Chapter 31

THE USE OF HEAVY MINERALS IN DETERMINING THE PROVENANCE AND TECTONIC EVOLUTION OF MESOZOIC AND CAENOZOIC SEDIMENTARY BASINS IN THE CONTINENT-PACIFIC OCEAN TRANSITION ZONE: EXAMPLES FROM SIKHOTE-ALIN AND KORYAK-KAMCHATKA REGIONS (RUSSIAN FAR EAST) AND WESTERN PACIFIC

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ABSTRACT

This paper documents the achievements of Russian sedimentologists and mineralogists who have used heavy minerals to reconstruct the provenance and source lithologies of Mesozoic-Caenozoic sedimentary complexes of the Far East and the western Pacific Ocean, and identify their plate tectonic settings. We provide a review of publications, written mostly in Russian, which have not been available or intelligible to non-Russian speakers. Investigations concentrated mainly on the sedimentary and volcano–sedimentary rocks of the Sikhote-Alin fold belt and Koryak-Kamchatka region, but they also included the Pengina Bay and the Vanuatu Trench in the Pacific Ocean.

Caenozoic sediment samples were collected during marine geological expeditions and analysed using traditional microscopy of detrital minerals, bulk sediment chemistry, and electron microprobe analysis. Distinctive heavy mineral associations have been recognised that indicated their deposition in particular plate tectonic settings. Geochemical analysis of individual heavy minerals has revealed their source lithologies in a plate tectonic context.

The Sikhote-Alin sediments were derived from the continental Siberian and Chinese cratons, complemented—at the beginning and the close of the Phanerozoic—by minor input from contemporary oceanic fragments, including volcanics. In the Koryak-Kamchatka region, forearc

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basins were fed almost entirely by intermediate and basic rocks amongst which the products of island arc volcanism played a dominant role throughout the Phanerozoic. The principal source of detrital heavy minerals of the Middle Eocene-Pleistocene deep-sea sediments of the Vanuatu Trench was the tholeiitic basalts of the Vanuatu island arc with limited addition from ocean-floor basalts. Only insignificant amounts of terrigenous material reached the depositional area from the Australian continent.

Keywords: heavy mineral associations; Sikhote-Alin; Koryak-Kamchatka Region; plate tectonic settings

1. INTRODUCTION

The aim of this contribution is to provide a brief, informative summary of the achievements of Russian sedimentologists and mineralogists who used heavy mineral analysis in the study of Mesozoic-Caenozoic sedimentary and volcano–sedimentary successions in the Russian Far East and in some parts of the western Pacific Ocean. A review of previous publications, published mostly in Russian that have not been available or intelligible to non-Russian speakers, is presented.

During the last twenty years our group's research focused on the Mesozoic and Caenozoic evolution of the transitional zone between East Asia and the Pacific Ocean. The foci of main interest were the Sikhote-Alin fold belt, the Koryak-Kamchatka region (P.V. Markevich and A.I. Malinovsky) including the Pengina Bay area (M.I. Tuchkova, V.N. Grigoryev, S.D. Sokolov, and P.V. Markevich) and certain areas of the western Pacific (A.I. Malinovsky) (Fig. 1).

Heavy mineral analysis proved a powerful tool in the study of Caenozoic oceanic and marginal sea floor sediments in the Pacific and Indian Oceans, surveyed during numerous marine geological expeditions (Nechaev, 1991; Nechaev and Isphording, 1993; Nechaev et al., 1996), and has achieved the characterisation of different types of environments. Results also served as a reference database for the study of other older settings.

Several hundred samples were obtained from the Sikhote-Alin area between 1980 and 2000. The Olyutorsky Terrane was sampled between 1978 and 1986 (from the Northern Province 277 and Southern Province 118 samples were collected). In 1992–1993, sampling was extended to the Udyl area (189 samples), and between 1997 and 2002 to the Kema Terrane (from the Kema fragment 103, Sovgavansky 62, and Vysokogorsky 55 samples were taken). From the Vanuatu trench, 77 samples were collected in 1988, while between 2000 and 2004, $\sim$100 samples were taken from the Penzhina area. Details of analytical data can be obtained from the authors on request, and data published in English can be found in Nechaev (1991); Nechaev and Isphording (1993); and Nechaev et al. (1996).

Preparation for heavy mineral analysis included conventional crushing (up to 0.25 mm), sieving, washing off the $<$0.01-mm-size fractions with distilled water, followed by drying and heavy liquid separation. Around 50–100 g dry samples were used from which two size fractions, viz. 0.01–0.10 mm and 0.10–0.25 mm, were retained for the heavy mineral separation, using bromoform (density 2.85). Heavy mineral compositions were studied under the polarising microscope in immersion oil

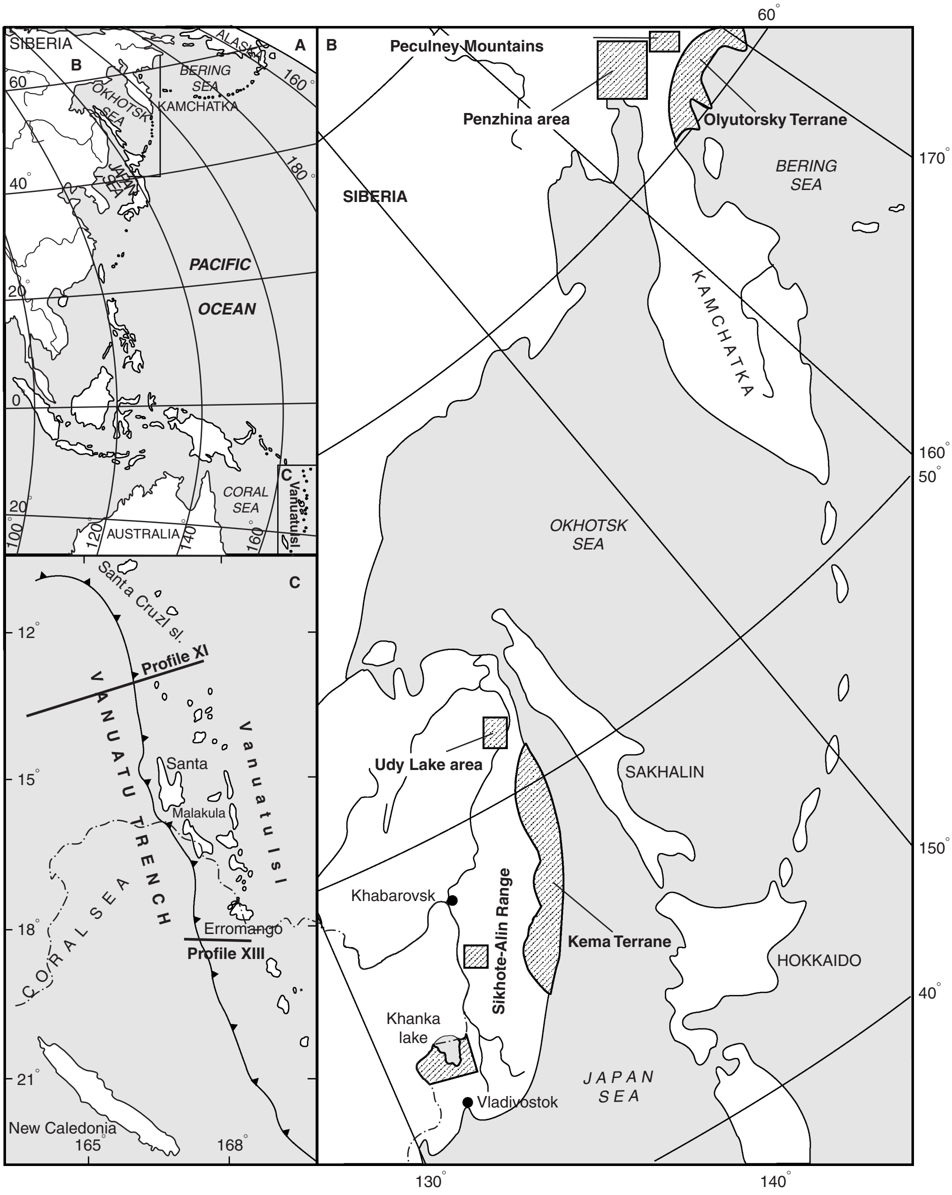

Fig. 1. Investigated areas of the Russian Far East and West Pacific. (A): General map; (B): Russian Far East; (C): Vanuatu area (for profiles XI and XIII: see Fig. 2).

grain mounts, using both size fractions, and point counting at least 200 grains on each grain mount. The average values of their point counts were used for data presentation and plots. In order to unmask the relationship between particular minerals and recognise those that carry the most informative palaeogeographic signatures, only the detrital mineral components were counted.

