicomponent diagrams, the Late Cretaceous plateau ignimbrites and Paleocene–Eocene caldera ignimbrites have similar trace-element distributions (Fig. 7). However, the Paleocene hyaloignimbrites of the Yakutinskaya VD show clear negative Sr, Ba, and Eu anomalies. Their minimal values could be caused by the mobility and removal of these elements from the melt by the transmagmatic fluid flow [13]. In general, the Late Cretaceous and Paleogene ignimbrites correspond, respectively, to the "eutectoid and cotectoid" types of the volcanic rocks of continental-margin volcanic belts considered in debatable papers [20, 25].

The distribution of high-field strength and rare-earth elements in the rocks of the Late Cretaceous and Early Paleogene complexes is controlled by the different compositions of the accessory minerals. In particular, the elevated content of heavy REE in the ignimbrites of the Bogopolsky Complex is explained by the high content of allanite and monazite in them. The predominance of zircon and apatite in the Late Cretaceous volcanic rocks was responsible for the higher LREE contents.

To decipher the geodynamic settings of the East Sikhote Alin ignimbrite volcanism, we applied the generally accepted geochemical classifications of J.A. Pearce and N.B.W. Harris, as well as a modified diagram of Velikoslavinskii [8]. In these diagrams, the data points of the Late Cetaceous volcanic rocks fall in the field of collisional and volcanic-arc granites corresponding to the modern island arc (subduction) geodynamic settings. The data points of the Bogopolsky volcanic rocks occupy an intermediate position between the fields of the island-arc and within-plate granitoids, while the compositions of the ignimbrites of the Yakutinskaya VD mostly correspond to the latter (Fig. 6).

According to the modified diagram of Frost et al. [45], the Late Cretaceous ignimbrites of the Primorsky Complex (the Levosobolevsky and Siyanovsky complexes) are ascribed to S-type granites (syncollisional granitoids after Pearce, or continental collisional granitoids after Maniar and Piccoli [54]). Their typical representatives are the peraluminous leucogranites of the Himalayas, South Dakota (USA), and northern Portugal, which were formed by the partial melting of metasedimentary rocks [45]. This can be indirectly supported by the Al_2O_3/(MgO + FeO)—CaO/(MgO + FeO) diagrams [47], in which the data points of the Late Cretaceous ignimbrites correspond to magmas derived by partial melting of metagraywackes, while the Paleocene–Eocene ignimbrites were generated by the melting of metapelites. At the same time, the plateau ignimbrites of the Primorsky Complex, in terms of some geochemical features, cannot be classified as affiliating to a single petrogenetic type. They have features typical of suprasubduction granitoids of Cordilleras, some part of which is classed as I-type granites formed from magmatic (or metamagmatic) rocks.

The data points of the hyaloignimbites of the Bogopolsky Complex are plotted in the overlapping field of S- and A-type granites (Fig. 4b) and form an evolutionary trend from S-type (for the volcanic rocks of the initial stage) to A-type (final stage of the ignimbrite eruptions) in the A/(C + N + K)–(N + K) diagram [53] (Fig. 5). The compositions of the biotites from the volcanic rocks of the Bogopolsky Complex also indicate the affiliation of these rocks to A-type granitic magmas [16]. The origin of A-type magmatic rocks, according to [46], could be related to the partial melting of quartz–feldspathic crustal rocks; the differentiation of basaltic magma; or a combination of the two first models, in which the differentiation of basaltic melts is accompanied by their assimilation with felsic crustal material. The Paleocene–Eocene ignimbrites of the Yakutinskaya VD are similar in composition to the fayalite ignimbrites of the rhyolites of the Yellowstone caldera (USA) [52] and the Red Mountains caldera (the Altenberg–Teplice Caldera, Central Europe) [44], which were generated by heating and partial melting of the lower crust under the effect of voluminous mantle upwelling [44, 52]. The geochemical features of the volcanic rocks of the Bogopolsky Complex also indicate their derivation from a mixed magmatic source. The appearance of magmas with such geochemical features could be caused by the setting of a transform margin on local extension zones, where asthenospheric windows are formed due to slab break off [12]. The formation of ferroan A-type melts was related to the interaction of mantle-derived melts with subducted sediments and the oceanic lithosphere. The mantle diapir during its ascent and development generated highly fluidized magmatic melts variably contaminated by crustal material. The mixing of different proportions of melts derived from different sources in the intermediate and subsurface chambers was responsible for the combination of within-plate and island arc geochemical signatures in the transform-margin volcanic rocks. This is confirmed by the initial $^{87}Sr/^{86}Sr$ ratios varying from 0.70659 to 0.70810 in the hyaloignimbrites of the Yakutinskaya volcanic structure [50]. The summary table (Table 4) lists the main distinctive petrographic and geochemical features of the Late Cretaceous and Paleogene complexes of East Sikhote-Alin (Primorye).

