Journal Title Geochemistry international

NEW: Main Library
same

Volume/Issue 41 (8)
Month/Year 2003
Pages 787-798
Author Simanenko V.P., Khanchuk A.I.
Title Cenomanian volcanism of the Eastern Sikhote-Alin volcanic belt: geochemical features

Geochemistry International, Vol. 41, No. 8, 2003, pp. 787–798. Translated from Geokhimiya, No. 8, 2003, pp. 866–878.

Cenomanian Volcanism of the Eastern Sikhote-Alin Volcanic Belt: Geochemical Features

V. P. Simanenko and A. I. Khanchuk

Far East Geological Institute, Far East Division, Russian Academy of Sciences, pr. Stoletiya Vladivostoka 159, Vladivostok, 690022 Russia
e-mail: fegi@online.marine.su; http://www.fegi.ru

Received December 14, 2001

Abstract—A geochemical study of the Cenomanian andesitic and basaltic volcanic rocks in the lower part of the Eastern Sikhote-Alin volcanic belt was performed. Petrologic and geochemical features of the rocks correspond to products of calc-alkaline magmas of the subduction-related continental-margin belts. The Cenomanian volcanics differ in some geochemical features from the Aptian–Albian Sikhote-Alin island-arc rocks and the Albian–Cenomanian rocks characterizing the geodynamic regime of a Californian-type transform continental margin.

GENERAL GEOLOGY

Middle Cretaceous (Aptian–Albian–Cenomanian) igneous complexes that originated in various geodynamic settings are abundant in the Sikhote-Alin mountains. An island-arc origin is suggested for the Aptian–Albian volcanic complexes in the coastal zone of the Sikhote-Alin (Kema terrane) [1, 2]. The igneous complexes located further west in the intracontinental basins show major- and trace-element features typical of volcanics on a Californian-type transform continental margin [3, 4]. The Cenomanian andesitic rocks are developed along the coast of the Sea of Japan, postdate the volcanics of the transform continental margin, and compose a part of the Eastern Sikhote-Alin volcanic belt. Until recently it was considered that the continental-margin volcanic belt had continuously developed above a subduction zone since the Late Cretaceous to the Miocene [5, 6]. However, Yu.A. Martynov [7] has shown that the Cenozoic volcanism of the Eastern Sikhote-Alin was not related to a subduction zone. The Paleogene volcanic rocks that compose a bimodal series with dominant high-Al basalts have geochemical features (elevated K_2O and TiO_2 contents; high Ni/Co, Ti/V, and Ba/La ratios; and low La/Nb, La/Ta, etc.) resembling those of the extension-related volcanics, e.g., the rocks of the bimodal series of the North America transform continental margin. As a result, the Cenozoic rocks were separated from the Eastern Sikhote-Alin volcanic belt, and the volcanic products of the Paleogene transform geodynamic regime were identified on the Asian continental margin of the Pacific Ocean [8]. The Miocene–Pliocene volcanics show geochemical features of intraplate rocks and postdate the opening of the Sea of Japan [9]. The subduction-related origin of the Late Cretaceous igneous rocks is also questioned by some researchers. V.P. Utkin believes that the formation of volcanic structures of the Eastern Sikhote-Alin volcanic belt is generally caused by sinistral strikeslip faults and related extension faults [10]; i.e., he supposes a rifting nature of the volcanism.

The geochemical signatures of igneous rocks often help to identify the geodynamic setting of their development. The composition of basic rocks is more informative in this respect, because these rocks were formed from more primitive magmas untouched by differentiation. Thus, we studied the Cenomanian volcanics with a large proportion of andesites and basalts located in the lower part of the volcanic belt section. The geology of these volcanics is well known, whereas trace element data (particularly, complete spectra of REE distribution) are scarce for them.

The structure, stratigraphy, tectonics, and magmatism of the Eastern Sikhote-Alin volcanic belt are considered in many publications [11–14]. The volcanic belt is generally composed of siliceous volcanics extruded during the Coniacian–Campanian stages. The Cenomanian and Maestrichtian stages were accompanied by extensive eruption of andesitic magmas. The Cenomanian igneous complexes are generally located in the inner (western) part of the Eastern Sikhote-Alin volcanic belt and their distribution is constrained by Pribrezhnyi (Coastal) and Vostochnyi (Eastern) faults [14]. These complexes are known in various parts of the Eastern Sikhote-Alin volcanic belt as the Sinancha, Bazovskaya, Kastofunova, Cheremukhovaya, Kuksinskaya, Bol'bino formations, as well as "andesite" or "andesite porphyrite" sequences. These stratigraphic units are principally composed of andesites and their tuffs with subordinate basalts, dacites, and rhyolites, and their tuffs. The acid-to-basic tendency in the compositional evolution of volcanism is expressed in some areas in the development of basaltic andesite and basalt lavas in the upper parts of the units [13, 15]. The volca-