It proved important to integrate the heavy mineral technique with the analysis of framework components (quartz, feldspars, and rock fragments), bulk chemical compositions and the products of synsedimentary volcanism (lava, tuffs, and tephra). Because an association of heavy minerals can originate from different sources (for example, magnetite and ilmenite may originate from different granites, metamorphic rocks, basalts, and andesites), chemical analysis is essential to link assemblages to their particular source rocks which, in turn, can reveal the plate tectonic setting of the depositional area. For this purpose electron microprobe analysis was conducted on diagnostic heavy minerals, using a JEOL JXA-5A electron microprobe.

2. STUDY AREAS

2.1. Oceanic Volcanic Island Arc Sedimentation: the Vanuatu Region

The Vanuatu region of the south-western Pacific (Fig. 1) is the southernmost of the unique island arc and deep-sea trench system that extends from New Guinea to latitude 23° South, covering a length of 2500 km. The peculiarity of the Vanuatu island arc system is that the trench is situated westward and the Benioff zone is inclined eastward (Vasiliev, 1990; Tanahashi, 1994).

Across the 5500 m isobath, the Vanuatu Trench is ~1600 km long and 40 km wide. Its deepest parts have a slightly inclined floor 0.5–1.5 km wide with a maximum depth of 9174 m. The trench has stepped slopes, and relief is very complex, consisting of a chain of depressions 7000–9000 m deep, separated by barriers that are only 5500–6000 m deep. Friable (non-lithified) sediments in the Vanuatu Trench and on the adjacent Coral Sea floor were collected at profiles XI and XIII by hydrostatic and gravitational samplers and by dredging (Fig. 2). Material taken represents all types of Tertiary and Quaternary sediments in the trench and comprises clay, carbonates, and tephra.

Heavy minerals of the Middle Eocene-Holocene deep-sea sediments of the Vanuatu Trench are homogeneous, and characterised by the predominance (up to 100%) of island arc volcaniclastic clino- and orthopyroxene (Opx), magnetite, olivine, and hornblende (Hb) (Fig. 2). A typical association consists of clinopyroxene (Cpx) (30–92%) and magnetite (10–62%). Orthopyroxene (2–43%), hornblende (0.1–17%), and olivine (up to 10%) are less abundant, while heavy minerals of the sialic association (zircon, sphene, apatite, rutile, garnet, and corundum) are present only in accessory ($<2.5\%$) amounts, attesting to the insignificant occurrence of sialic source rocks in the region.

The MF (total amount of olivine, ortho- and clinopyroxene, green hornblende) component (MF: see caption, Fig. 3) permits identification of detritus from oceanic and island arc volcanics and, within them, differentiation of arcs that have either oceanic or continental basement. The island arc material differs from oceanic basement by the high percentage of orthopyroxenes and the low proportion of olivine. Orthopyroxene strongly prevails over olivine, which bears witness to the domination of island arc material.

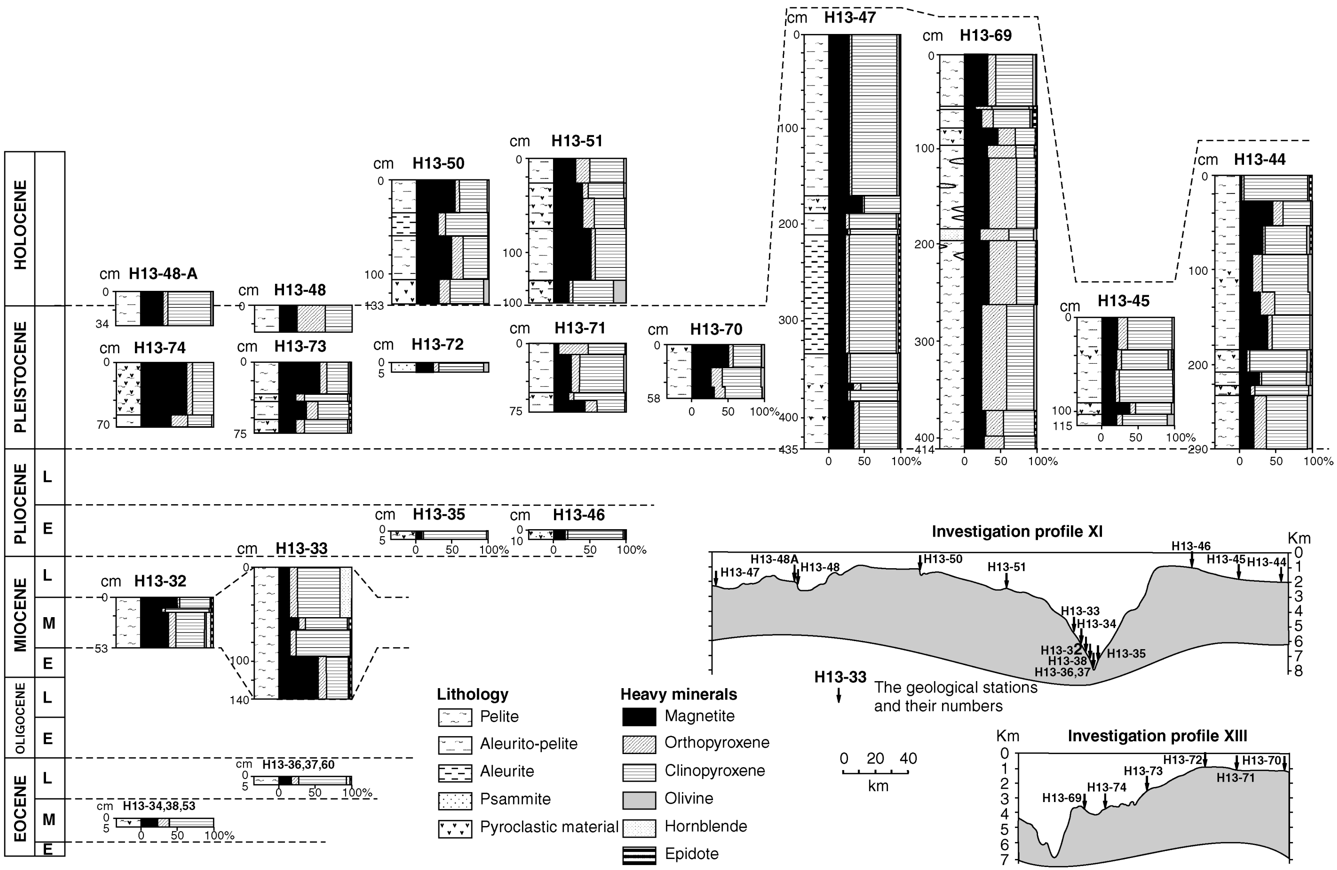

Fig. 2. Heavy mineral distribution in the deposits of the investigated profiles across the Vanuatu deep-water trench, (after Vasiliev, 1990). For locations of profiles XI and XIII: see Fig. 1.