Note in conclusion that a certain type of granites cannot be directly correlated with a certain tectonic setting, since the geochemical compositions of the granitic magmas primarily depend on the composition of their sources. At the same time, the geodynamic regime defines the specifics of the formation of the

Table 4. Main distinctive features of the Late Cretaceous and Paleogene ignimbrites from Eastern Sikhote Alin

	Primorsky Complex	Levosobolevsky and Siyanovsky complexes	Bogopolsky Complex
Distribution, type of eruptions and volcanic edifices	Plateau-ignimbrite fields compose the main linear structure of the ESAVB; the formation was related to the fissure eruptions; "rootless" volcanic massifs	Compose volcanic edifices both among ignimbrite fields of ESAVB and beyond its limits; polygenic (festoon) calderas, graben-like depressions, central-type chamber structures	Developed mainly beyond the ESAVB; central (Katmai) eruption type; collapsed caldera and individual depression-type volcanic structures in extension zones (pull-apart basins)
Age	Turonian–Campanian	Maastrichtian–Paleocene	Paleocene–Early Eocene
Predominant rocks	Predominance of gray-green massive crystal tuffs and crystal ignimbrites	Predominance of lithic-crystal tuffs, welded tuffs and ignimbrites; sharp facies variability	Predominance of welded lithic crystal tuffs, hyaloignimbrites, horizons of ash tuffs, and volcanic glass
Petrographic composition	Psammitic crystal clastic and fluidal textures. Phenocrysts 40–60%. Bypiramidal quartz, oligoclase, K-feldspar, and rare biotite and hornblende. The latters are chloritized and epidotized. The accessories are dominated by magnetite	Psephitic crystal clastic and spherulitic textures. Phenocrysts up to 15%. Quartz, orthoclase, and oligoclase; scarce mafic minerals are strongly chloritized and epidotized. Accessories are ilmenite and titanite	Psephitic crystal clastic, fluidal, and spherulitic textures. Phenocrysts 1–25%. Leucocratic or biotite-bearing varieties in the lower part, biotite–amphibole and pyroxene-bearing rocks in the upper part of the section; quartz, sanidine, albite–oligoclase, ferrohedenbergite; ferrohypersthene; fayalite, ferroan hornblende, and biotite. Accessories are ilmenite, "balls" of native iron, and cogenite
Petrochemical composition	Very peraluminous and peraluminous, calc-alkaline, and tholeiitic after [55]; magnesian and ferroan after [45], S-type after [53]	Metaluminous and peraluminous; tholeiitic and, more rarely, calc-alkaline after [55]; ferroan and magnesian after [45]; S-type and only individual samples correspond to I- and A-type after [53]	Metaluminous and agpaitic, tholeiitic after [55], ferroan and more rarely magnesian after [45]. The ignimbrites of the early eruption stages are partly ascribed to the S type, while the volcanics of the final stages, to the A type (after [53])
Geochemical specialization	Elevated contents of Mg, Mn, Ti, and ΣFe and Ca, Sr, and Ba	Significant compositional variations; elevated contents of Mg, Mn, ΣFe, and Ca	Elevated contents of Si, K, Na, and Rb and extremely low Ca, Sr, and Mg

crustal magmas and their interaction with mantle melts.

CONCLUSIONS

Fissure or areal eruptions of the Late Cretaceous crystal-rich plateau ignimbrites of the Primorsky Complex produced the main volume of the East Sikhote Alin volcanic belt, one of the chains of the East Asian continental-margin belt. Their magnesian–ferroan, calcic, and calc-alkalic composition corresponds to S-type pearluminous felsic magmas. The formation of such melts is explained by the partial melting of metasedimentary and metamagmatic rocks under an oxidizing setting with the assistance of aqueous fluids typical of suprasubduction volcanism.

The Paleocene–Eocene ignimbrites of the Bogopolsky Complex show ferroan, calc-alkalic, and alkali-calcic metaluminous to peraluminous compositions. They define the trend caused by the successive changing of the S- and A-type type sources of felsic magmas. The A-type magmas were formed with the participation of reduced (essentially hydrogen) fluids, which were derived from the enriched mantle during the formation of felsic ignimbrite-forming magmas. Similar conditions of volcanic evolution are known in extension and collision zones formed in a transform continental-margin setting [40].

The Maastrichtian–Paleocene ignimbrites of the Levosobolevsky and Siyanovsky complexes could be ascribed to the transitional type of volcanic rocks reflecting the magmatism of the tectonic rearrangement of the region.

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