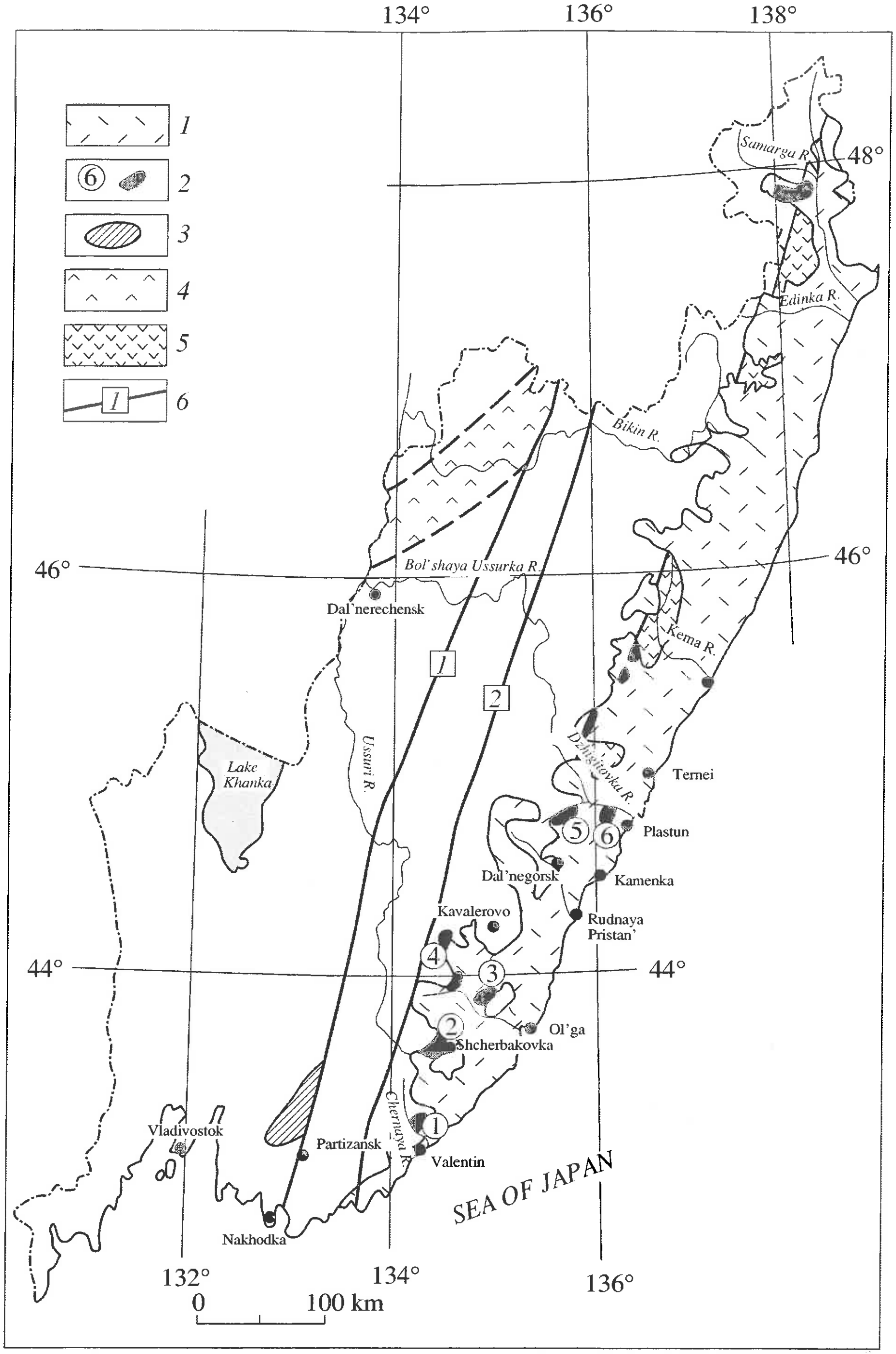

Fig. 1. Distribution of the Aptian–Albian–Cenomanian igneous rocks in Primor'e. (*1*) Eastern Sikhote-Alin continental-margin volcanic belt; (*2*) main areas of the Cenomanian volcanics in the Primor'e part of the Eastern Sikhote-Alin volcanic belt and study sites: 1—Chernaya river area, 2—Sinancha volcano-tectonic structure, 3—Kastofunova Formation on the left side of the Avvakumovka River (Kastofunova, Grushevaya, and Petrozuevka ravines), 4—Sinancha Formation in the Uglovaya volcano-tectonic structure, 5—same in the Dal'negorsk volcano-tectonic structure, 6—same in the Plastun volcano-tectonic structure; (*3, 4*) Albian–Cenomanian volcanics of a Californian-type transform continental margin: (*3*) Partizansk coal basin, (*4*) Alchan depression; (*5*) Aptian–Albian volcanics of the Kema terrane of the Moneron–Samarga island arc; (*6*) main faults: *1*—Arsen'evsk, *2*—Central Sikhote-Alin.

nic rocks closely associate with subvolcanic, extrusive, and intrusive rocks represented by andesites, basaltic andesites, basalts, dacites, diorites, gabbro-diorites, and gabbro-diabases. The rocks of the above stratigraphic units are dated by the K–Ar method at 110–75 Ma, with the mode at 95–90 Ma [13, 14]. The fossil flora in the volcano-sedimentary deposits of these units indicates their Cenomanian, Cenomanian–Turonian, or, in some cases, Late Albian age.

SAMPLES AND ANALYTICAL METHODS

We studied the composition of the intermediate to basic volcanic rocks of the Sinancha Formation in the southern and central parts of Primor'e (Fig. 1) in the drainage areas of the following rivers: (1) Chernaya (near Sokol'chi village), (2) Margaritovka (near Shcherbakovka village within the Sinancha volcano-tectonic structure [11]), (3) Avvakumovka (the Kastofunova Formation in the Kastofunova, Grushevaya, and Petrozuevka ravines), (4) Uglovaya (the Sinancha Formation of the Uglovaya volcano-tectonic structure [16–19]), (5) Cheremukhovaya (Dal'negorsk volcano-tectonic structure [14]), and (6) Dzhigitovka (Plastun volcano-tectonic structure [11, 12, 14]).

The major elements were determined by classical silicate analysis in laboratories of the Far East Geological Institute, Far East Division, Russian Academy of Sciences (analysts S.P. Slavkina and S.P. Batalova); most of the trace elements were determined by quantitative spectral analysis in the spectral laboratory of the Far East Geological Institute (analysts T.V. Sverkunova and L.I. Azarova); large-ion lithophile elements, by XRF spectrometry in the PGO laboratory (analyst M.V. Voityshina); radioactive and rare-earth elements were measured by neutron activation in IGFM, National Academy of Sciences of Ukraine (analyst L.V. Kononenko) and by ICP-MS in the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences.

PETROGRAPHY

The andesitic and basaltic rocks of the Cenomanian units within various volcano-tectonic structures comprise aphyric and porphyritic varieties with plagioclase, hornblende–plagioclase, pyroxene–plagioclase, and pyroxene–magnetite–plagioclase phenocryst assemblages. Plagioclases are normally zonal andesines. Pyroxenes dominate by clinopyroxene (augite), while orthopyroxene is rare. The groundmass has pilotaxitic or microlitic texture. Most rocks are altered with the formation of sericite after plagioclase and chlorite after mafic minerals and groundmass glass.

MAJOR- AND TRACE-ELEMENT CHEMISTRY

Major elements. The studied rocks are generally basaltic andesites and andesites, while basalts and dacites are subordinate (Table 1, Fig. 2). The rocks have normal alkalinity and differ from the Aptian–Albian high-K calc-alkaline and shoshonitic basic rocks of the Kema island-arc terrane [2]. The rocks belong to the potassium–sodium series with $K_2O/Na_2O < 1$. Most rocks belong to the calc-alkaline series, and the rest, to the tholeiitic series, as determined in the FeO*/MgO–SiO_2 and FeO*–FeO*/MgO diagrams. All rocks fall in the calc-alkaline series field in the Zr–Ti–Y diagram [18].

The volcanic rocks are dominated by low-Ti varieties (TiO_2 is normally <1 wt %) with a maximum TiO_2 content of 1.2 wt %. Al_2O_3 contents are <18% in 90% of the samples analyzed. They present moderately aluminous rocks. The rest samples present the highly aluminous rocks and contain 18–20 wt % Al_2O_3. MgO contents are normally below 6 wt % and reach 7.3 wt % in extrusive gabbro-diabases and some basalt samples from the Kastofunova ravine. Elevated MgO contents are also typical of basalts of the Uglovaya volcano-tectonic structure (up to 8.29 wt %). Total iron content varies from 5 to 10 wt %. FeO dominates over Fe_2O_3. The oxygen potential slightly increases with increasing silica contents for the rocks of individual volcano-tectonic structures. Andesites contain 3–6 wt % CaO; basalts, up to 9–10 wt % CaO.

Trace elements. The concentrations of V and Cr that replace Fe^{3+} in the water-bearing minerals and magnetite vary within one to two orders of magnitude (from 23 to 320 ppm and from 5 to 770 ppm, respectively) (Table 2). The contents of these elements correlate with silica contents and increase from andesites to basalts with a V/Cr ratio varying from 5 to 18. Only in the rocks of the Uglovaya volcano-tectonic structure do Cr contents range within 120–770 ppm at almost constant V contents (100–200 ppm); the V/Cr ratio is <1. The Cr concentrations increase in these rocks with increasing MgO contents. Vanadium correlates with FeO*.

The concentrations of Ni and Co replacing Fe^{2+} and Mg in olivine and pyroxene vary from 3 to 58 ppm with a Ni/Co ratio (indicator of the depth of magma formation [20]) from 0.3 to 2. The volcanics of the Uglovaya volcano-tectonic structure have elevated Ni concentrations (49–260 ppm). They also have elevated Co contents (13–32 ppm) and high Ni/Co ratios (about 4).

The studied rocks are similar in Rb concentration to calc-alkaline andesites of island arcs and active continental margins. Rubidium contents vary from 13 to 72 ppm in andesites, from 12 to 108 ppm in basaltic andesites, and from 10 to 47 ppm in basalts; i.e., they slightly increase with increasing silica and potassium contents. K/Rb ratios increase from basalts (79–132) to andesites (73–908).