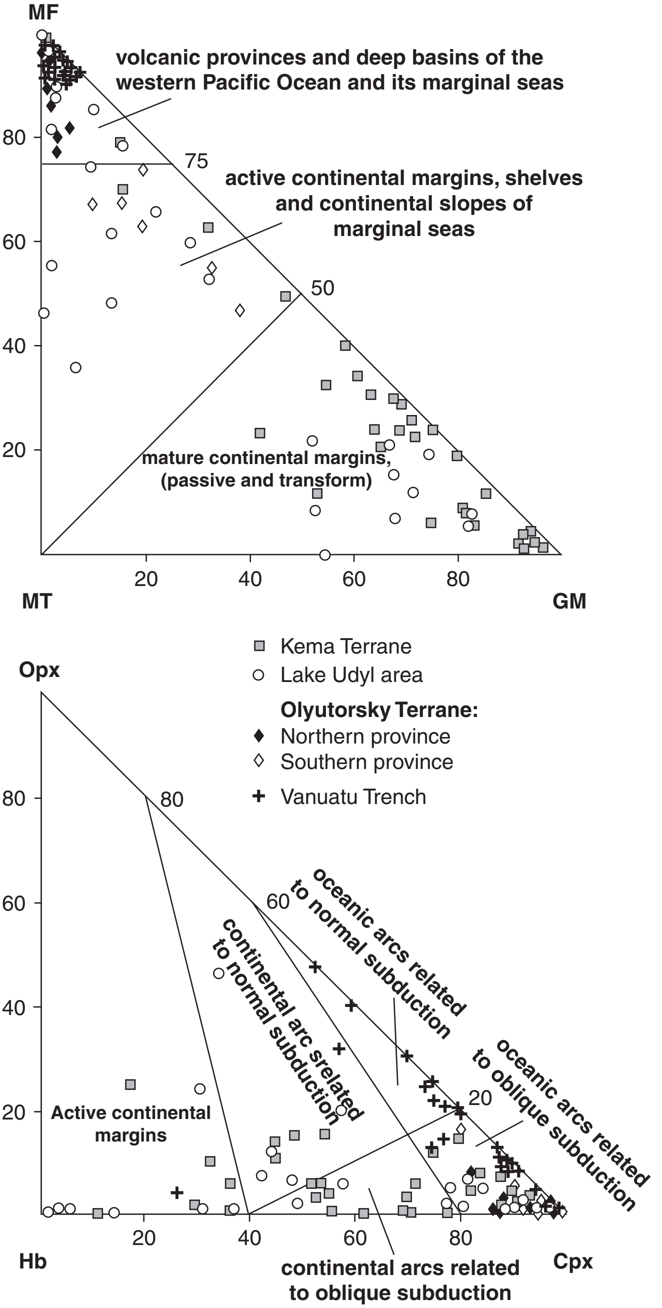

Fig. 3. Correlation of mineral compositions of heavy minerals from sandstones of different ancient rocks and modern sediments from various geodynamic settings on MF-GM-MT and Opx-Hb-Cpx diagrams (after Nechaev and Isphording, 1993). Values on axes are in percentages. MF: total amount of olivine, ortho- and clinopyroxene, green hornblende; MT: total amount of epidote, garnet, blue-green amphibole; GM: total amount of zircon, tourmaline, staurolite, monazite, sillimanite, kyanite, and andalusite. Opx: orthopyroxene; Hb: hornblende; Cpx: clinopyroxene.

Analytical data of heavy minerals, plotted as MF-MT-GM diagrams in Fig. 4 (Nechaev and Isphording, 1993), show the clustering of data points close to the MF apex, indicating their correspondence with assemblages of deep-sea sediments in the depressions of the Pacific Ocean marginal seas.

The Opx-Cpx-Hb ratios (Fig. 3), where the principal heavy mineral is hornblende, allows division of the continental and oceanic arc-derived detritus (Nechaev and Isphording, 1993). In the studied sediments, hornblende abundance is low, and an oceanic island arc source (e.g., in the Vanuatu Islands) is therefore likely (Hanus and Vanek, 1983). A changing ratio of orthopyroxene vs. other components over time allows us to assess the temporal evolution of tectonic plate convergence. Thus increased proportions of orthopyroxenes with sediment younging indicate that the Middle Eocene-Pliocene oblique plate convergence and subduction changed to orthogonal (normal) in the Late Pliocene (Fig. 3).

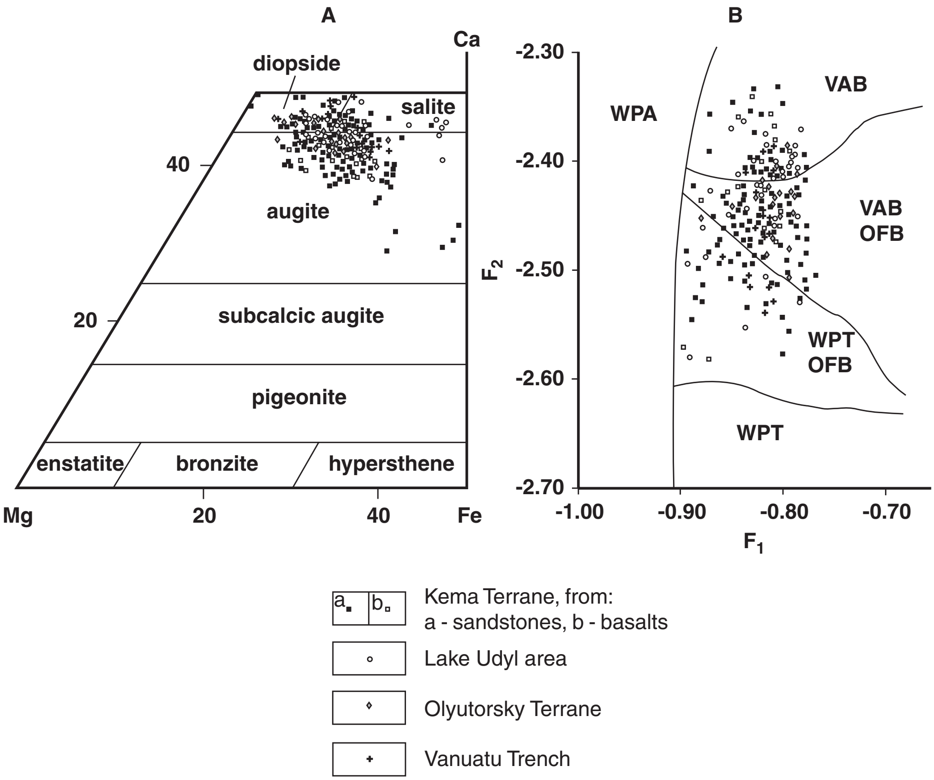

Fig. 4. (A): Comparative diagram showing composition of clinopyroxenes from basalts and sandstones; (B): Discriminant diagram for basalt-hosted clinopyroxenes from different geodynamic settings (after Nisbet and Pearce, 1977). VAB: volcanic arc basalts; OFB: ocean-floor basalts; WPT: within-plate tholeiitic basalts; WPA: within-plate alkaline basalts. $F_1 = -0.012 \times SiO_2 - 0.0807 \times TiO_2 + 0.0026 \times Al_2O_3 - 0.0012 \times FeO - 0.0026 \times MnO + 0.0087 \times MgO - 0.0128 \times CaO - 0.0419 \times Na_2O$;
$F_2 = -0.0496 \times SiO_2 - 0.0818 \times TiO_2 - 0.02126 \times Al_2O_3 - 0.0041 \times FeO - 0.1435 \times MnO$-$0.0029 \times MgO - 0.0085 \times CaO + 0.0160 \times Na_2O$.

The character of the volcanic sediment source can be identified by the chemical composition of diagnostic heavy minerals: ortho- and clinopyroxenes, olivine, and hornblende. In this regard clinopyroxene proves to be the most informative. Chemical composition (Fig. 4A) of the Vanuatu Trench clinopyroxenes corresponds to diopside, augite and, to a lesser degree, salite. Their origin can be seen from the discriminant diagrams, permitting us to confirm with more than 80% probability that these pyroxenes are from basalts, and that they were generated in different tectonic settings. Fig. 4B (Nisbet and Pearce, 1977) shows that the majority of pyroxenes correspond to clinopyroxenes of island arc basalts, and in part to those of ocean-floor basalts, originating probably from the island arc's roots. The composition of clinopyroxenes, analysed from sediments collected from the proximity of the island arc, shows a clear link to those of ocean-floor basalt. In the discriminant diagram 1 of Fig. 5 (Leterrier et al., 1982) all pyroxenes from the Vanuatu Trench occupy the fields not far from the line separating clinopyroxenes from alkaline intraplate and oceanic island basalts (A) from non-alkaline basalts (T).

Similar to those of the other analysed terranes, they have low titanium and sodium contents and thus cannot be allocated to the alkaline basalt category. Diagram 2 divides non-alkaline basalts into MORB basalts (D) and calc-alkaline and tholeiitic

