堆積学研究, 43号, 69-81, 1996
J. Sed. Soc. Japan, No. 43, 69-81, 1996

TECTONIC SETTING OF THE CRETACEOUS SEDIMENTS IN THE LOWER AMUR REGION, RUSSIAN FAR EAST

Victor P. Nechaev *, Pavel V. Markevich *, Alexander I. Malinovsky *, Anatoly N. Philippov *, Sergei V. Vysotskiy *

Data on heavy minerals from the Valanginian-Cenomanian sedimentary rocks of the Lower Amur region are interpreted on the basis of actuallistic approach with the use of previous study results on heavy mineral assemblages from the modern deposits accumulated in the known plate-tectonic conditions. As a result, the following has been found out; Deposits of the Valanginian-Barremian ensimatic island arc and its adjacent marginal sea, Barremian-Albian active continental margin, and Albian-Cenomanian passive (or transform) continental margin were combined in terranes of the Lower Amur region. Major tectonic processes that resulted in these were large-scale strike-slip movements and accretion processes associated with oblique subduction, and some collisions among the arcs mentioned, continental margins, and rigid blocks of oceanic lithosphere.

Key words : heavy minerals, tectonic setting, early Cretaceous, Lower Amur, Northern Sikhote-Alin, Far East

Introduction

During the last decade, I studied an influence of major-type plate-tectonic settings on heavy-mineral assemblages accumulated in the modern marine and oceanic sediments. On its first stages, the study was carried out in the Pacific Ocean and its marginal seas. As a result, it has been found out that certain heavy-mineral assemblages and quantitative relationships among them could serve as reliable indicators of different geodynamic settings and associated magmatic processes (Nechaev, 1987, 1991 ; Nechaev and Derkachev, 1989, in press ; Nechaev and Isphording, 1993).

The data obtained were proposed to be used for paleotectonic reconstruction. Comparison between modern and ancient heavy-mineral assemblages was expected to be useful especially for the study of Phanerozoic volcanogenic-sedimentary deposits belonging to various tectonic terranes of uncertain origin in many cases. The hopeful subjects for such reconstruction are the Cretaceous sediments which we recently found out in the Lower Amur region, northern Sikhote-Alin foldbelt. Some (graywacke-type) of these deposits were surely accumulated under the influence of different volcanic arcs, while the others, for example, arkosic sediments do not indicate any volcanic contribution.

The study was supported by the Russian Fundamental Science Foundation (Project 95-05-15187 "Reconstruction and Correlation of the Mesozoic Sedimentation History in Different Terranes of Sikhote-Alin") and International Science Foundation (Project RJK000 "Heavy-Mineral, Chemical, and Radiolarian Compositions of Cherts as Indicators of the Late Paleozoic-Mesozoic Evolution in Paleopacific").

Geological Outline

The study area belongs to the Lower Amur terrane by Khanchuk *et al.* (1990) or the Kiselevsk-Monaminsk terrane by Natal'in (1991). The latter was interpreted as an accretionary wedge of the

Received, November 23, 1995 ; Accepted, February 14, 1996
* Far East Geological Institute, Vladivostok 690022, RUSSIA

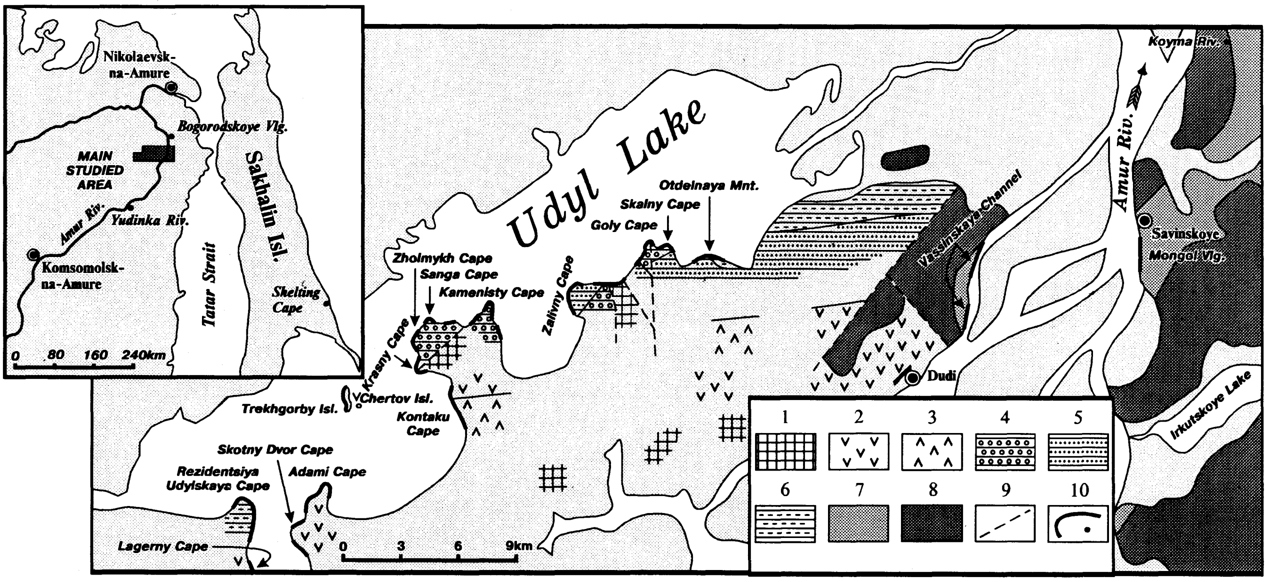

Fig. 1 Geological scheme of the Udyl Lake area and its adjacent territories (in the upper left corner).
1 : Kiselevsky Complex, 2-3 : Udylsky Complex (2-Tuff Formation, 3-Tuff-sedimentary Formation), 4-6 : Terrigenous (graywacke) Complex (4-Mixtite-mudstone Formation, 5-Sandstone Formation, 6-Mudstone Formation), 7 : Terrigenous (arkosic) Complex, 8 : Upper Cretaceous volcanic rocks in the East Sikhote-Alin volcanic belt, 9 : fault, 10 : outcrops studied.

Cretaceous Khingan-Okhotsk accretionary system. The south-eastern part of this terrane consists of the Jurassic-Lower Cretaceous oceanic cherts associated with alkaline basalts and limestones, Aptian-Albian siliceous shales, and Albian-Cenomanian terrigenous deposits (Zyabrev, 1994 ; Khanchuk *et al.*, 1994). In contrast, the north-eastern part (Udyl Lake and adjacent areas on the left bank of Amur River) studied in this paper contains tectonic fragments of volcanic arc (Markevich *et al.*, 1989 ; Philippov *et al.*, in press). We distinguished the following four complexes : 1) Kiselevsky : Valanginian-Barremian, 2) Udylsky : Hauterivian-Albian, 3) Terrigenous (graywacke) : Albian-Cenomanian, 4) Terrigenous (arkosic) : Albian-Cenomanian (Fig. 1).

The Kiselevsky Complex consists of radiolarian chert, within-plate alkaline volcanic rocks and rarely siliceous shale (Fig. 2).