Barium shows similar behavior. Its concentrations vary from 280 to 775 ppm in basalts, from 226 to 883 ppm in basaltic andesites, and from 350 to 1847 ppm in andesites. The highest Ba contents (1400–

Table 1. Major element contents in the Cenomanian volcanic rocks of the Eastern Sikhote-Alin volcanic belt

Component	PT-2	PT-7	PT-33	PT-35/1	PT-36	PT-38	F-47	PT-44	F-20	F-22	PT-51
	1	2	3	4	5	6	7	8	9	10	11
SiO_2	59.54	58.52	49.74	60.63	61.30	63.98	50.68	53.88	55.64	55.62	59.35
TiO_2	0.83	1.15	1.41	0.97	1.18	0.70	0.82	0.96	1.12	1.21	0.91
Al_2O_3	14.23	16.01	17.38	15.38	15.30	13.78	13.19	16.46	17.42	17.44	15.63
Fe_2O_3	5.31	3.36	5.11	2.27	2.97	1.10	1.99	2.87	5.35	1.67	3.69
FeO	2.36	2.70	4.00	2.88	2.59	2.16	5.78	5.10	3.22	6.86	5.97
MnO	0.07	0.10	0.16	0.09	0.07	0.07	0.17	0.17	0.07	0.18	0.18
MgO	2.04	2.61	2.86	1.98	1.93	1.90	7.34	2.84	1.88	3.72	2.35
CaO	3.33	4.40	9.46	3.83	3.31	4.99	10.20	8.19	6.98	6.31	3.27
Na_2O	2.44	3.30	2.26	2.84	3.81	1.31	2.17	2.26	3.46	2.69	2.62
K_2O	1.07	2.19	1.43	2.12	1.86	2.27	0.89	0.50	2.30	1.41	0.55
P_2O_5	0.57	0.59	0.66	0.45	0.44	0.23	0.27	0.36	0.37	0.40	0.18
H_2O^-	1.14	0.20	0.00	0.35	0.15	0.00	0.25	0.20	0.00	0.12	0.00
H_2O^+	7.01	4.51	7.54	5.71	4.80	7.06	2.88	6.54	1.87	2.13	5.09
Total	99.94	99.64	100.65	99.55	99.74	99.55	99.77	100.34	99.68	99.16	99.78
FeO/MgO	3.15	3.55	3.00	2.48	2.72	1.65	1.02	2.70	4.27	2.24	3.95
K_2O/Na_2O	0.42	0.28	0.46	0.90	0.49	1.73	0.41	0.22	0.66	0.52	0.20
σ	0.73	1.94	2.02	1.39	1.75	0.61	1.21	0.70	2.62	1.33	0.61

Component	F-19	PT-226	PT-228	K-475	268/87	K-475/5	K-475/9	K-488/4	223/87	1
	12	13	14	15	16	17	18	19	20	21
SiO_2	46.20	62.09	60.85	50.60	50.38	51.39	53.49	53.29	50.40	58.50
TiO_2	0.53	0.64	1.02	1.28	1.22	1.19	1.07	0.97	1.15	0.74
Al_2O_3	20.70	16.78	16.20	17.74	18.73	16.84	18.17	19.38	16.49	16.44
Fe_2O_3	2.97	2.06	4.63	3.90	1.86	3.20	2.49	5.66	3.73	0.91
FeO	4.48	4.17	2.34	4.89	8.29	5.03	4.27	4.97	4.94	5.74
MnO	0.14	0.20	0.11	0.17	0.51	0.19	0.13	0.21	0.18	0.14
MgO	7.37	1.27	1.17	3.59	4.80	3.59	2.13	2.65	7.55	4.61
CaO	12.77	5.80	4.78	7.83	5.30	8.51	7.68	5.18	8.33	5.37
Na_2O	1.55	3.11	3.39	2.95	1.41	2.41	2.32	3.21	2.72	2.97
K_2O	0.32	1.60	2.71	0.40	1.49	0.27	1.11	2.05	1.11	2.65
P_2O_5	0.20	0.37	0.50	0.70	0.49	0.70	0.51	0.40	0.27	
H_2O^-	0.28	0.69	1.22	0.00	0.08	0.00	0.00	0.00	0.15	
H_2O^+	2.04	0.69	0.58	6.04	4.82	6.21	6.34	1.72	2.84	
Total	99.77	99.47	99.50	100.04	99.49	99.53	99.71	99.69	99.86	
FeO/MgO	1.62	4.74	5.56	2.34	2.07	2.20	2.10	3.79	1.09	1.47
K_2O/Na_2O	0.20	0.57	0.89	0.13	1.0	0.11	0.41	0.63	0.40	0.89
σ	1.08	1.16	2.08	1.47	1.13	0.85	1.12	2.68	1.98	2.04

Note: (1, 2) Andesites, Chernaya River; (3–6) Sinancha volcano-tectonic structure: 3—basalt, 4—andesite, and 5, 6—andesite-dacite; (7–12) Kastofunova Formation, Kastofunova and Petrozuevka ravines: 7—basalt, 8–10—basaltic andesites, 11—andesite, 12—subvolcanic gabbro-diabase; (13, 14) andesites of the Plastun volcano-tectonic structure; (15–19) volcanics of the Dal'negorsk volcano-tectonic structure: 15–17—basalts, 18 and 19—basaltic andesites; (20, 21) volcanics of the Uglovaya volcano-tectonic structure: 20—basalt, 21—andesite after [19]. $\sigma = (K_2O + Na_2O)^2/SiO_2 - 43$.

1847 ppm) are found in andesites from the Chernaya river area. They have lower Rb/Ba ratios (2.7–6.4) as compared to andesites (10.9–24.5) and even basalts (3.7–16.3) of the other volcano-tectonic structures.

Strontium in the Cenomanian volcanics correlates positively with Ca and negatively with Ba. Strontium contents decrease from basalts (362–988 ppm) to basaltic andesites (241–554 ppm) and andesites (374–747 ppm). Ca/Sr ratios slightly decrease from basalts (68–164) to basaltic andesites (85–136) and andesites (20–131). Correspondingly, Ba/Sr ratios increase from basalts (0.42–0.99) to basaltic andesites (0.31–1.88) and andesites (0.55–3.72).

The Nb, Zr, Ta, and Hf concentrations in the rocks of the Cenomanian complexes of the Sikhote-Alin notably vary but are low in all rocks and independent of silica, alkali, or magnesia contents. For example, the rocks contain 8–21 ppm Nb, 77–240 ppm Zr, 0.18–1.2 ppm Ta, and 0.39–5.68 ppm Hf.

Uranium and thorium concentrations in the studied rocks vary from 0.72 to 1.86 ppm and from 2.7 to 13.5 ppm, respectively. The leucocratic and more aluminous rocks have higher U and Th contents than the melanocratic and more magnesian rocks. The Th/U ratios varying within a narrow interval of 2.7–4.8 compose a single trend for the whole data set. The K/U ratios range from 0.9 to 6.3×10^4, which are typical of the continental and island-arc basalts of the Sea of Japan region [21].

Rare earth elements. The REE concentrations in the rocks studied are relatively high. They vary insignificantly with silica contents: LREEs are somewhat higher and HREEs are somewhat lower in andesites and dacites than in basalts. The (REEs + Y) contents in lavas vary from 115 to 210 ppm. The gabbro-diabases of the Kastofunova ravine have the lowest (REEs + Y) contents (37.5 ppm). The REE index suggested by Yu.P. Troshin [22] [K_{REE} = 0.1La/Yb + Ho/Yb + (Dy + Ho)/(Yb + Lu), where concentrations are normalized to chondrite values] is within a narrow range of 2.7–3.5 for rocks of all types. Normalized REE distribution patterns (Fig. 3) are similar to those of the rocks of the calc-alkaline and shoshonite–latite series [27] and descend as the element number increases. REE spectra have moderate slopes, are devoid of bends in the central parts and distinct Eu anomalies, and gradually flatten at HREE from Tb to Lu. The Eu/Eu* ratio in volcanic rocks of various volcano-tectonic structures ranges from 0.77 to 1 and is 1.25 in subvolcanic rocks. $(La/Sm)_n$ ratios characterizing the slope for LREEs vary from 2–3.6 in basalts and basaltic andesites to 3.4–6 in andesites. $(Ce/Yb)_n$ ratios vary from 3.5 to 10.4 and are generally higher in andesites than in basalts.