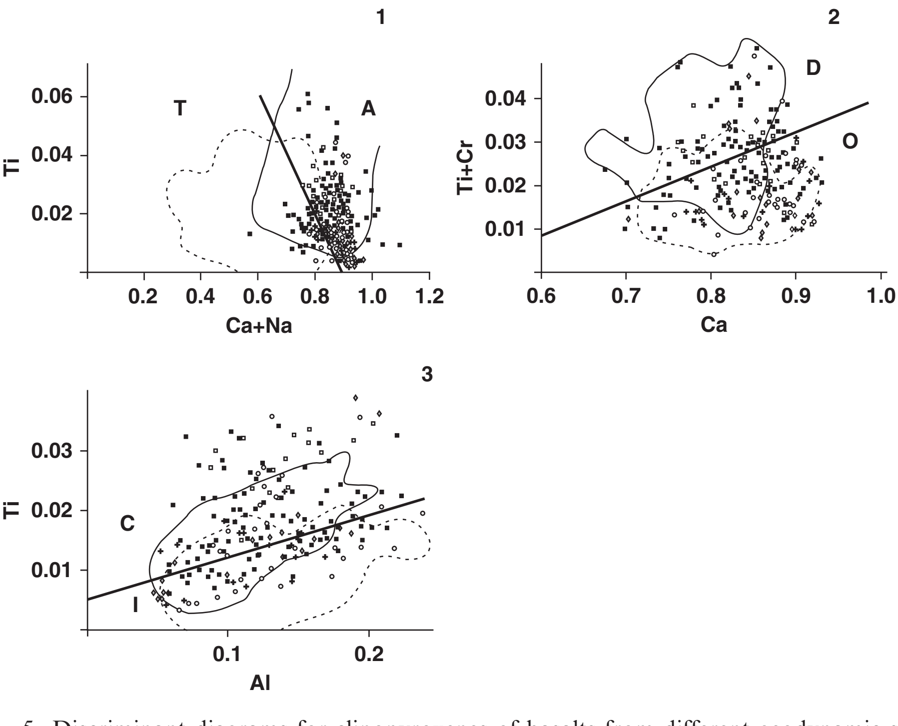

Fig. 5. Discriminant diagrams for clinopyroxenes of basalts from different geodynamic settings (after Leterrier et al., 1982). 1: alkaline intraplate basalts (A) and non-alkaline (T) basalts; 2: non-alkaline basalts distinguishing MORB (D) from calc-alkaline and tholeiitic basalts of epicontinental and island arcs (O); 3: calc-alkaline (C) and tholeiites of epicontinental and island arcs (I). The fields corresponding to different basalts are represented by solid and dashed lines; elements are given in formula units.

basalts of the continental margin and island arcs (O); all detrital clinopyroxenes of the Vanuatu Trench prove to be of island arc origin. Diagram 3 divides island arc clinopyroxenes into calc-alkaline (C) and tholeiitic types, and here the pyroxenes define a tholeiitic basalt source. The island arc character of the hornblendes is demonstrated in the diagram of 10Ti-Al-Fe (Nechaev, 1991), where low total chromium and titanium contents suggest that the amphiboles were derived from basic and intermediate volcanic rocks of the island arcs (Fig. 6B).

Our analyses indicate that the principal source of detrital heavy minerals of the Middle Eocene-Pleistocene deep-sea sediments of the Vanuatu Trench was predominantly the tholeiitic basalts of the island arc with limited addition from ocean-floor basalts. Heavy minerals also reveal that only insignificant amounts of terrigenous material reached the depositional area from the Australian continent.

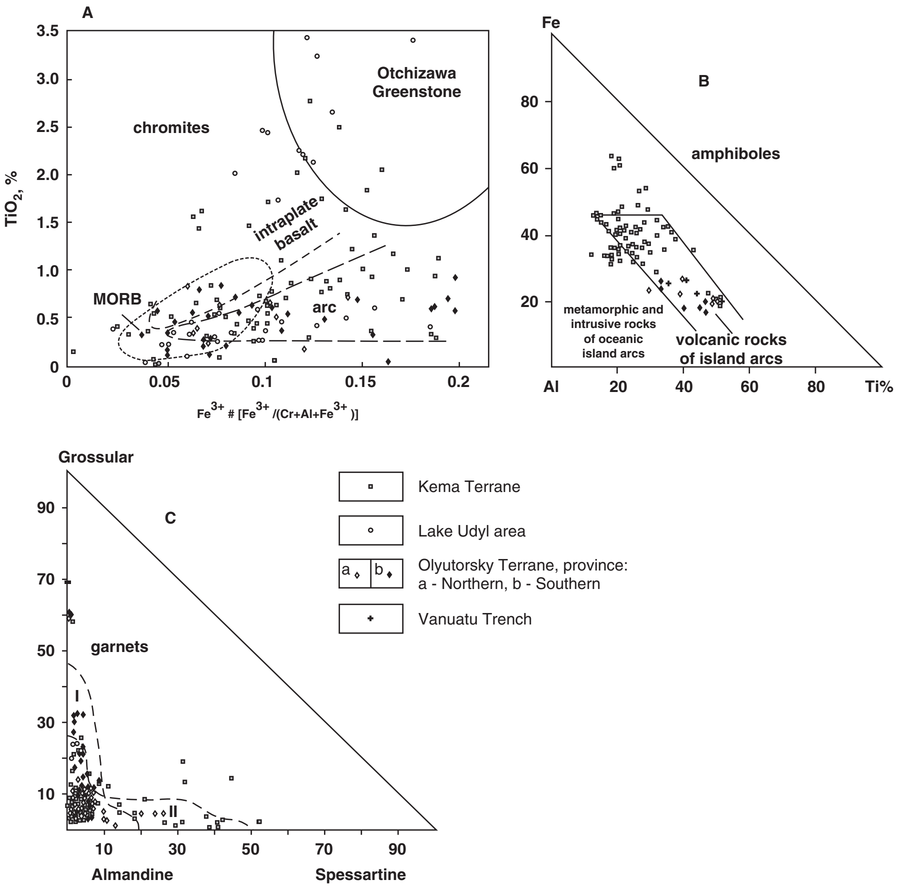

Fig. 6. Diagrams of the composition of heavy minerals of sandstone from different sedimentary successions. Discrimination fields for magma chemistry. (A): For chromites (after Arai, 1992); (B): For amphiboles (after Nechaev, 1991); (C): For garnets—from acidic volcanic rocks (I) and intrusive rocks (II) (after Kazachenko, 2001). All Ti values are multiplied by 10 and recalculated as percentages.

2.2. Sikhote-Alin Range

The main part of this Mesozoic complex consists of marine arkoses, which contain rock-forming and accessory minerals of continental, granitic, and metamorphic provenance. Locally narrow belts of sialic continental and mafic, oceanic volcanic arc systems also occur with fragments of volcano–sedimentary, forearc and backarc basin sediments, intercalated with andesitic and basaltic rocks. Two main types of sediment composition and corresponding sedimentation can be distinguished in the Sikhote-Alin fold system: (1) mixed epiplatformal and (2) epioceanic, arkosic sediments.

2.2.1. Mixed epiplatformal sedimentation.

Mesozoic epiplatformal sedimentation has been identified positively only on the eastern margin of the Khanka crystalline massif, which is postulated to be a fragment of the North China craton (Bersenev, 1969). In the Central Sikhote Alin (Fig. 1) during the Late Triassic, the sediment source province comprised acid volcanics, granites, and sedimentary rocks, as indicated by high amounts of zircon (up to 85%) and by the presence of lithic fragments from these rocks in the analysed sandstones. In adjacent Chinese territory, heavy minerals of the sandstones include 60–78% zircon with minor leucoxene, apatite, magnetite, and hornblende.

In the southern Sikhote-Alin, Mesozoic heavy minerals have been studied only cursorily in Triassic and Late Jurassic to Berriasian sediments, where they are represented chiefly by zircon (40–88%), suggesting a source in the granitic and metamorphic rocks of the Khanka crystalline massif, located to the west. Small quantities of tourmaline, zircon, garnet and magnetite, minor leucoxene, titanite, apatite, glauconite, and rare staurolite grains were also found.

2.2.2. Arkosic and epioceanic sedimentation: accretionary complexes of the Sikhote-Alin range.

In the Sikhote-Alin range (Fig. 1) the majority of the Mesozoic heavy minerals are represented by the sialic association (zircon, apatite, garnet, sphene, tourmaline, and rutile), derived from acid magmatic and metamorphic rocks of continental origin. This association constitutes, on average, 56–82% of all clastic heavy minerals. The major component of this association is zircon (up to 95%) of granitic and acid–volcanic derivation. Less common is the mafic, oceanic (femic) association (18–44%), which includes chromite, ilmenite, and leucoxene, associated with ultrabasic source rocks, together with clinopyroxene, hornblende, and epidote, derived mainly from basic volcanic island arc complexes. The chemical composition of most of the chromites from the upper Aptian-Albian part of the succession is very similar to chromites of the Jurassic meimechite-picrite assemblage (TiO_2-rich ultramafic volcanic rocks, containing high-titanium spinels) of Sikhote-Alin. Other chromites are low in titanium and occupy the field of ultramafic chromites. Some grains are high in alumina and correspond with chromites of dunite-hartzburgite (Alpine-type) peridotites. In the lower part of the succession, there is a limited upward increase in the proportion of mafic mineral associations, which become particularly evident in the upper part. This signature in the lower part of the succession therefore records the onset of pre-orogenic volcanism.