We divided the Udylsky Complex into two parts, namely, the lower Tuff Formation and the upper Tuff-sedimentary Formation. The Tuff Formation is represented by sediments of an island-arc volcaniclastic apron. It consists of sand-size, crystal-vitric, basic tuff interbedded with volcaniclastic turbidites, tuffaceous sandstones and mudstones, and, rarely tuffaceous siliceous shales and basalts. The Tuff-sedimentary Formation consists of clayey and siliceous deposits associated with turbidites and debris flow deposits which were derived from the volcanic rocks of arc origin. This formation was deposited most likely on or near a remnant island arc without volcanism.

The Terrigenous (graywacke) Complex may be divided into three formations. The lower one, namely the Mixtite-mudstone Formation, is composed of the mixed clastic rocks with an irregular distribution of different-size (up to 30 m) clasts and boulders. These are gravity deposits of a wide range from submarine landslides to debris flow. The gravity sediments are associated with mudstones, siliceous mudstones, bottom-current sediments, and rarely, moderately acid tuffs. The clasts are represented by the same rocks such as cherts, basic volcanic rocks, and, rarely, intermediate and acid tuffs, siliciclastic rocks and limestones. The middle part of the complex, namely the Sandstone Formation, consists chiefly of sandstone

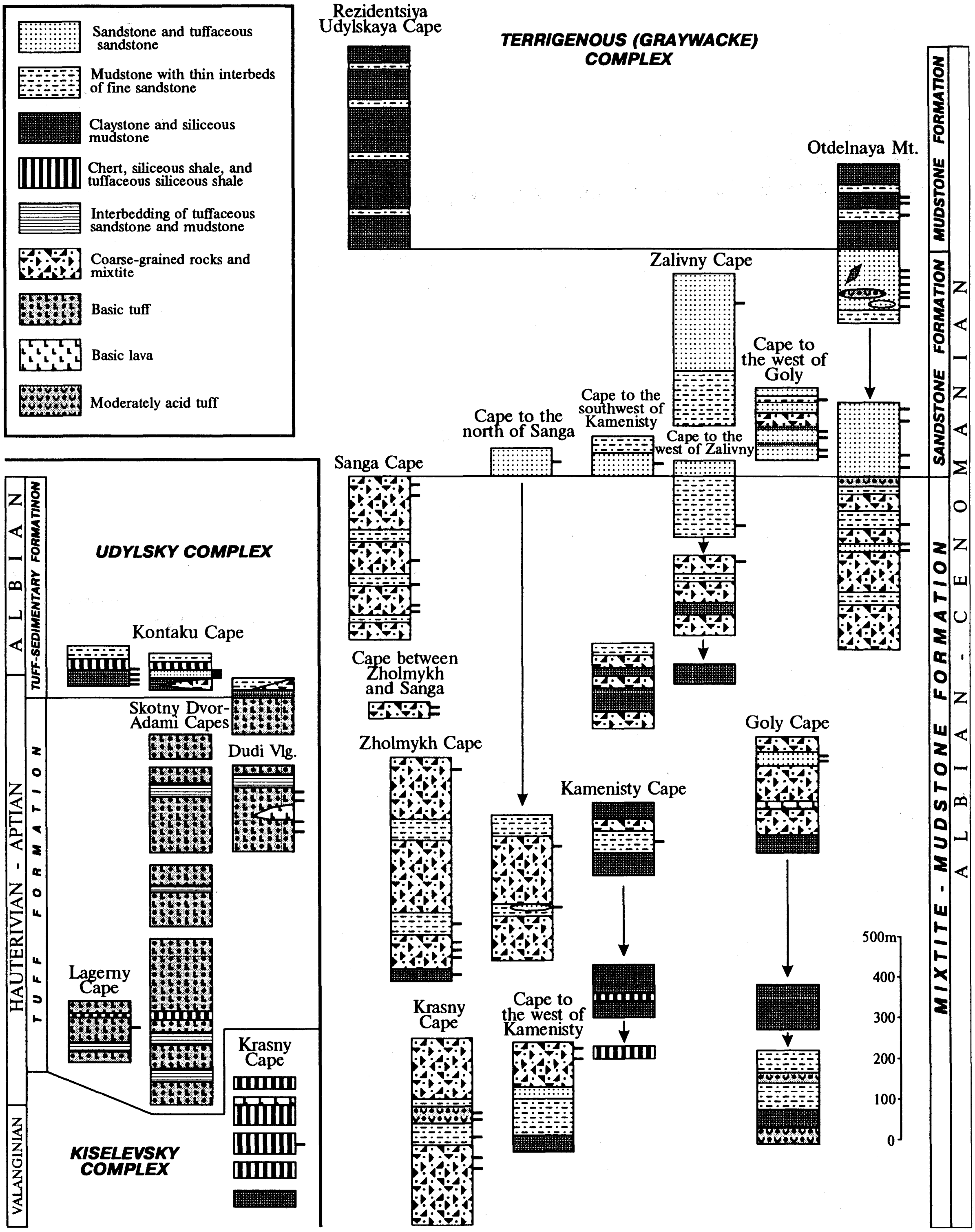

Fig. 2 Lithology and stratigraphy of the Udyl Lake area.
The horizons of studied samples are shown by the bars beside of the columnar sections.

turbidites, rarely associated by mudstones, claystones, mixtites and acidic tuffs. The upper part named as the Mudstone Formation is composed of mudstones interbedded with siltstones and sandstones. The complex is characterised by the sandstone and siltstone of graywacke composition. It was most likely deposited on the inner slope of a trench associated with a volcanic arc.

There also are the Albian-Cenomanian mudstones and sandstones established as the Terrigenous (arkosic) Complex in the Udyl Lake area. This complex differs from the previous ones by well-manifested arkosic composition of its deposits. This completely lacks any volcaniclastic admixture, and seems to be the sediments supplied from the provenance consisting of granitic and metamorphic rocks. Hence, this complex is formed on a continental margin, and does not belong to the Lower Amur terrane.

In addition, the arc volcaniclastic deposits from East Sakhalin (Shelting Cape) are briefly considered in the paper for comparison (Govorov *et al.*, 1993). The sedimentary rocks are represented by tuffaceous mudstones and sandstones of the Rakitinskaya Suite, age of which was suggested previously to be Late Cretaceous (Grannik, 1978). According to our data, tuffaceous mudstones from the coastal outcrops of the Shelting Cape contain the following radiolarians : *Tricolocapsa* aff. *pricarum* Yao, *Tricolocapsa* sp., *Archicapsa pachyderma* (Tan Sin Hok), *Hsuum* sp., that indicate Middle-Late Jurassic age (identified by I.V. Kemkin). K-Ar age of the associated Mg-rich rhyolite is 140 Ma. Therefore, the suite is older than the ascribed Late Cretaceous.

The locations of the study strata, their lithology and sample horizons are shown in Figs. 1 and 2.

Methods

Samples used in this study were collected during the field works by the sedimentological group of the Far East Geological Institute, Russian Academy of Sciences, in 1992-1993. The mineralogical and microprobe analyses were performed conventionally. Rock samples were crushed to the fraction finer than 0.25 mm, and then, washed out by distilled water in order to get the fraction 0.01-0.25 mm. After that, heavy minerals were extracted from the fraction in tribromomethane of 2.90g/cm^3. The heavy minerals were identified using the petrographic microscope. The mineral composition was determined by counting more than 100 grains (more than 250 grains in most cases) for each analysis. Authigenic minerals and lithoclasts were not counted. When necessary, mineral identification was carried out with the help of immersion oils and electron microprobe analyser. All the analyses were averaged in accordance to our methodology to interpret such data.