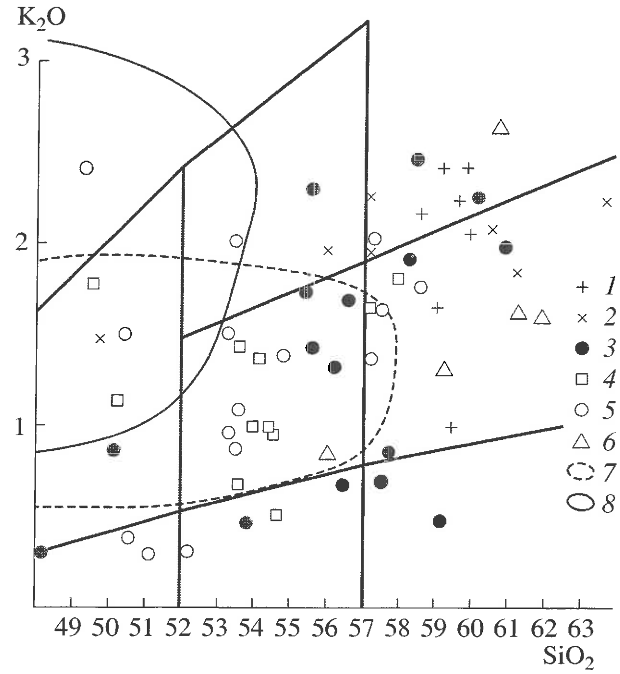

Fig. 2. Cenomanian volcanic rocks of the Eastern Sikhote-Alin volcanic belt in a K_2O–SiO_2 diagram. (*1*) Chernaya River; (*2*) Sinancha volcano-tectonic structure; (*3*) Kastofunova Formation on the left side of the Avvakumovka River; (*4*) Uglovaya volcano-tectonic structure; (*5*) Dal'negorsk volcano-tectonic structure; (*6*) Plastun volcano-tectonic structure. (*7*) Field of the Albian–Cenomanian volcanics of the Partizansk coal basin [4]; (*8*) field of basalts of the Kema island-arc terrane [2].

DISCUSSION

The Cenomanian volcanic rocks from different volcano-tectonic structures of the Eastern Sikhote-Alin volcanic belt have many chemical features in common. In contrast, volcanics of the Uglovaya volcano-tectonic structure differ in having elevated MgO contents and a higher concentration of the other mafic components, while subvolcanic gabbro-diabases of the Kastofunova ravine have lower REE concentrations. However, many incompatible element ratios, e.g., Ce/La, Zr/La, Nb/La, Th/La, and Yb/La, are almost constant and correlate with each other. These features usually characterize comagmatic rocks and indicate that the rocks of different volcano-tectonic structures belong to the same magmatic series.

The Eastern Sikhote-Alin volcanic belt is usually considered as an Andean-type active continental margin [5, 6]. The geochemical data obtained on the Cenomanian volcanics verify this suggestion. The rocks studied are close in geochemical features to the subduction-related volcanics of similar silica and alkali contents. For example, the Cenomanian volcanics plot in the fields of rocks of active continental margins and island arcs in some binary and ternary diagrams (TiO_2–Zr, Ti/100–Zr–Sr/3, Ti–Zr–Y × 3, Rb–(Y + Nb) [18], La/10–Y/15–Nb/8 [28], Ti–V [29], and Th–Hf/3–Ta [30]) (Fig. 4) and J. Pearce's discriminant diagrams [31]. The Cenomanian rocks are plotted within the fields of tholeiitic, high-Al, and calc-alkaline lavas of

Table 2. Trace element contents (ppm) in the Cenomanian volcanic rocks of the Eastern Sikhote-Alin volcanic belt

Element	PT-2*	PT-7*	PT-33	PT-35/1*	PT-36*	PT-38*	F-47	PT-44	F-20	F-22	PT-51*
	1	2	3	4	5	6	7	8	9	10	11
Ni	25	8	35	11	16	10	76	12	16	10	23
Co	18	8.7	16	9.5	12	7.4	33	20	15	23	15
Cr	7.5	7.8	45	5.0	14	7.2	250	29	32	14	22
V	85	70	215	39	55	23	182	163	159	200	270
Cu	40	18	41	40	37	23	44	18	7.2	21	3.5
Pb	5.8	3.0	12	5.0	5.8	4.7	5.7	7.5	9.3	11	2.2
Zn	83	36	110	73	73	33	81	8.2	6.6	218	50
Sn	1.8	0.9	2.0	0.8	0.9	1.0	0.7	1.9	1.4	1.0	1.2
Zr	119	126	174	156	140	135	144	144	146	144	127
Rb	49	36	47.2	29	15	61	17.5	16	42.8	40.3	31
Sr	418	645	958	468	558	401	522	435	468	522	394
Y	46	10	30.5	–	–	–	24	26.2	26.9	28.2	–
Nb	12	8.0	20.9	14	17	8	11.8	16.0	11.9	11.8	8
Ba	1556	1420	775	430	314	734	550	431	883	4.83	348
Hf	25	4.8	4.3	0.71	1.7	3.1	2.97	3.86	3.84	3.75	0.39
Ta	–	1.2	0.97	–	1.0	1.25	0.50	0.73	0.53	0.72	–
Th	5.2	1.3	6.6	6.9	12	7.25	4.23	6.44	5.72	5.56	4.1
U			1.56				0.98	1.72	1.50	1.37	
La	59.7	32.9	33.2	37.6	33.7	28.1	16.95	22.88	26.7	21.5	18.8
Ce	95.2	51.0	70.4	50.1	59.6	54.5	33.45	47.58	52.0	44.3	44.9
Pr			8.6				4.19	5.51	5.77	5.53	10
Nd	53	47	34	23	25	37	17.78	23	22.4	22.2	2.89
Sm	14.8	4.89	6.9	3.92	6.06	4.07	3.90	4.89	4.58	4.60	1.0
Eu	3.49	1.45	2.0	1.06	1.36	1.23	1.28	1.35	1.50	1.50	
Gd			6.5				4.12	4.49	4.38	4.53	
Tb	1.59	0.61	0.95	–	0.91	–	0.63	0.71	0.66	0.67	0.61
Dy			5.1				3.71	4.33	4.02	4.32	
Ho			1.67				0.84	0.89	0.93	0.94	
Er			2.63				1.98	2.33	2.28	2.40	
Tm			0.38				0.32	0.35	0.36	0.36	
Yb	4.69	3.55	2.46	1.23	2.16	2.32	1.95	2.28	2.40	2.10	1.87
Lu	0.77	0.53	3.0	0.16	0.27	0.37	0.29	0.34	0.33	0.34	0.38
ΣREE			175.9				91.4	120.9	128.3	114.3	
Eu/Eu*			0.89				0.97	0.86	1.00	0.99	
K_{REE}			3.52				3.09	3.00	3.05	3.23	

Table 2. (Contd.)