2.2.3. Epicontinental volcanic island arc sedimentation: Kema Terrane.
The Kema Terrane is situated in the eastern part of the Sikhote-Alin range, extending as a band up to 80 km wide along the Japan Sea coast (Figs. 1 and 7). The terrane includes Barremian(?)-Albian deposits, with turbidites, siltstones, and mixtites (unsorted, mixed grain-size sedimentary rocks). Mafic lavas and their pyroclastics are widespread, interpreted as the backarc basin fill of the Early Cretaceous Moneron-Samarga island arc system. Volcanic island arc sources have been identified for the Early Cretaceous deposits of the Kema Terrane (Primorsky region of Russia) (Malinovsky et al., 2002).

Fragments of the Kema Terrane are also exposed in the "windows" among the rocks of the Late Cretaceous East Sikhote-Alin volcanic belt. Volcano–sedimentary formations were studied in three fragments: Kemsky (Kema River basin), Sovgavansky (Buta River basin) and Vysokogorsky (Muly River basin) (Figs. 7 and 8). The lithostratigraphy of sections in the studied Kema Terrane fragment is described below (Fig. 8).

In the *Kemsky fragment* the lower turbidite unit (up to 1100 m thick) lies at the base of the type section (Fig. 8), consisting of alternating packages of sandstones and siltstones with typical turbidite characteristics. The alternation is occasionally interrupted by siltstones with thin sandstone horizons, slump deposits, and gravelstones (cemented gravels comprising clasts 2–10 mm in size). The overlying coarse clastic unit ($\sim$1500 m) is represented by conglomerate, gravels, sandstones, mixtites, rare packages of rhythmically alternating sandstones and siltstones, slump horizons, tuffs, and isolated basalt flows. Above this is the volcanic unit (up to 770 m) consisting mainly of basalts, tuffs, and tephra; in places there are volcaniclastic sandstones, rhythmical alternations of sandstones and siltstones, horizons of slump deposits and mixtites. The upper turbidite unit (up to 1700 m) is characterised by thick rhythmic alternations of sandstones and siltstones. This monotonous succession is, in places, interrupted by thinner horizons of sandstones, siltstones and mixtites, and is complicated by deformation related to subaqueous landslides. The uppermost part is a sandstone unit (up to 550 m), containing rare horizons of conglomerates, gravels and siltstones and, in the lower part, andesitic basalt layers.

In the *Sovgavansky fragment* (Fig. 8), the basal sandstone and siltstone unit (up to 800 m*)* is composed of sandstones with gravels, conglomerates, and packets of rhythmically intercalated sandstones and siltstones, containing mixtite horizons. The overlying turbidite-clayey unit (up to 1600 m) consists mainly of siltstones, passing up into rhythmical intercalations of sandstones and siltstones, occasionally with sandstones and mixtites. A turbidite-sandstone unit (up to 1500 m), representing the upper part of the section, comprises rhythmically alternating sandstones and siltstones, with thick sandstone intervals, containing gravel lenses. Siltstone horizons are comparatively rare in the thick sandstone beds.

The *Vysokogorsky fragment* (Fig. 8) contains a siltstone and sandstone unit ($>$1550 m thick) at the base of the lower part of the section, comprising siltstones and sandstones or, occasionally, sandstones with siltstone intercalations. Above this lies the turbidite unit ($>$870 m) with sandstone and siltstone rhythmites, sometimes interrupted by siltstones or sandstones. Next is a volcano–sedimentary unit ($>$1450 m), which has significant volcanic products—diabases, basalts, and basic tuffs—together with volcaniclastic sandstones, siltstones, conglomerates, mixtites,

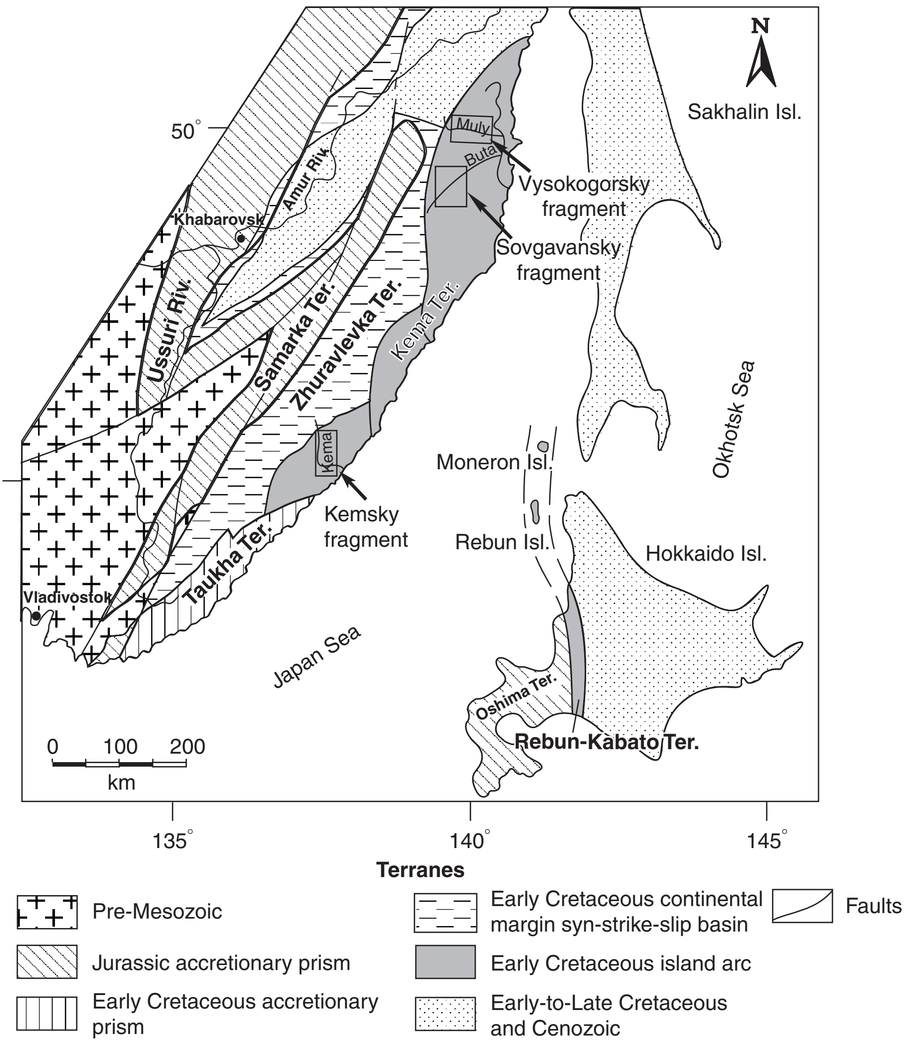

Fig. 7. Major terranes of the Russian Far East and adjacent area (after Malinovsky et al., 2002).

and rhythmically interbedded sandstone/siltstone couplets. The overlying siltstone unit (>850 m) is made up of massive siltstones with lenses and interlayers of sandstones, conglomerates, and mixtites. The uppermost sandstone unit (~2200 m) consists mainly of sandstones, with siltstones and gravel lenses and thin rhythmical sandstone/siltstone couplets.

Two heavy mineral associations have been distinguished in the Kema Terrane. The first is volcanogenic, constituting ~40% of all heavy minerals, and including typical representatives of island arc volcaniclastics: ortho and clinopyroxenes, hornblende, chromite, and magnetite. Most of these minerals are in the Kema River fragment where some samples contain up to 100% heavy minerals. The dominant