Interpretation of the mineralogical data was carried out on the basis of actualistic approach and of our previous studies on the modern sediments (Nechaev, 1987, 1991 ; Nechaev and Derkachev, 1989, in press ; Nechaev and Isphording, 1993). In general, the following was our findings: In the sediments of mature passive continental margins, heavy minerals derived from the granitic rocks and associated metamorphic rocks, namely zircon, tourmaline, staurolite and others (GM suite) , predominate over the common volcanogenic minerals like pyroxenes, olivine, and brown-green hornblende (MF suite) as well as minerals derived from basic metamorphic rocks like greenschists and amphibolites being epidote, garnet, blue-green and pale-colored amphiboles (MT suite). The MF suite predominates in sediments of the modern Pacific Ocean, including : 1) spreading zones, where olivine is most abundant ; 2) intraoceanic ridges like the Hawaiian one, where brown Ti-rich clinopyroxene predominates ; 3) volcanic arcs and deep basins inside the ocean and in the marginal seas, where orthopyroxene, green clinopyroxene, and brown-green hornblende predominate. According to our recent study, partly published (Nechaev and Derkachev, in press), interrelationships among the latter three minerals in sediments of volcanic arcs and associated trenches can serve as indicators of different tectonic settings on convergent plate boundaries. So, almost absolute predominance of clinopyroxene is characteristic of the ensimatic island arcs associated with oblique (less than 55°) subduction, like the Izu-Bonin Arc. The orthopyroxene-clinopyroxene assemblage also indicates the ensimatic arcs, but only the arcs associated with normal subduction, like the Mariana Arc. The clinopyroxene-hornblende association are derived from the ensialic arcs situated where the plates convergence at the angle of 40-55°, like the Philippine Arc. Hornblende predominates near active continental margins like the Andean one. All the three minerals are in almost equal abundance in sediments deposited under the influence of common ensialic arcs like the Japan Arc.

Results

The results are shown in Table 1, and the following heavy-mineral assemblages are recognised in the

Table 1 Heavy-mineral analyses (group means, %) of sedimentary rocks from the Lower Amur, northern Sikhote-Alin and Eastern Sakhalin regions.

Location, sample	*N*	*Cr*	*Mt*	*Ilm*	*Lcx*	*Opx*	*Cpx*	*Hb*	*Ep*	*Zr*	*Grn*	*Sph*	*Trm*	*Ap*	*Rt*	*An*
Kiselevsky Complex, J-K_1 Brm																
Krasny Cape	1	0.0	0.5	0.0	0.0	1.0	69.0	16.2	5.6	2.5	4.1	0.0	0.0	1.0	0.0	0.0
Tuff Formation, Udylsky Complex, K_1 Hau-Brm																
Lagerny and Skotny Dvor Capes, Dudi Vlg.	6	0.6	9.1	0.0	0.0	0.7	86.8	1.8	0.1	0.0	0.0	0.8	0.0	0.2	0.0	0.0
Tuff-sedimentary Formation, Udylsky Complex, K_1 Brm-Cen																
Kontaku Cape	12	2.0	25.9	0.0	0.0	1.1	34.5	2.0	23.6	1.4	4.6	1.2	0.0	1.6	0.1	0.0
Mixtite-mudstone Formation, Terrigenous (graywacke) Complex, K_{1-2} Alb-Cen																
Krasny Cape	4	15.0	0.4	14.4	1.5	0.6	6.6	4.2	12.7	33.6	6.2	0.8	0.1	3.7	0.3	0.0
Zholmykh Cape	5	19.1	0.8	1.5	0.8	12.4	15.3	22.3	2.8	6.4	1.0	9.6	0.0	7.4	0.0	0.0
Zholmykh-Sanga Capes	2	6.2	1.0	35.6	0.0	1.4	24.6	5.5	1.4	14.5	4.5	1.7	0.0	3.8	0.0	0.0
Sanga Cape	4	4.8	4.0	0.4	0.1	0.7	36.6	9.0	0.6	28.4	11.9	2.5	0.0	1.2	0.0	0.0
East of Sanga Cape	4	54.1	0.9	0.0	0.3	1.7	31.2	4.0	0.5	4.3	0.5	1.1	0.0	1.4	0.0	0.0
West of Kamenisty Cape	4	47.0	0.3	0.7	0.7	0.0	1.3	21.0	0.6	10.9	3.8	10.9	0.2	2.4	0.1	0.0
Kamenisty Cape	1	94.0	0.0	0.0	1.4	0.0	0.0	1.0	0.0	0.0	0.0	0.9	0.0	2.7	0.0	0.0
East of Zalivny Cape	2	42.8	1.2	0.0	0.0	0.3	1.7	50.6	1.2	1.2	0.2	0.0	0.0	1.0	0.0	0.0
Goly Cape	2	51.1	16.3	1.9	0.0	0.5	24.8	1.6	1.9	1.0	0.2	0.0	0.0	0.8	0.0	0.0
Skalny Cape	3	69.7	2.6	3.4	0.6	0.0	0.3	16.7	2.8	0.5	0.6	2.0	0.0	0.7	0.0	0.0
Formation in average	*31*	*40.4*	*2.7*	*5.8*	*0.5*	*1.8*	*14.2*	*13.6*	*2.4*	*10.1*	*2.9*	*3.0*	*0.0*	*2.5*	*0.0*	*0.0*
Siliciclastic Inclusions:																
Krasny Cape, 93370	1	67.4	1.4	0.0	0.0	1.4	18.4	2.8	5.0	2.8	0.0	0.7	0.0	0.0	0.0	0.0
Krasny Cape, 93374	1	91.8	2.8	0.0	0.0	0.0	2.2	0.3	2.6	0.0	0.3	0.0	0.0	0.0	0.0	0.0
Sandstone Formation, Terrigenous (graywacke) Complex, K_{1-2} Alb-Cen																
East of Sanga Cape	1	2.0	0.0	2.7	0.0	0.7	2.7	2.7	0.0	61.0	22.8	4.0	0.0	1.3	0.0	0.0
East of Kamenisty Cape	1	0.0	9.3	0.0	0.0	0.0	0.0	0.0	0.0	41.9	34.9	0.0	0.0	14.0	0.0	0.0
Zalivny Cape	1	12.2	2.8	0.0	0.0	0.0	0.9	14.1	1.9	50.9	8.5	7.5	0.0	0.9	0.0	0.0
West of Goly Cape	8	73.5	1.3	2.1	1.7	0.8	4.4	5.3	3.9	2.2	0.4	3.3	0.0	0.9	0.0	0.0
Skalny Cape	4	6.7	1.7	5.9	1.3	0.2	38.4	1.9	25.4	11.3	6.7	0.2	0.1	0.2	0.0	0.0
Otdelnaya Mnt.	8	5.5	1.3	2.8	7.5	0.5	56.0	5.5	1.5	12.0	3.1	3.4	0.4	0.4	0.0	0.0
Formation in average	*23*	*16.7*	*2.7*	*2.2*	*1.7*	*0.4*	*17.1*	*4.9*	*5.4*	*29.9*	*12.7*	*3.1*	*0.1*	*2.9*	*0.0*	*0.0*
Mudstone Formation, Terrigenous (graywacke) Complex, K_{1-2} Alb-Cen																
Otdelnaya Mnt.	3	42.9	0.4	2.3	0.2	0.0	2.3	14.4	16.1	2.8	11.1	5.7	0.2	1.5	0.0	0.0
Terrigenous (arkosic) Complex, K_{1-2} Alb-Cen																
Vassinskaya Channel I	7	0.9	0.9	0.2	2.0	0.0	1.4	1.4	0.7	12.8	2.8	2.7	0.1	73.8	0.1	0.0
Yudinka River I	3	0.1	0.4	0.5	5.3	0.0	0.8	1.7	0.6	37.7	5.3	0.4	0.4	46.5	0.3	0.0
Koyma River	8	5.0	0.5	4.0	4.6	0.0	0.2	15.2	0.1	60.6	5.7	0.1	0.4	2.6	0.6	0.1
Vassinskaya channel II	7	2.8	1.4	1.4	4.3	1.4	4.1	1.7	0.5	43.7	32.5	0.1	0.6	4.3	0.8	0.3
Yudinka River II	15	1.1	0.6	2.9	9.5	0.1	0.3	5.4	5.8	66.3	2.5	0.8	1.2	3.0	0.4	0.1
Mongol River	14	2.4	0.6	7.2	10.3	0.1	3.3	5.5	0.9	53.2	11.8	0.4	0.6	3.1	0.8	0.1
Eastern Sakhalin, J_2-K_1 B rm																
Shelting Cape	2	0.0	28.3	0.0	0.0	1.8	64.1	5.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