Element	F-19	PT-226*	PT-228*	K-475	268/87	K-475/5	K-475/9	K-488/4	223/87	1
	12	13	14	15	16	17	18	19	20	21
Ni	58	12	6.8	13	17	11	6.9	9.7	226	21
Co	33	20	11	21	22	20	18	18	36	
Cr	199	12	8.5	26	50	26	9.2	9.2	532	
V	141	310	100	220	233	218	166	166	202	
Cu	7.5	110	1.0	15	7	15	6.3	11	33	
Pb	7.8	40	28	9.7	10	14	11.3	13.7	3.54	0.9
Zn	51	160	100	98	108	112	113	132	74	
Sn	0.6	1.8	2.2	2.8	5.3	2.8	3.1	8.0	2.1	
Zr	77	123	239	182	134	170	209	219	126	121
Rb	10	10	36	11.2	78.6	10.9	55.5	146	31.4	102
Sr	616	493	396	725	284	671	483	449	362	292
Y	8.2	14	22	29.2	30.9	31.3	34	40.5	25.5	22.3
Nb	2.1	15	16	15.7	12.8	17.0	20.4	18.9	10.5	7.0
Ba	94	136	696	310	451	321	468	366	281	450
Hf	1.85	2.2	4.1	4.36	3.65	4.34	4.99	5.68	2.96	3.87
Ta	0.18	–	1.1	1.07	0.68	0.71	0.92	1.24	0.50	
Th	1.31	5.5	10.7	5.46	4.36	5.97	8.80	13.5	3.70	19.3
U	0.48			1.22	0.99	1.24	1.82	1.86	0.77	4.95
La	4.99	14.1	34.9	25.0	17.4	27.8	34.1	27.8	14.6	30.2
Ce	11.2	33	72.5	56.7	39.0	61.6	72	62.4	33.2	62.6
Pr	1.32			6.81	4.91	7.32	8.22	7.82	4.12	7.16
Nd	5.53	20	40	28.1	21.3	29.3	33.6	32.4	17.3	24.8
Sm	1.15	3.28	7.38	5.94	4.82	6.48	6.22	7.31	4.03	4.95
Eu	0.51	1.23	1.61	1.58	1.31	1.62	1.72	1.89	1.16	0.98
Gd	1.27			5.36	4.97	5.82	6.15	7.49	4.15	4.43
Tb	0.18	0.83	0.87	0.82	0.79	0.87	0.91	1.08	0.60	0.67
Dy	1.22			4.84	4.85	5.35	5.13	6.78	4.02	3.97
Ho	0.29			1.08	1.14	1.15	1.17	1.45	0.96	0.81
Er	0.69			2.66	2.83	2.76	2.82	3.83	2.22	2.34
Tm	0.11			0.39	0.44	0.42	0.42	0.62	0.38	0.36
Yb	0.72	2.42	4.03	2.51	2.82	2.58	2.71	3.63	2.40	2.29
Lu	0.12	0.55	0.62	0.36	0.40	0.35	0.39	0.52	0.30	0.35
ΣREE	29.3			142.1	107.0	153.4	175.5	165.0	89.44	149.0
Eu/Eu*	1.28			0.84	0.81	0.79	0.84	0.77	0.86	0.62
K_{REE}	2.44			3.21	2.75	3.44	3.33	2.84	2.98	3.00

Note: REEs, Th, Hf, and Ta in samples marked with * are determined by neutron activation; in the other samples, by ICP-MS.

island arcs and are close to basalts of the Large Tolbachik eruption, Kamchatka in the La/Yb–K_2O diagram [32]. Only a small part of the analyses are in the field of alkaline rocks (Fig. 5). The La/Ta ratios in the rocks studied are 22.4–50.4, which are close to those in volcanics from active continental margins. Low La/Ta ratios (<20) are characteristic of the rocks from the intraplate continental and oceanic settings. The Cenomanian rocks are close to orogenic andesites in their La/Ba (11–80), La/Th (2–7), and La/Nb (1–5) ratios. La/Yb ratios in the Cenomanian volcanics range within 6–30 (normally >10), which are higher than in the island-arc volcanics (La/Yb = 1–10) and are typical of the rocks of the continental-margin belts. For example,

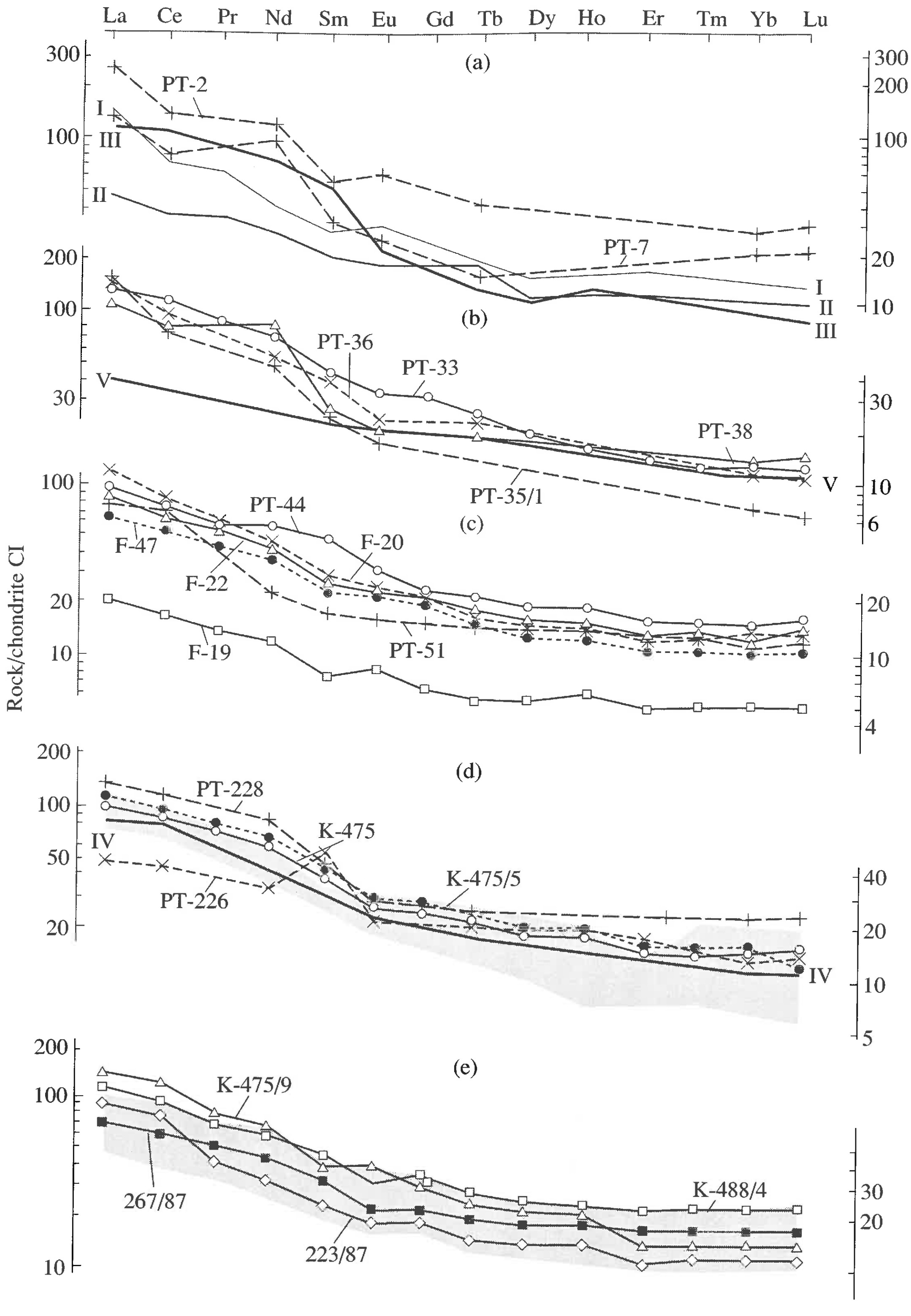

Fig. 3. Chondrite-normalized REE patterns of the Cenomanian volcanics of the Eastern Sikhote-Alin volcanic belt.
(a) Chernaya River; (b) Sinancha volcano-tectonic structure; (c) Kastofunova Formation; (d, e) Dal'negorsk, Plastun, and Uglovaya volcano-tectonic structures. REE patterns for the rocks of type structures: (I–I) andesites of the Omolon massif of the Okhotsk–Chukotka volcanic belt [23], (II–II) average island-arc andesite, (III–III) basalts of the northern zone in the Andean volcanic belt [24], (IV–IV) basaltic andesites of the southern zone in the Andean volcanic belt [25], (V–V) basaltic andesites of the High Cascades [26]. Shaded areas are Albian–Cenomanian volcanics of the Partizansk coal basin in (d) and Aptian–Albian volcanics of the Kema island-arc terrane in (e).