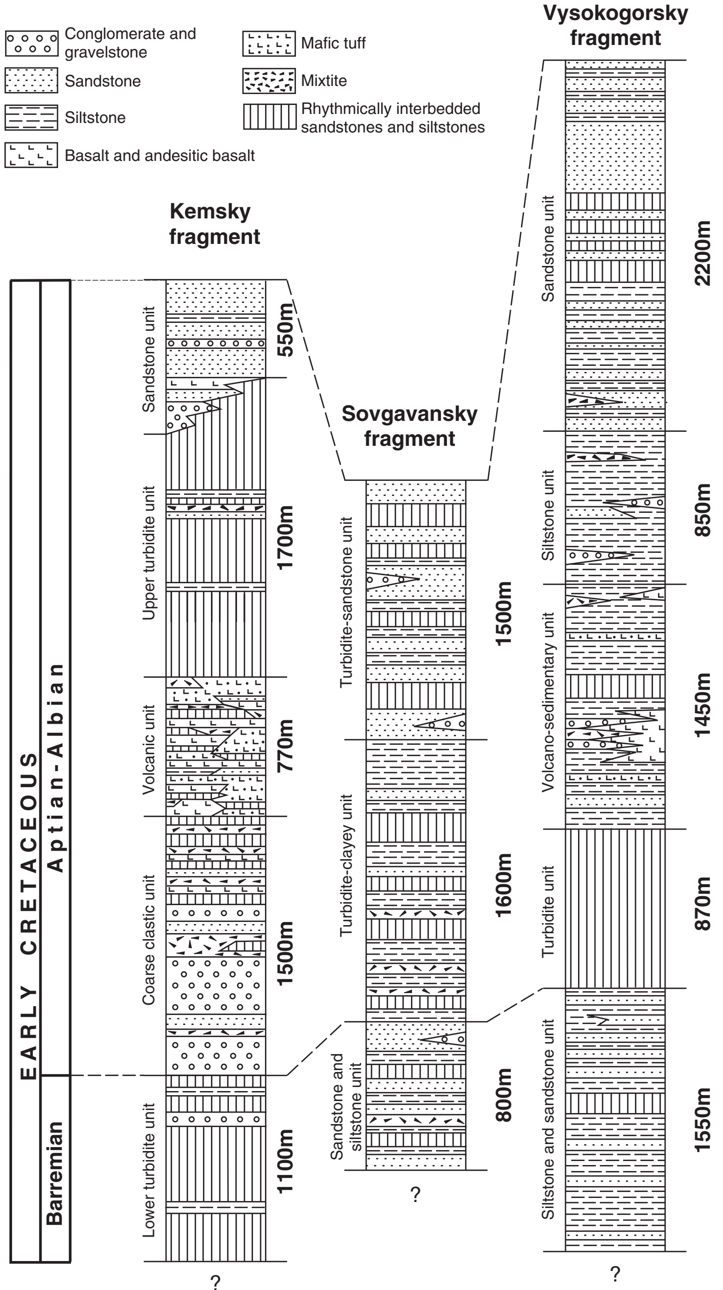

Fig. 8. Correlation of the lithostratigraphic columns of the of the Kema Terrane's different fragments.

mineral of the volcanic association is clinopyroxene (up to 98%), followed by hornblendes (up to 60%), orthopyroxenes (up to 38%), chromites (up to 46%), and magnetite (up to 25%). The second association is sialic and includes on average of 60% of all heavy minerals; it comprises zircon, garnet, tourmaline, epidote, apatite, sphene, and rutile. The principal mineral is zircon (up to 100% in some samples), followed by, in decreasing abundance, garnet (up to 77%), tourmaline (up to 18%), and epidote (up to 11%).

It is well documented for this region that the different tectonic settings have distinctive heavy mineral associations (Nechaev et al., 1996; Markevich et al., 1997). Our analysis of the heavy mineral associations from the Kema Terrane is shown in the MF-MT-GM and Opx-Hb-Cpx diagrams of Nechaev and Isphording (1993). Fig. 3 shows that they originate from two contrasting sources. The volcanogenic association corresponds to a continental volcanic arc and/or an active continental margin at a low plate convergence angle. This association originates, principally, from island arc volcanics, which contribute considerably larger amounts than does the sialic source in the Kema River fragment. The source of the sialic association was probably the continental foundation of the arc. As a possible source a convergent plate boundary without volcanic activity, perhaps like northern Peru, can also be considered.

The nature of the volcanic sediment source (Fig. 4) can be best identified by the chemical composition of clinopyroxenes in the sandstones. In Fig. 4, their compositions are compared with pyroxenes from basalts that are widespread in the Kema Terrane. In the Mg-Ca-Fe plot (Fig. 4A) the composition of the pyroxenes corresponds to augite, diopside, and salite (a rare intermediate member of the diopside-hedenbergite series). The diagrams also allow the discrimination of pyroxenes from different geodynamic settings, with a confidence level of more than 80%. In Fig. 4B (after Nisbet and Pearce, 1977), the majority of the detrital pyroxenes correspond to pyroxenes of volcanic island arc basalts, and partially to pyroxenes of oceanic-floor basalts that probably intruded into the island arc's foundation. The plots of Ti/(Ca + Na), (Ti + Cr)/Ca, and Ti/Al (Fig. 5, after Leterrier et al., 1982) allow the distinction of pyroxenes from different geodynamic settings with probability similar to those shown in Fig. 4. In plot 1 of Fig. 5, clinopyroxenes (including those from basalts) cluster close to the line that demarcates clinopyroxenes of the alkaline intraplate (intracontinental and oceanic islands) basalts (A) from non-alkaline basalts (T). Part of the clinopyroxenes plot in the alkaline basalt field, but their low titanium and sodium content prevent them from being assigned to that group. Fig. 5, diagram 2, divides non-alkaline basalts into MORB basalts (D) and calc-alkaline and tholeiitic basalts with continental margin and island arc signatures (O). This plot shows that the detrital clinopyroxenes are situated in, or close to, the island arc field. Diagram 3 divides island arc pyroxenes into calc-alkaline (C) and tholeiitic (I) origin. This plot shows that the source of the pyroxenes is calc-alkaline basalts, characteristic of a backarc setting.

In Fig. 6A, the composition of the detrital chromite is plotted (Arai, 1992). Most of the data points are located in the field of island arc basalts with a minor part pointing to chromites from high-alkaline intraplate basalts. The compositions of amphiboles (Fig. 6B) from the sandstones are close to those of island arc volcanics, thus indicating a mainly island arc source (Nechaev, 1991). Garnets from sandstones are mainly pure almandine and only incidentally contain grossular or spessartine components. They originate, most likely, from acid intrusive and effusive volcanic rocks, although metamorphic parageneses cannot be ruled out (Fig. 6C, after Kazachenko, 2001). Garnets were, probably, eroded from blocks of sialic continental crust, which constitutes the foundation of the island arc.

In summary, in the Kema Terrane heavy mineral compositions reveal three sources of the detritus: (1) sub-alkaline and calc-alkaline basalts of a volcanic island arc, (2) island arc foundation, consisting of fragments of continental crust and (3) oceanic crust, accreted to the arc. This indicates that the study sediments accumulated on the active continental margin in a backarc basin of a continental volcanic island arc.

2.2.4. Oceanic volcanic island arc system: the Udyl Lake area.
In the Lower Amur region of the northern Sikhote-Alin, which includes the Udyl Lake area (Markevich et al., 1997), a series of fragments of the oceanic volcanic island arc system have been identified (Figs. 1 and 9). Strata include chert, volcaniclastic greywacke, and arkosic rock complexes (Fig. 10).

The cherty complex (Fig. 10) consists of radiolarian cherts, mudstones, rare alkaline oceanic basalts, and pelagic limestones. In this complex island arc-derived green clinopyroxene predominates in association with orthopyroxene, hornblende, and magnetite from similar sources. Terrigenous zircon, garnet, apatite, and epidote are rare. Although the cherty complex has typical oceanic characteristics, the basin may have formed in a backarc setting of a marginal sea, as suggested by the prevalence of the amphibole–pyroxene association (MF, Fig. 3). As a whole, the MF-MT-GM components ratio is most characteristic of the deep-water parts of the Pacific marginal seas, where the main source of detritus was a volcanic island arc complex, complemented by terrestrial material from the continental margin.

The volcano–sedimentary complex (Fig. 10), representing a forearc basin, consists entirely of alternating tuffs, volcaniclastic sandstones, mixtites, tuffaceous siliceous mudstones ('silicites'), mudstones, and clayey-cherty rocks, including radiolarian cherts, with only rare basalts. Heavy minerals of the lower part of this complex are almost entirely volcanogenic clinopyroxene, magnetite, hornblende, and orthopyroxene (Fig. 3). In the upper part, these components are mixed with abundant epidote, garnet, chromite, zircon, apatite, sphene, and rutile. Such a heavy mineral sequence reflects the evolution of the basin fill that accumulated in forearc and island arc basins. At the initial stage, deposition was paralleled by synsedimentary volcanism. The succeeding volcaniclastic sediments incorporate material from a consumed accretionary prism that contained fragments of the volcanic arc, oceanic islands, and ophiolites.