N:number of analyses, *Cr*:chromite, *Ilm*:ilmenite, *Mt*:magnetite, *Lcx*:leucoxene, *Opx*: orthopyroxene, *Cpx*:green clinopyroxene, *Hb*:brown-green hornblende, *Ep*:epidote, *Zr*:zircon, *Grn*:garnet, *Sph*:sphene, *Trm*:tourmaline, *Ap*:apatite, *Rt*:rutile, *An*:anatase.

study complexes.

In the pelagic sediments of the Kiselevsky Complex, where we have only one representative analysis because of a low total content of heavy minerals in siliceous rocks, green clinopyroxene is predominant. This mineral is associated with other common representatives of arc volcaniclastics such as brown-green hornblende, orthopyroxene and magnetite as well as more rare minerals such as zircon, garnet, apatite and epidote derived from granitic and metamorphic rocks.

In the Udylsky Complex, minerals of the same associations are represented, but their relationship markedly differs between the formations in the complex. The Tuff Formation is characterised by the primitive mineral composition : it is absolutely predominated by green clinopyroxene, magnetite, brown-green hornblende and orthopyroxene, indicating ensimatic island arc volcanics in origin. These minerals are mixed with epidote, garnet, zircon, apatite, sphene and rutile in the Tuff-sedimentary Formation. A relative predominance of epidote in this admixture indicates that some of the source rocks for the sediments were most likely metamorphosed volcanic rocks which might underlie the arc volcanics. Ophiolitic intrusive rocks indicated by a small amount of chromite are also supposed in the provenance.

In the Terrigenous (graywacke) Complex, we can distinguish several groups of heavy mineral assemblages which seem to have different origins.

In the Mixtite-mudstone Formation from the Kamenisty, Skalny, Goly and Sanga Capes, as well as in the Sandstone Formation from the location north to the Goly Cape, we found high content of chromite (50-94%) , sometimes associated with clinopyroxene (up to 37%). It suggests that the major source of the heavy minerals from these rocks was ophiolites. This suggestion is supported by the abundance of chromite in siliciclastic inclusions (clasts) of the Mixtite-mudstone Formation, since siliceous rocks are a common constituent of the ophiolitic complexes. Chromite-rich siliciclastic sediments occur only as clasts in the Mixtite-mudstone Formation. This fact evidences that the major erosion of ophiolite and siliceous rocks took place before the deposition of the Mixtite-mudstone Formation, that is, in the pre- or early Albian time. Perhaps, it was the time of an oceanic-type earth's crust thrusting.

Clastic rocks of the Mixtite-mudstone Formation from the Krasny Cape, and those of the Sandstone Formation from the east of the Sanga Cape, southeast of the Kamenisty Cape and the Zalivny Cape are distinguished by the high contents of zircon and garnet. These rocks were undoubtedly deposited under a significant influence of granitic and acidic metamorphic source rocks.

The Mixtite-mudstone Formation from the Zholmykh Cape, Sanga Cape, and a small cape between them, as well as the Sandstone Formation from the Skalny Cape and Otdelnaya Mount are relatively rich in pyroxenes, amphiboles and epidote, and poor in chromite. These rocks were likely derived from volcanic rocks and metamorphosed volcanic rocks.

As mentioned above, the provenance of the Terrigenous (graywacke) Complex was heterogeneous, and the complex seems to be formed most likely as an accretionary wedge of which sediments were derived from oceanic, continental and/or volcanic arc sources. In addition, the deposition of sediments in the complex was accompanied by volcanism indicated by the interbeds of acidic tuff. A role of the volcanic source was decreasing in time, since the total contents of pyroxene and hornblende (MF suite) decrease from the Mixtite-mudstone to Sandstone, and then, to Mudstone Formations ; 30, 22, and 17% in average, respectively.

In the Terrigenous (arkosic) Complex, zircon, garnet and apatite are dominant. They are associated with a small amount of hornblende, chromite, magnetite, ilmenite, rutile, sphene, leucoxene, tourmaline and pyroxene. This assemblage is typical for the most of the Cretaceous deposits in the Sikhote-Alin accumulated before the formation of East Sikhote-Alin volcanic belt (Markevich *et al.*, 1987, 1989). These minerals were certainly derived from a mature continental margin lacking of any volcanic activity. It is important for the following discussion that there is a small, but significant difference between the heavy-mineral assemblage predominating in the Terrigenous (arkosic) Complex and the similar sialic mineral assemblage in the Kiselevsky and Terrigenous (graywacke) Complexes :

the rutile content in the latter two complexes does not exceed 0.1%, whereas that in the former is 0.1-0.8 % (Table 1). Therefore, the contribution rate of the continental margin as provenance were different between both groups.

Discussion

The heavy-mineral assemblages described above suggest that the four rock complexes in the Lower Amur region formed under the influence of the five different-type sources : two volcanic arcs (Valanginian-Barremian and Albian-Cenomanian in age), two continental margins (conventionally named as "Northern" and "Southern") and an ophiolitic complex.

The Valanginian-Barremian volcanic arc was chiefly responsible for the primitive heavy-mineral assemblages in the Kiselevsky and Udylsky Complexes, especially in the Hauterivian-Barremian Tuff Formation. Predominance of green clinopyroxene in the formation is characteristic of arc volcaniclastics deposited on the boundaries with a small angle of plate convergence (Fig. 3, Opx-Hb-Cpx diagram). This means a direct influence of the arc like the Izu-Bonin one (Nechaev and Derkachev, in press).

In the Kiselevsky Complex and in the Tuff-sedimentary Formation of the Udylsky Complex, heavy-mineral suites are more complicated. In comparison to the Tuff Formation, they are more abundant in epidote derived likely from metamorphosed volcanic rocks, as well as in zircon, garnet and other minerals derived from sialic rocks, although clinopyroxene keeps to be a major heavy mineral (Table 1).