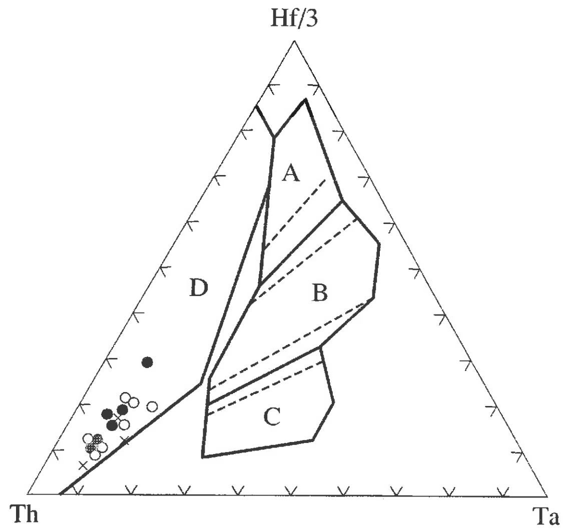

Fig. 4. A Th–Hf/3–Ta diagram [30] for the Cenomanian volcanics of the Eastern Sikhote-Alin volcanic belt. Symbols are in Fig. 2. Fields in the diagram: (A) N-type MORB; (B) E-type MORB and intraplate basalts; (C) alkaline intraplate basalts; (D) basalts of island arcs and active continental margins.

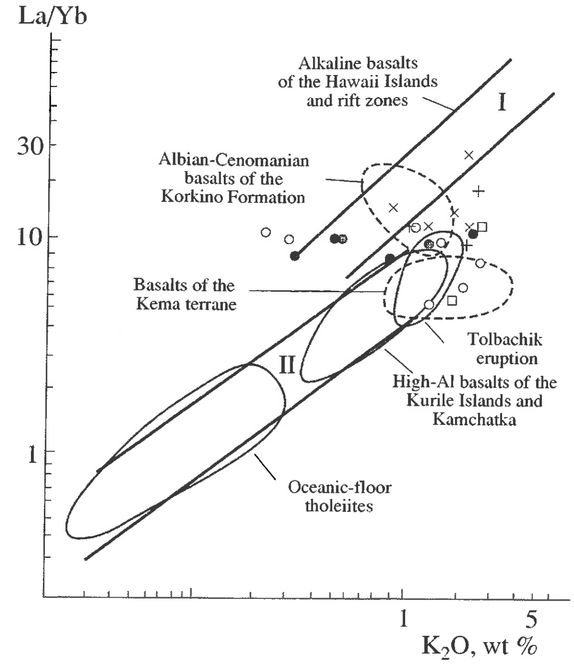

Fig. 5. A La/Yb–K_2O diagram [32] for the Cenomanian volcanics of the Eastern Sikhote-Alin volcanic belt. (I) Trend of alkaline basalts; (II) trend of tholeiitic, high-Al, and calc-alkaline basalts. Symbols are in Fig. 2.

Fig. 3 shows that the Cenomanian volcanics of the Sikhote-Alin are richer in LREEs than the intermediate volcanics of island arcs and close in these elements to volcanic rocks of the Andean and Okhotsk–Chukotka continental-margin belts. The MORB-normalized trace-element patterns (Fig. 6) also demonstrate the similarity of the studied volcanics to the rocks of active continental margins. Positive K, Rb, Ba, Th, Ce, and negative Ta, Nb, Zr, Hf, and Ti anomalies are distinct in this diagram. Having similar REE contents with the Aptian–Albian volcanics of the Kema terrane of the Moneron–Samarga island arc, the Cenomanian volcanics show notable a Eu minimum (Fig. 3). The Cenomanian volcanics have rectilinear REE patterns in contrast to the sigmoidal patterns typical of the Albian–Cenomanian volcanics of the Korkino Group and Dadanshan Formation of the Partizansk coal basin in Primor'e [4], which originated in the geodynamic regime of a Californian-type transform continental margin.

Major and trace elements, particularly REEs, are frequently used for revealing conditions of magma generation and mineral composition of the primary magma sources. It is generally accepted that the calc-alkaline magmas of island arcs and active continental margins form in the Benioff zones by melting of amphibolites (or eclogites) at depths as low as 70 km [33]. Some researchers believe that high potassium and incompatible element contents and high K/Na ratios indicate larger melting depths at small-degree partial melting in the mantle. Primary mantle magmas have high Ni/Co ratios (2.2–7.6) [20].

The Cenomanian volcanics of the Eastern Sikhote-Alin volcanic belt, except for the rocks of the Uglovaya volcano-tectonic structure, have crustal Ni/Co ratios. The relation between Rb and Sr concentrations (Fig. 7) indicates that the Cenomanian magmas of the Sikhote-Alin were generated at depths of 20–35 km (in the lower crust), which is typical of the volcanics of active continental margins. The volcanic rocks of the Uglovaya volcano-tectonic structure with elevated MgO and high mafic element contents and a mantle-type Ni/Co ratio could be considered as products of the deepest magmas for the studied area in the Cenomanian. This is probably caused by the geological setting of the Uglovaya volcano-tectonic structure in the westernmost part of the Eastern Sikhote-Alin volcanic belt, most distant from the coast (Fig. 1), i.e., from a Benioff paleozone.

The $(Ce/Yb)_n$–Ce_n diagram (Fig. 8) shows that the Cenomanian magmas originated trough a high degree of melting degree of an amphibolite protolith in the continental crust. The amphibole-rich protolith and relatively small depths of magma generation are also consistent with the low K_{REE} values in the rocks. This index is about 5 or >7, respectively, if pyroxene or garnet occur among the melting phases [22]. As can be seen for the rocks of the Uglovaya and Dal'negorsk volcano-tectonic structures, basalts originated at a higher melting degree, while andesites are the products of lower degree melting (Fig. 8). All these rocks can be considered as products of primary magma crystallization.