The greywacke complex (Fig. 10) consists mainly of mudstones and sandstone, with horizons of tuffs and varied gravitational deposits: mixtites, turbidites, and contourites. The proportions of heavy minerals vary (Fig. 3) as shown by the occasionally elevated (50–94%) percentages of chromite, associated sometimes with pyroxene (up to 37%). The principal heavy minerals were sourced from ophiolites. Some beds contain large amounts of zircon and garnet, reflecting input from a granitic and metamorphic continental source. Lastly, in some cases, sediments are enriched in pyroxenes, amphiboles, and epidote with minor chromite content. The greywacke complex reflects derivation from island arc volcanics and their

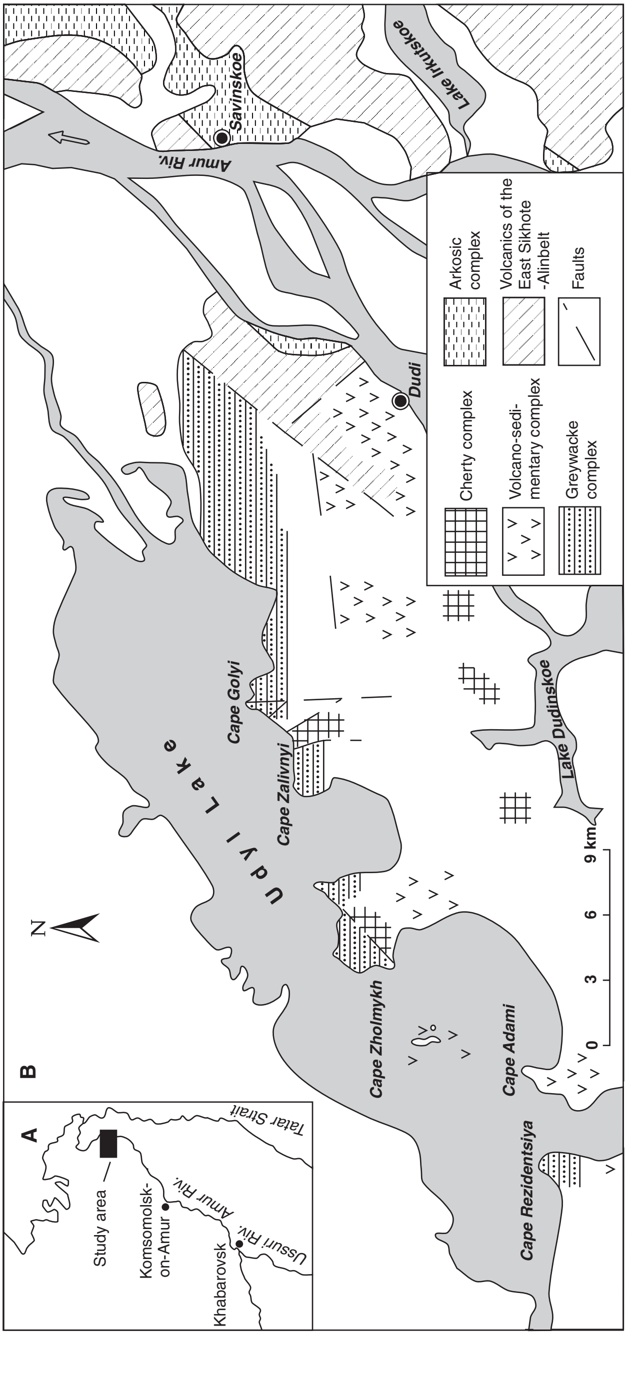

Fig. 9. Location (A) and schematic geologic map (B) of the Udyl Lake area (after Markevich et al., 1997).

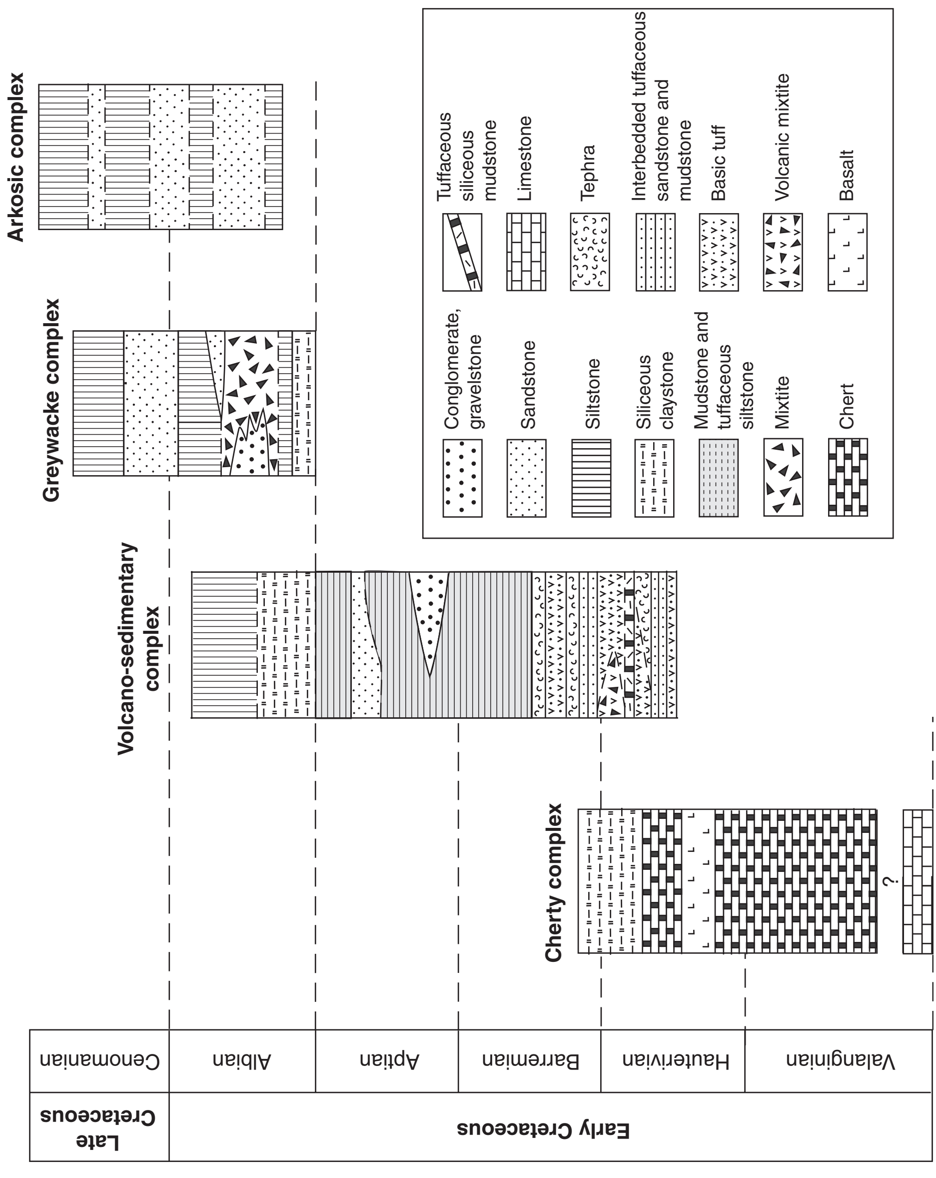

Fig. 10. Stratigraphic position and generalised structure of the lithofacies assemblages (after Markevich et al., 1997).

metamorphic equivalents. Thus, the heavy mineral spectrum indicates that detritus were derived from a heterogeneous source region. The greywackes were, most probably, shed by an accretionary prism, receiving material from oceanic, island arc, and continental parentages.

In the lower part of the arkosic complex (Fig. 10) sandstones are prevalent, whereas mudstones with some sandstone predominate in the upper part. The heavy mineral associations of this complex (Fig. 3) differ sharply from those of the three previous rock complexes with the dominance of zircon, garnet and apatite, accompanied by minor hornblende, chromite, magnetite, rutile, sphene, leucoxene, tourmaline, and pyroxenes. This association is typical of Sikhote-Alin Cretaceous successions and is interpreted as originating from mature continental margin sources without any volcanic input.

Heavy mineral distributions of the analysed successions pinpoint five main source provinces that furnished the fore- and backarc basins of island arcs. The parent rocks include two volcanic arcs of different age and origin (Valanginian-Barremian and Albian-Cenomanian), two continental blocks (northern and southern), and an ophiolite complex (Fig. 11).