On the basis of the interrelation among MF, MT, and GM suites (Fig. 3), the heavy-mineral assemblage of the Kiselevsky Complex is similar to that in modern sediments of marginal seas in the Pacific region, where the arc volcaniclastics (from the ensimatic arc in this case) is mixed with terrigenous material from a continental margin. The Tuff-sedimentary Formation was likely deposited on the same island arc when the associated subduction was blocked by an oceanic rise, and volcanic activity on the arc was ceased. The Yap Arc on the southeastern margin of the Philippine Sea can serve as an actual example of such a setting. Modern sediments of the Yap Arc have a good similarity as shown in Fig. 3, MF-MT-GM diagram. During the deposition of the Tuff-sedimentary Formation (Barremian-Aptian), the supposed remnant arc was likely situated quite close to the "Southern" continental margin, so that the sialic minerals such as rutile, reached the site of sedimentation.

The two samples of the Middle Jurassic to Barremian tuffaceous sandstones from the Eastern Sakhalin are very similar in mineralogy to our samples from the Tuff Formation of the Udylsky Complex (Table 1, Fig. 3). Perhaps, in both cases, we studied sediments of the same arc that was crushed and pulled apart as a result of complex plate-tectonic interactions. The first event of those might be a collision between the arc and an oceanic rise in Barremian age.

The Albian-Cenomanian volcanic arc includes its accretionary wedge, the fragments of the Valanginian-Barremian arc, the "Northern" continental margin, and ophiolites. They served as heterogeneous sources of heavy minerals in the Terrigenous (graywacke) Complex deposited most likely on the inner trench slope. The low ratio of Opx/(Cpx + Hb) in the complex correspond to the ensialic arc and/or active continental margin associated with a low angle of plate convergence (Fig. 3).

An influence of the Valanginian-Barremian ensimatic arc is indicated by the high (more than 80%) ratios of Cpx/(Opx + Hb) and low content of chromite in some sediments in the complex, for example, in the Mixtite-mudstone Formation at the Sanga Cape and the location between the Zholmykh and Sanga Capes, as well as in most rocks of the Sandstone Formation (Fig. 3).

The sialic material of the "Northern" continental margin is represented by the suite of zircon, garnet, sphene, apatite and tourmaline, sometimes associated with a very low content of rutile (Fig. 3). The Mixtite-mudstone Formation at the Krasny Cape, and the Sandstone Formation at Zalivny Cape and the locations to the east of the Sanga and Kamenisty Capes are especially rich in these minerals. These sediments are suggested to have been deposited in

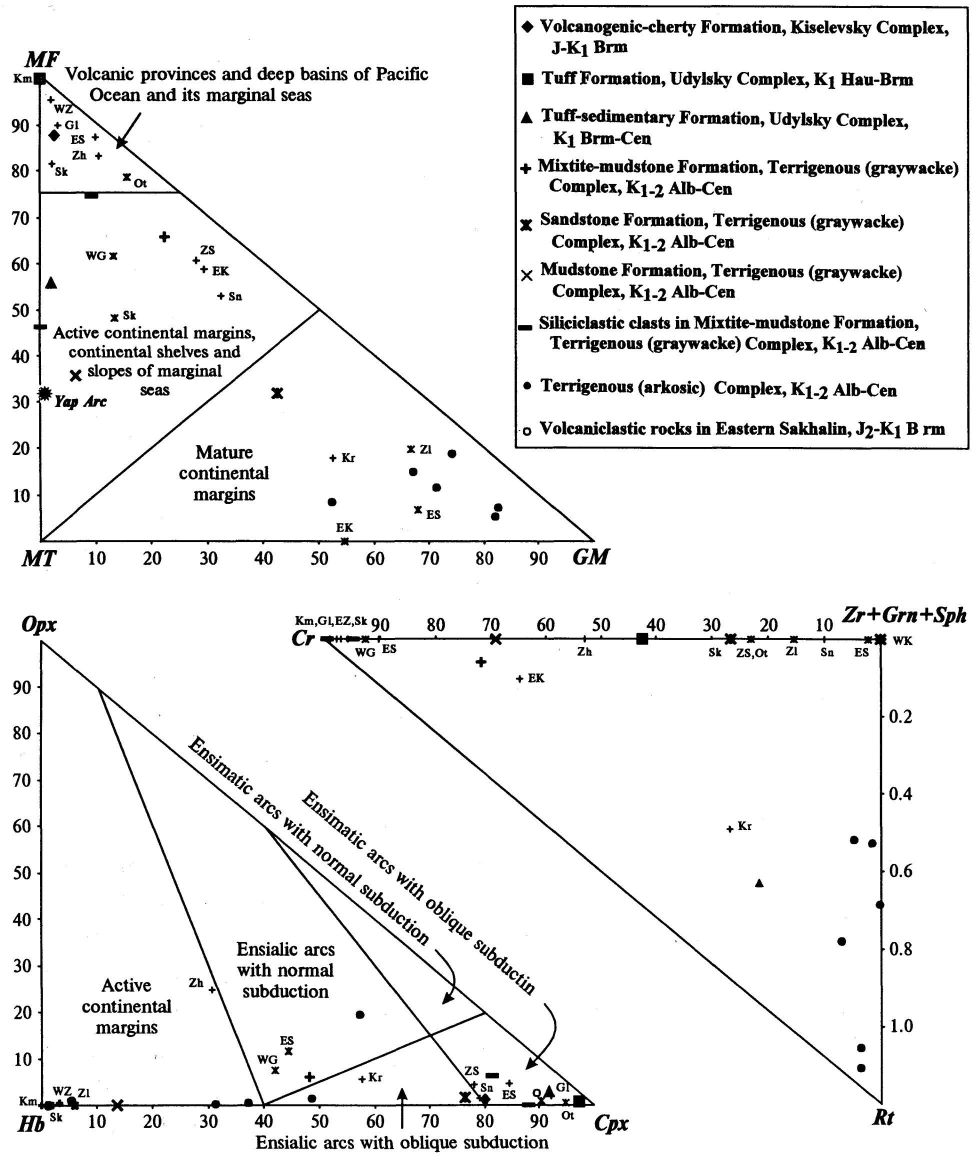

Fig. 3 Comparison of heavy-mineral composition among the Cretaceous deposits in the Udyl Lake area and Eastern Sakhalin on the discrimination diagrams of plate-tectonic settings proposed by Nechaev (1991), Nechaev and Isphording (1993), and Nechaev and Derkachev (in press).

MF : total of clino-and orthopyroxenes and brown-green hornblende

MT : total of epidote, garnet , pale-colored and blue-green amphiboles

GM : total of zircon, tourmaline, staurolite, kyanite, sillimatnite and andalusite

Other abbreviations are same as in Table 1. Large symbols indicate the averages of the each formation, while the small ones indicate group means for the separate sections (only for the Mixtite-mudstone and Sandstone Formations of the Terrigenous (graywacke) Complex :

Km-Kamenisty Cape ; EZ-small cape to the east of Zalivny Cape ; Gl-Goly Cape, ES-small cape to the east of Sanga Cape, Zh-Zholmykh Cape, Sk-Skalny Cape, WG-small cape to the west of Goly Cape, ZS-small cape between Zholmykh and Sanga Capes, WK-small cape to the west of Kamenisty Cape, EK-small cape to the east of Kamenisty Cape ; Sn-Sanga Cape, Kr-Krasny Cape, Zl-Zalivny Cape ; Ot-Otdelnaya Mount.

the close vicinity to some elevations of the arc sialic basement.