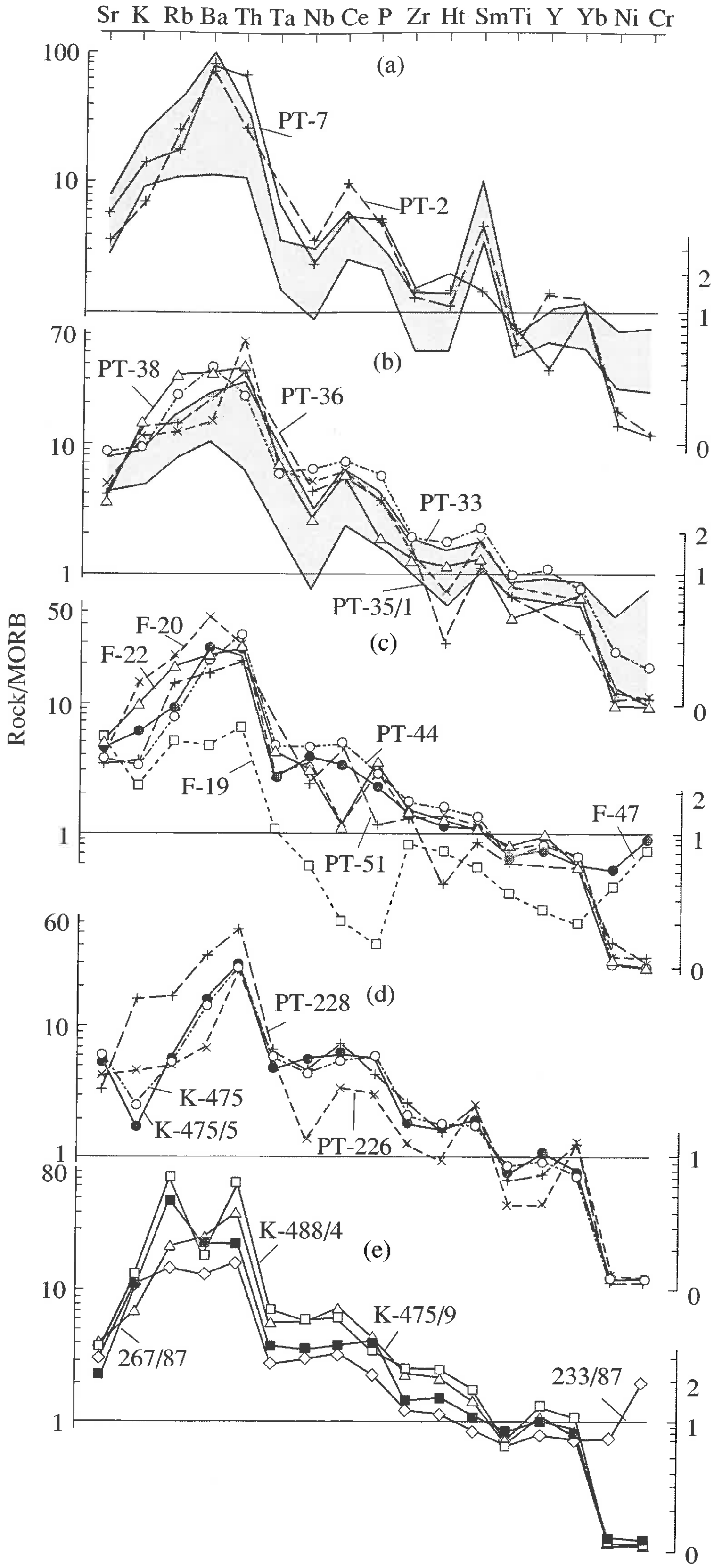

Fig. 6. MORB-normalized trace-element patterns for the Cenomanian volcanics of the Eastern Sikhote-Alin volcanic belt. Symbols are in Fig. 3. Shaded areas are Aptian–Albian basalts of the Kema island-arc terrane in (a) and Albian–Cenomanian volcanics of the Partizansk coal basin in (b).

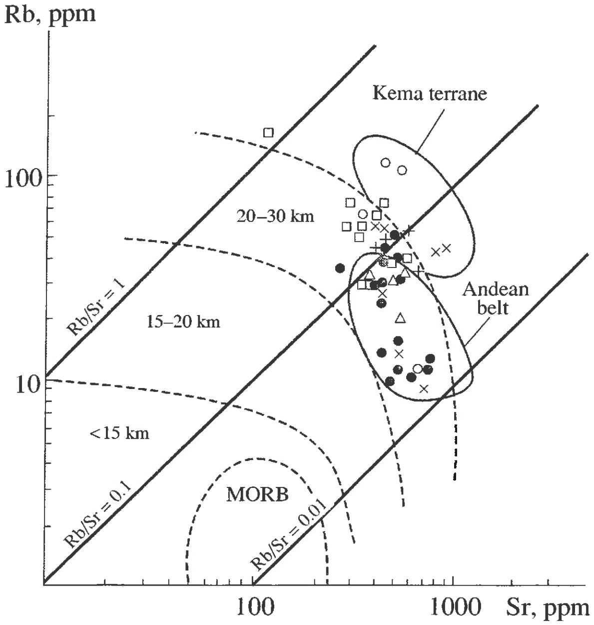

Fig. 7. A Rb–Sr diagram [34] for the Cenomanian volcanics of the Eastern Sikhote-Alin volcanic belt. Symbols are in Fig. 3. MORB—mid-oceanic ridge basalts.

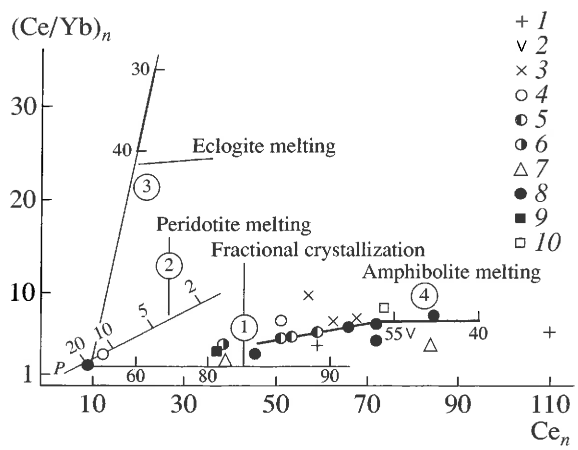

Fig. 8. A $(Ce/Yb)_n$–Ce_n diagram [35] for the Cenomanian volcanics of the Eastern Sikhote-Alin volcanic belt. (*1*) Andesites of the Chernaya River; (*2*) basalts of the Sinancha volcano-tectonic structure; (*3*) andesites of the same structure; (*4*) andesites from the Kastofunova ravine; (*5*) basaltic andesites from the same ravine; (*6*) basalts from the same ravine; (*7*) andesites of the Plastun volcano-tectonic structure; (*8*) basalts and basaltic andesites of the Dal'negorsk volcano-tectonic structure; (*9*) basalts of the Uglovaya volcano-tectonic structure; (*10*) andesites of the same structure.

This is verified by the absence of Eu anomalies in the Cenomanian volcanics as a criterion of primary magma [32] and by the geological relationship with the acid-to-basic sequence of magma eruption. Residual liquids deplete in some trace elements with the appearance of small negative or positive Eu anomalies because of early fractional crystallization of primary magmas with separation of mafic minerals, magnetite, and plagioclase [32]. Depletion of subvolcanic gabbro-diabases of the Kastofunova ravine in all trace elements at similar style of REE distribution pattern could be an example of such differentiation.

CONCLUSIONS

(1) The Cenomanian volcanic rocks of various volcano-tectonic structures of the Eastern Sikhote-Alin volcanic belt are similar in some major- and trace-element features and REE concentrations to subduction-related calc-alkaline volcanics of an Andean-type active continental margin.

(2) The acid-to-basic sequence of magma eruption, REE concentrations, and absence of Eu minima indicate that the rocks studied are products of primary lower crustal–upper mantle magmas generated by partial melting of amphibolites.

(3) Showing similar REE concentrations, the Cenomanian volcanics differ in the absence of Eu minima from the Aptian–Albian island-arc rocks and in REE distribution patterns from the Albian–Cenomanian rocks of a Californian-type transform continental margin.

ACKNOWLEDGMENTS

The study was supported by the Russian Foundation for Basic Research, project nos. 98-05-65343 and 99-05-64727.

REFERENCES

1. Simanenko, V.P., Late Mesozoic Volcanic Arcs in the Eastern Sikhote-Alin Range and Sakhalin Island, *Tikhookean. Geol.*, 1986, no. 1, pp. 7–13.
2. Simanenko, V.P., Basalt–Andesitic Associations of Paleozoic and Mesozoic Island Arcs, in *Tikhookeanskaya okraina Azii. Magmatizm* (The Asian Pacific Margin: Magmatism), Shcheglov, A.D., Ed., Moscow: Nauka, 1991, pp. 58–72.
3. Khanchuk, A.I., Paleodynamic Analysis of Ore Deposits in the Far East, Russia, in *Rudnye mestorozhdeniya kontinental'nykh okrain* (Ore Deposits of Continental Margins), Vladivostok: Dal'nauka, 2000, pp. 5–34.
4. Simanenko, V.P., Khanchuk, A.I., and Golozubov, V.V., First Geochemical Data on the Albian–Cenomanian Volcanism of Southern Primor'e, *Geokhimiya*, 2002, no. 1, pp. 95–99.
5. *Vulkanicheskie poyasa Vostoka Azii. Geologiya i metallogeniya* (Volcanic Belts in the East Asia: The Geology and Metallogeny), Moscow: Nauka, 1984.
6. Zonenshain, L.P., Kuz'min, M.I., and Natapov, L.M., *Tektonika litosfernykh plit territorii SSSR* (The Plate Tectonics of USSR), Moscow: Nedra, 1990, vol. 2.
7. Martynov, Yu.A., *Geokhimiya bazal'tov aktivnykh kontinental'nykh okrain i zrelykh ostrovnykh dug na primere severo-zapadnoi Patsifiki* (The Geochemistry of Basalts

and Mature Island Arcs: Evidence from the Northwest Pacific Region), Vladivostok: Dal'nauka, 1999.