Chromite, a reliable indicator of the ophiolitic contribution to sediments, is abundant in the Terrigenous (graywacke) Complex. There, it is sometimes associated with clinopyroxene, epidote and hornblende. The high contents of chromite and clinopyroxene in the siliciclastic rocks from the inclusions of the Mixtite-mudstone Formation are especially indicative.

The electron microprobe analyses for the clinopyroxenes and chromites show that they were derived from arc volcanic rocks, ophiolites, and alkaline magmatic rocks (Fig. 4). The alkaline magmatic rocks are abundant in the within-plate setting. Thus, we supposed that ophiolitic and alkalin rocks were exposed to erosion by deep thrusting and consequent accretion to continent of the marginal-sea

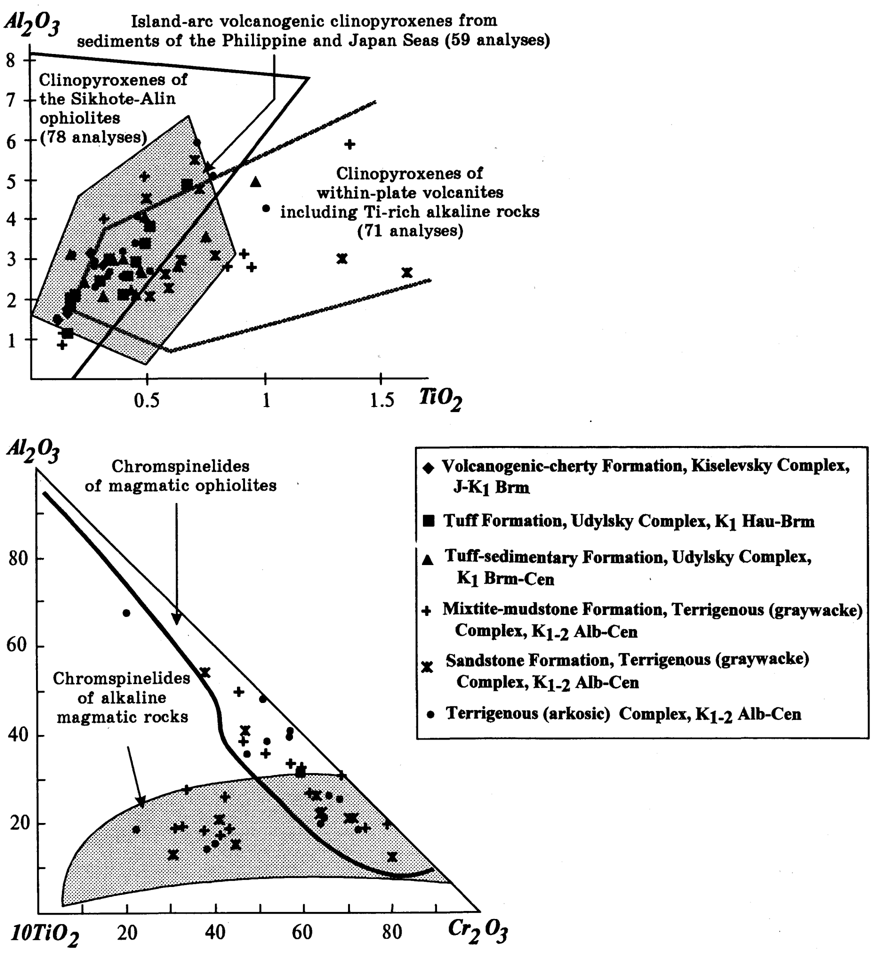

Fig. 4 Discrimination diagrams showing chemical compositions of clinopyroxene and chromite from the Cretaceous sediments of the Udyl Lake area in comparison with those from different magmatic complexes. The fields on the upper diagram were outlined using the unpublished data by A.I. Khanchuk and from the literature by Bougault *et al.* (1982), Dick *et al.* (1980), Dmitriev (1980), Fodor and Klaus (1975), Fodor and Rosendahl (1980), Fodor *et al.* (1980), Mattey and Muir (1980), Mattey *et al.* (1981), Nechaev (1991), Ridley *et al.* (1974), Sharaskin (1982), Thompson and Humphris (1980), Vysotskiy and Okovity (1990), and Zakariadze *et al.* (1981). The lower diagram is based on the work by Shcheka and Vrzhosek (1983).

earth's crust including blocks of a rigid lithosphere (like that in the northwestern Philippine Sea) and trapped between the "Northern" continental margin and the fragment of ensimatic island arc. The abundance of chromite in the siliciclastic inclusions from the Mixtite-mudstone Formation suggests that the ophiolites were accreted to the "Northern" continental margin during the deposition of this formation, that is, in the Albian-Cenomanian time. The siliciclastic rocks themselves were likely deposited by erosion of the marginal sea thrust-faulted crust. A volcanic activity on the Albian-Cenomanian arc was probably resulted from its tectonic collision with the Valanginian-Barremian remnant arc discussed above. In this case, the clinopyroxene-rich rocks of the Mixtite-mudstone Formation at the Sanga Cape and the location between the Sanga and Zholmykh Capes may serve as indicators of this event, and be considered as the uppermost horizons of the formation.

The "Southern" continental margin controlled the heavy-mineral assemblages in the sandstones of Terrigenous (arkosic) Complex. The major components of the assemblages are zircon, garnet, tourmaline, sphene, apatite and rutile. They indicate a non-volcanic provenance composed of mature continental earth's crust (Fig. 3). A transform plate boundary without any volcanism may not be excluded as well. The Terrigenous (arkosic) Complex is characterised by the constant presence of rutile and low content of chromite (Table 1, Fig. 3). This property enable to distinguish it from all other complexes studied. Therefore, the "Southern" continental margin might be far away from the depositional sites of the Kiselevsky, Udylsky and Terrigenous (graywacke) complexes. The only one exception is the Tuff-sedimentary Formation in the Udylsky Complex. The clastic materials from the "Southern" continental margin might have reached its depositional site in a small amount. The tectonic amalgamation of the Terrigenous (arkosic) Complex to the other complexes occurred in the post-Cenomanian time.

As a result, we can propose the following scheme of the Cretaceous tectonic evolution in the Lower Amur region (Fig. 5).

For the Valanginian-Barremian time, we reconstructed a convergent plate boundary : the "Northern"

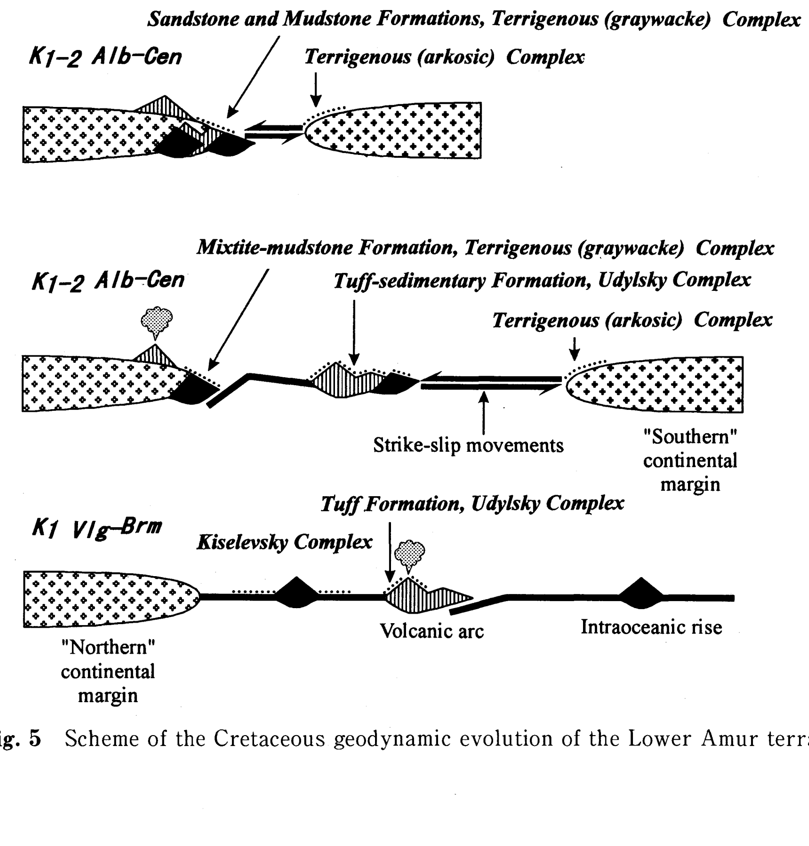

Fig. 5 Scheme of the Cretaceous geodynamic evolution of the Lower Amur terrane.

continental margin with marginal sea and ensimatic island arc. This geodynamic system is indicated by the heterogeneous heavy-mineral assemblage of the Kiselevsky Complex that contains clastic material derived from volcanic-arc and continental margin, and the primitive volcanogenic assemblage of the Tuff Formation in the Udylsky Complex and of volcanic sediments in the Eastern Sakhalin. In the Barremian, this system was stopped due to the blocking of subduction by collision of a large oceanic rise. Ophiolites of this rise supplied chromite to the Tuff-sedimentary Formation of the Udylsky Complex. As a reaction of this collision, a new subduction was resumed close to the "Northern" continental margin. The calcalkaline volcanism began consequently on the continental margin in the Albian-Cenomanian time. The marginal-sea lithosphere that had not cooled enough, was subducted with some difficulties, because rigid blocks of the marginal-sea crust (ophiolites and alkaline magmatic rocks) were accreted to the continental margin. This situation might cause many strong earthquakes, and numerous mass movements such as slumping and olistostrome took place, resulting in the Mixtite-mudstone Formation.

This geodynamic system was unstable considerably, and, consequently, did not continue so long (less than 20 Ma). It was likely stopped by the collision of the remnant volcanic arc to the "Northern" continental margin. After that, the plate convergence was impossible in the region. This phenomenon may be due to either the lack of subductable lithosphere or the change of plate motion.

Considering the scheme in Fig. 5, one should take into account that the Jurassic-Middle Cretaceous plate convergence had a significant strike-slip component. The Cpx-Opx-Hb interrelation of the deposits in all the volcanogenic formations studied indicate that the angle of plate convergence was less than 55°. This angle became much less than 40° in the post-Cenomanian time, and the convergence stopped. The motion between the "Northern" and "Southern" continental margins might change into a strike-slip motion.

Conclusive remarks

The scheme mentioned above and shown in Fig. 5 is concordant in principle with the regional paleotectonic reconstruction for the same time by Borukayev and Natal'in (1994), Rozhdestvensky (1993), Kiminami *et al.* (1992), and Natal'in (1993). Our study has found out the details that could not be seen by the other conventional methods. For example, in the reconstruction by Natal'in (1991, 1993), an accretionary wedge of the Kiselevsk-Monaminsk Terrane formed merely as a result of the collision between the Khingan-Okhotsk active continental margin and the Sikhote-Alin fold belt in Albian-Cenomanian age. We have been able to elcidate a more complex history, that is, the interaction among two volcanic arcs different in age and origin, two continental margins, and some oceanic rises, as discussed before. On the other hand, our data are not enough for the general correlation among all the major events during the Cretaceous in the Far East. So, we offer our methodology to researchers for studying the other key areas in this region.

The authors are indebted to Valentina I. Tikhonova, Polina D. Gasanova and Valery I. Sapin for the mineralogical and microprobe analyses which they performed. Irina V. Smirnova who prepared the samples is also thanked.

This paper was read at the workshop titled "Sandstone Petrology in Relation to Tectoncs and Paleoenvironments" in the anual meeting of the Sedimentological Society of Japan held at Shinshu University, Matsumoto, Novemver 23-25, 1995.

REFERENCES

Borukayev, Ch.B., Natal'in, B.A., 1994, Accretionary tectonics of the southern Russian Far East. *Geologiya i Geofisika*, 35, 89-93. (in Russian)

Bougault, H., Maury, R.C., El Azzoizi, M., Joron, J.L., Cotten, J. and Treuil, M., 1982, Tholeiites. basaltic andesites, and andesites from Leg 60 sites : geochemistry, mineralogy, and low partition coefficient elements. *In* : D.M. Hussong, S. Uyeda *et al.*, *Init. Rep. Deep-Sea Drill. Proj.*, 60.

657-678.

Dick, H.J.B., March, N.G., and Bullen, T.D., 1980, Deep Sea Drilling Project Leg 58 abyssal basalts from the Shikoku Basin : their petrology and major-element geochemistry. *In* : G. deV. Klein, K. Kobayashi *et al.*, *Init. Rep. Deep-Sea Drill. Proj.*, **58**, 843-872.

Dmitriev, Y.I., 1980, Basalts from the East Pacific Rise near 9oN drilled on DSDP Leg 54 compared with marginal-basin and ocean-island basalts. *In* : B.R. Rosendahl, R. Hekinian *et al.*, *Init. Rep. Deep-Sea Drill. Proj.*, **54**, 695-704.

Fodor, R.V. and Klaus, K., 1975, Contributions to the mineral chemistry of Hawaiian rocks. IV. Pyroxenes in rocks from Haleakala and West Volcanoes, Maui, Hawaii. *Contrib. Mineral. Petrol.*, **50**, 173-195.

Fodor, R.V. and Rosendahl, B.R., 1980, Petrology of basalts dredged from the central axis of the Galapagos Spreading Center. *In* : B.R. Rosendahl, R. Hekinian *et al.*, *Init. Rep. Deep-Sea Drill. Proj.*, **54**, 751-754.

Fodor, R.V., Berkley, J.L., Keil, K., Hustler, J.W., Ma, M.-S., and Shmitt, R.A., 1980, Petrology of basalt drilled from the Galapagos Spreading Center, DSDP Leg 54. *In* : B.R. Rosendahl, R. Hekinian *et al.*, *Init. Rep. Deep-Sea Drill. Proj.*, **54**, 737-750.