8. Khanchuk, A.I., Golozubov, V.V., Martynov, Yu.A., and Simanenko, V.P., Early Cretaceous and Paleogene Transform Margins: The California Type, in *Tektonika Azii* (The Asian Tectonics), Moscow: GEOS, 1997, pp. 58–79.

9. Martynov, Yu.A. and Levashov, G.B., Geochemical Criteria for Riftogene Origin of Pliocene–Pleistocene Basalts in Eastern Sikhote-Alin, *Dokl. Akad. Nauk SSSR,* 1988, vol. 303, no. 2, pp. 472–476.

10. Utkin, V.P., Horst–Accretional Systems, Rift-type Grabens, and Volcanic–Plutonic Belts: Structural–Lithologic Characteristics and Formation Regularities, *Tikhookean. Geol.,* 1997, vol. 16, no. 6, pp. 58–79.

11. Fremd, G.M., *Orogennyi vulkanizm Yuzhno-Dzhungarskogo i Vostochno-Sikhote-Alinskogo poyasov* (The Orogenic Volcanism of Southern Dzhungar and Eastern Sikhote-Alin Belts), Tomsk: Tomsk. Univ., 1972.

12. Vetrennikov, V.V., *Osobennosti vulkanizma, tektoniki i orudeneniya okrainno-materikovykh vulkanicheskikh poyasov* (Volcanic Belts of Continental Margins: Volcanism, Tectonics, and Ore Mineralization), Moscow: Nedra, 1976.

13. Fedchin, F.G., Simanenko, V.P., Zalevskii, S.N., *et al., Geokhimiya Vostochno-Sikhote-Alinskogo i Okhotskogo poyasov* (The Geochemistry of Eastern Sikhote-Alin and Okhotsk Belts), Moscow: Nauka, 1981.

14. Mikhailov, V.A., *Magmatizm vulkano-tektonicheskikh struktur yuzhnoi chasti Vostochno-Sikhote-Alinskogo poyasa* (Magmatism in Volcanic–Tectonic Structures of the Southern Part of Eastern Sikhote-Alin Belt), Vladivostok, 1989.

15. Finashin, V.K., *Olovorudnye mestorozhdeniya Primor'ya* (Tin Ore Deposits in Primor'e), Vladivostok, 1986.

16. Matyunin, A.P., Magmatism of Kavalerovo and Verkhnyaya Arma Tin Ore Regions, *Cand. Sci. (Geol.–Mineral.) Dissertation*, Vladivostok: Dal'nevost. Geol. Inst., 1988.

17. Popovichenko, V.V., Evolution of Magmatism in the Kavalerovo Ore District, *Cand. Sci. (Geol.–Mineral.) Dissertation*, Vladivostok: Dal'nevost. Geol. Inst., 1992.

18. Pearce, J.A. and Cann, J.R., Tectonic Setting of Basic Volcanic Rocks Determined Using Trace Element Analyses, *Earth Planet. Sci. Lett.,* 1973, vol. 19, no. 2, pp. 290–300.

19. Gonevchuk, V.G., Ore-bearing Systems in the Far East: Magmatism and Ore Genesis, *Doctoral (Geol.–Mineral.) Dissertation*, Vladivostok: Dal'nevost. Geol. Inst., 1999.

20. Kogarko, L.I., Ni/Co Ratio as an Indicator of Magma Generation in the Mantle, *Geokhimiya,* 1978, pp. 1293–1321.

21. Zhitkov, A.S., Konovalov, Yu.I., and Evlanov, Yu.B., Uranium and Thorium as Indicators of Continental Basaltic Volcanism in the Sea of Japan, *Okeanologiya* (Moscow), 1985, vol. 25, no. 3, pp. 471–476.

22. Troshin, Yu.P., Grebenshchikova, V.I., and Boiko, S.M., *Geokhimiya i petrologiya redkozemel'nykh plyumazitovykh granitov* (The Geochemistry and Petrology of Rare-Earth-bearing Plumasite Granites), Novosibirsk: Nauka, 1983.

23. Zakharov, M.N., Konusova, V.V., and Smirnova, E.V., Rare Earth Elements in the Basaltoids of Omolon Region, *Geol. Geofiz.*, 1984, no. 4, pp. 62–70.

24. *Andean Magmatism: Chemical and Isotopic Constraints*, Harmon, E.S. and Barreiro, B.A., Eds., Nartwich: Shiva Publ., 1984.

25. Hickey, V.R., Roa, H.M., Lopes-Escobar, L., and Frey, F.A., Geochemical Variation in Andean Basaltic and Silicic Lavas from Villarica–Latin Volcanic Chain (39.5° S): An Evolution of Source Heterogeneity, Fractional Crystallization, and Crustal Assimilation, *Contrib. Mineral. Petrol.*, 1989, vol. 103, pp. 161–186.

26. Grove, T.L., Gerlach, D.C., and Sando, T.W., Origin of Calc-Alkaline Series Lavas at Medicine Lake Volcano by Fractionation, Assimilation, and Mixing, *Contrib. Mineral. Petrol.*, 1982, vol. 80, pp. 160–182.

27. *Magmaticheskie gornye porody (osnovnye porody)* (Igneous Rocks: Basic Rocks), Moscow: Nauka, 1985.

28. Cabanis, B. and Leclle, M., Le Diagramme La/10–Y/15–Nb/8 un Outil Pour la Discrimination des Series Volcaniques et la Mise en Evidence des Processus de Melange et/ou de Contamination Crustale, *C.R. Acad. Sci., Ser. II*, vol. 309, pp. 2023–2029.

29. Shervais, J.W., Ti–V Plots and the Petrogenesis of Modern Ophiolitic Lavas, *Earth Planet. Sci. Lett.,* 1982, vol. 59, pp. 101–118.

30. Wood, D.A., The Application of a Th–Hf–Ta Diagram to Problems of Tectonomagmatic Classification and to Establishing the Nature of Crustal Contamination of Basaltic Lavas of the British Tertiary Volcanic Province, *Earth Planet. Sci. Lett.*, 1980, vol. 50, pp. 11–30.

31. Pearce, J.A., Statistical Analysis of Major Element Patterns in Basalts, *J. Petrol.*, 1976, vol. 17, pp. 15–43.

32. Balashov, Yu.A., *Geokhimiya redkozemel'nykh elementov* (The Geochemistry of Rare Earth Elements), Moscow: Nauka, 1976.

33. Ringwood, A.E., *Composition and Petrology of the Earth's Mantle*, New York: McGraw-Hill, 1975. Translated under the title *Sostav i petrologiya mantii Zemli*, Moscow: Nedra, 1981.

34. Condie, K.C. and Baragar, W.R., Rare-Earth Element Distributions in Volcanic Rocks from Archean Greenstone Belts, *Contrib. Mineral. Petrol.*, 1974, vol. 45, pp. 237–246.

35. Gill, J.B., *Orogenic Andesites and Plate Tectonics*, New York, 1981.