Govorov, G.I., Vysotskiy, S.V., Boyko, S.A., 1993, The first finding of boninite on the Sakhalin Island. *Doklady AN Rossii*, **331**, 709-712. (in Russian)

Grannik, V.M., 1978, *The Upper Cretaceous sedimentaryformations of the East Sakhlin mounts.* Moscow, Izd. "Nauka", 163 p. (in Russian)

Khanchuk, A.I., Golozubov, V.V., Kemkin, I.V. and others, 1990, Pre-Upper Cretaceous structural-rock complexes of the Sikhote-Alin fold system. *In* : *Tektonika I Metallogeniya Severo-Vostoka SSSR* (abstract book), 232-234. (in Russian).

Khanchuk, A.I., Ognyanov, N.V., Popova, I.M., Philippov, A.N., 1994, New data on the Early Cretaceous deposits of the Lower Priamurye. *Doklady AN Rossii*, **338**, 666-671. (in Russian).

Kiminami, K., Niida K., Ando, H., Kito, N., Iwata, K., Miyashita, S., Tajika, J. Sakakibara M., 1992, Cretaceous-Paleogene arc-trench systems in Hokkaido. *In* : M. Adachi and K. Suzuki (Eds.), *Paleozoic and Mesozoic terranes : basement of the Japanese Island Arcs.* 29th IGC Field Trip Guidebook. Nagoya Univ., **A01** : 1-43.

Markevich P.V., Malinovsky, A.I., Mikhailik, E.V., Philippov, A.N., Chetyrbotsky, A.N., Kitaev, I.V., 1989, Terrigenous rocks. *In* : *Tikhookeanskaya okraina Azii, Geology*. Moscow, Izd. "Nauka", 106-132 . (in Russian)

Markevich P.V., Philippov, A.N., Malinovsky, A.I., Mikhailik, E.V., Kitaev, I.V., Tikhonova, V.I., Trushkova, V.I., 1987, The Phanerozoic geosynclinal sedimentation of Sikhote-Alin and Koryak-Kamchatka region. *In* : *Geosynclinalnoye osadkonakopleniye na granitse continent-ocean.* Moscow, Izd. "Nauka", 10-134. (in Russian)

Mattey, D.P. and Muir, I.D., 1980, Geochemistry and mineralogy of basalts from the Galapagos Spreading Center, DSDP Leg 54. *In* : B.R. Rosendahl, R. Hekinian *et al.*, *Init. Rep. Deep-Sea Drill. Proj.*, **54**, 755-772.

Mattey, D.P., March, N.G., and Tarney, J., 1981, The geochemistry, mineralogy and petrology of basalts from the West Philippine and Parece Vela Basins and from the Palau-Kyushu and West Mariana Ridges, Deep-Sea Drilling Project Leg 59. *In* : L. Kroenke, R. Scott *et al.*, *Init. Rep. Deep-Sea Drill. Proj.*, **59**, 753-800.

Natal'in, B.A., 1991, Mesozoic accretionary and collisional tectonics of the southern Far East of the USSR. *Pacific Geology*, **5**, 3-23. (In Russian)

Natal'in B., 1993, History and modes of Mesozoic accretion in Southeastern Russia. *The Island Arc*, **2**, 15-34.

Nechaev, V.P., 1987, The modern geosynclinal sedimentation and volcanism of the Philippine Sea. *In* : *Geosynclinalnoye osadkonakopleniye na granitse continent-ocean.* Moscow, Izd. "Nauka", 135-167. (in Russian)

Nechaev, V.P., 1991, Evolution of the Philippine and Japan Seas from the clastic sediment record. *Marine Geology*, **97**, 167-190.

Nechaev, V.P. and Derkachev, A.N., 1989, Particulars of sedimentation. *In* : *Tikhookeanskaya okraina Azii. Geology*. Moscow, Izd. "Nauka", 50-66. (in Russian)

Nechaev, V.P., Derkachev, A.N., (in press), Heavy-mineral assemblages in Quaternary sediments of the Philippine Sea as indicators of subduction/collision-related tectonics. *In* : S.A. Shcheka and H. Tokuyama (Eds.), *Geology and Geophysics of the Philippine Sea Floor*. Terra Publish Co., Tokyo, Japan.

Nechaev, V.P. and Isphording, W.C., 1993, Heavy-mineral assemblages of continental margins as indicators of plate-tectonic environments. *J. Sed. Petrology*, **63**, 1110-1117.

Ridley, W.J., Rhodes, J.M., Reid, A.M., Jakes, P., and Bass, M.N., 1974, Basalts from Leg 6 of the Deep Sea Drill. Project. *J. Petrol.*, **15**, 140-159.

Rozhdestvensky, V.S., 1993, Geodynamic evolution of the Hokkaido-Sakhalin fold system. *Pacific Geology*, **2**, 76-88. (in Russian)

Sharaskin, A.Y., 1982, Petrography and geochemistry of basement rocks from five Leg 60 sites. *In* : D.M. Hussong, S. Uyeda *et al., Init. Rep. Deep-Sea Drill. Proj.*, **60**, 647-656.

Shcheka, S.A., Vrzhosek, A.A., 1983, Ultrabasic volcanism of the Pacific belt and questions on systematics of meymechites and comatiites. *Vulkanologiya I Seismologiya*, 3-16.

Thompson, R.N. and Humphris, S.E., 1980, Silicate mineralogy of basalts from the East Pacific Rise, OCP Ridge, and Siqueiros Fracture Zone : Deep Sea Driliing Project, Leg 54. *In* : B.R. Rosendahl, R. Hekinian *et al., Init. Rep. Deep-Sea Drill. Proj.*, **54**, 651-670.

Vysotskiy, S.V. and Okovity, V.N., 1990, Ophiolites of the northern Primorye : petrology of the hyperbasite-gabbro association. *Pacific Geology*, **5**, 76-86. (in Russian)

Zakariadze, G.S., Dmitriev, L.V., Sobolev, A.V., and Suschevskaya, N.M., 1981, Petrology of basalts of holes 447A, 449 and 450, South Philippine Sea transect : Deep-Sea Drilling Project Leg 59. *In* : L. Kroenke, R. Scott *et al., Init. Rep. Deep-Sea Drill. Proj.*, **59**, 669-680.

Zyabrev, S.V., 1994, The Early Cretaceous cherts of the Kiselevsk-Monaminsk terrane-the earliest oceanic deposits in the structure of the southern Russian Far East. *Pacific Geology*, **6**, 74-82. (in Russian)

ロシア極東下部アムール地域の白亜紀堆積物のテクトニック・セッティング

V. P. Nechaev・P. V. Markevich・A. I. Malinovsky・A. N. Philippov・S. V. Vysotskiy

既知のプレートテクトニクス場における現世の堆積物中の重鉱物組成についてのこれまでの研究成果にもとづく現在主義的なアプローチを基に，下部アムール地域のバランギニアンからセノマニアンの堆積岩の重鉱物についてのデータを解釈した。その結果として以下のことが判明した。バランギニアンからオーテリビアンのシマ質の火山弧とその縁海の，バレミアンからアルビアンの活動的な大陸縁辺の，およびアルビアンからセノマニアンの非活動的な大陸縁辺（またはトランスフォーム境界）の堆積物が下部アムール地域の諸テレーンに結合されていた。それらをもたらした主要なテクトニクスは，斜め沈み込みに伴った走向移動運動と付加作用，および，島弧・大陸縁辺・海洋リソスフェアの硬いブロック間の衝突作用であった。