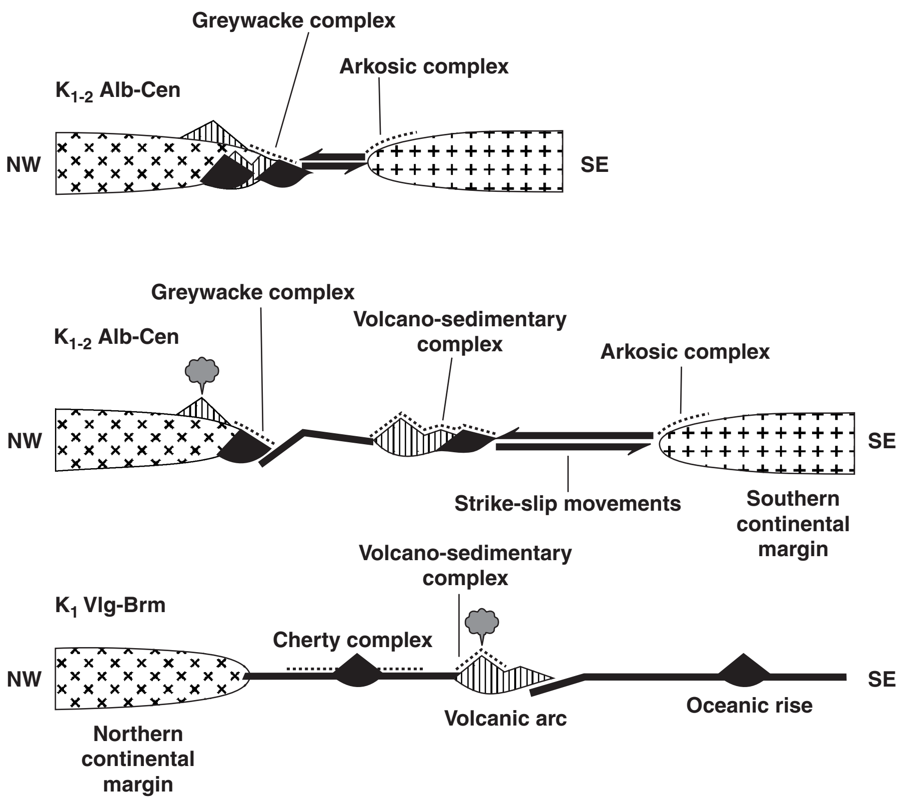

Fig. 11. Early Cretaceous geodynamic settings of the Udyl Lake area (after Markevich et al., 1997).

In summary, in the Udyl Lake area the Valanginian-Barremian volcanic island arc complexes, characterised by volcaniclastic sediments and chert, contain a low-diversity heavy mineral suite in which clinopyroxenes of augite and diopside compositions dominate, indicating a basaltic volcanic arc source (Figs. 4 and 5). The prevalence of clinopyroxenes is typical of obliquely convergent continental margins and volcanic arc (Nechaev et al., 1996) (Fig. 3: Opx-Hb-Cpx diagram), and shows the direct influence of an Izu-Bonin type oceanic arc.

The Albian-Cenomanian volcanic island arc and its foundation served as a source for the greywacke complex, which had been accumulated, most probably, on the inner slope of a deep-water trench. The composition of detrital pyroxenes and chromites attests to their island arc origin (Figs. 4, 5, and 6A). The Opx-Hb-Cpx ratio (Fig. 3) indicates continental volcanic arc and (or) active continental margin with oblique convergence (Fig. 11).

The heavy mineral association of the northern continental margin greywackes consists of zircon, garnet, sphene, apatite, and tourmaline with rare to absent rutile. Heavy mineral proportions are especially high in the middle part of the greywacke complex. These deposits accumulated, perhaps, adjacent to a continental rise at the arc's foundation. Almandine garnets (Fig. 6C) were probably derived from acid intrusive and effusive rocks, although a metamorphic source can also be considered (Kazachenko, 2001).

Lithologies exposed in the region of the southern continental margin provided the heavy mineral association of the arkosic complex. Its major components, zircon, garnet, tourmaline, sphene, apatite and rutile, indicate that a non-volcanic continental margin was eroded at the time of their deposition (Fig. 3).

The ophiolite-derived sedimentary complex was identified by the abundance of chromite in the greywackes, often associated with clinopyroxene, epidote, and hornblende. Electron microprobe analysis of the chromites and clinopyroxenes shows that those with high TiO_2 originate from alkaline magmatic rocks of inner-plate rises and islands (Figs. 4, 5, and 6A). Our proposed generalised sequence of tectonic events, documented by the sediment fill in the study areas, is shown in Fig. 11.

2.3. Koryak-Kamchatka Region

2.3.1. Penzhina area.

The studied region represents the northwest part of the Shelikhov Gulf, Penzhina Bay, and Kamchatka Peninsula (Figs. 1 and 12). It is situated between the western Koryak and Koryak-Kamchatka fold belts (Fig. 12), and is regarded as an active continental margin, consisting of deformed Palaeozoic to Mesozoic oceanic sediments, metamorphics, and volcanic rocks. The heavy mineral associations of the Cretaceous clastic deposits have been investigated from several areas (Fig. 13).

The tectonic development of the Cretaceous basins and the temporal variation of sedimentary environments were reconstructed using the heavy mineral assemblages of the basinal successions. They allowed the unravelling of major stages in the depositional and tectonic history of the sedimentary basins. Although heavy mineral studies are an appropriate tool for such investigations, this technique has not been systematically utilised until now in this region. We document the heavy mineral

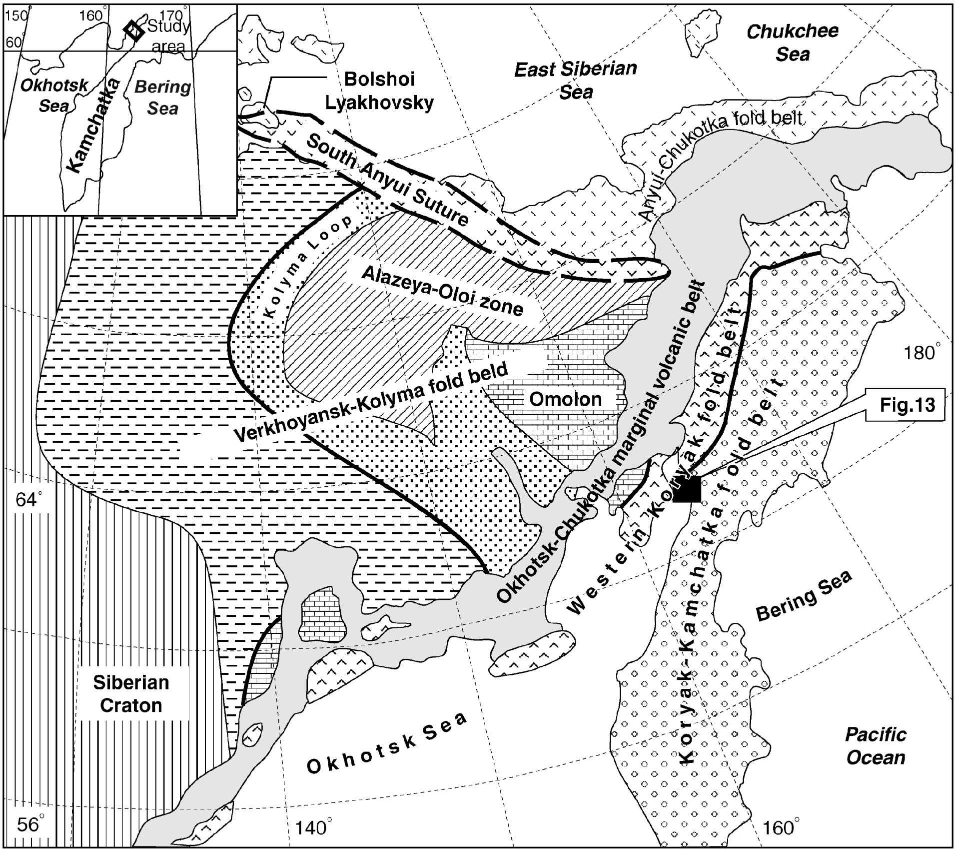

Fig. 12. The major tectonic elements in Northeast Asia (after Sokolov et al., 1999).

distributions in the Cretaceous deposits of Penzhina Bay, and present new data on the heavy mineral associations of Kamchatka's Cretaceous sedimentary basin. Results help reconstruction of the tectonic setting of the basin and its development with time. Heavy mineral associations have been investigated in the Upupkin, Kuyul, and Ainyn terranes (Figs. 12 and 13). The Ainyn Terrane includes the Yelistratov and Mametchinsky peninsulas, which share similar basin development, facies, and heavy mineral compositions.

The stratigraphic charts of Fig. 14 show the geological evolution of the area during the Cretaceous. In Berriasian-Early Albian times, deep-water clastics flysch successions were deposited on the continental slope (Sokolov et al., 1999; Tuchkova, 2003). By the Late Albian, sedimentation had changed from deep to shallow water. The earlier flysch was then deformed by the growth of the accretionary prism and by the accretion of the Kuyul Terrane. From Albian to Santonian times, sedimentation took place on shallow and deep-water shelves and in coastal environments.

Heavy minerals in Berriasian-Valanginian sediments are mainly zircon, tourmaline, apatite and, less abundantly, epidote and garnet, derived from granitic and metamorphic lithologies of the Upupkin and Ainyn terranes (Fig. 15). Metamorphic

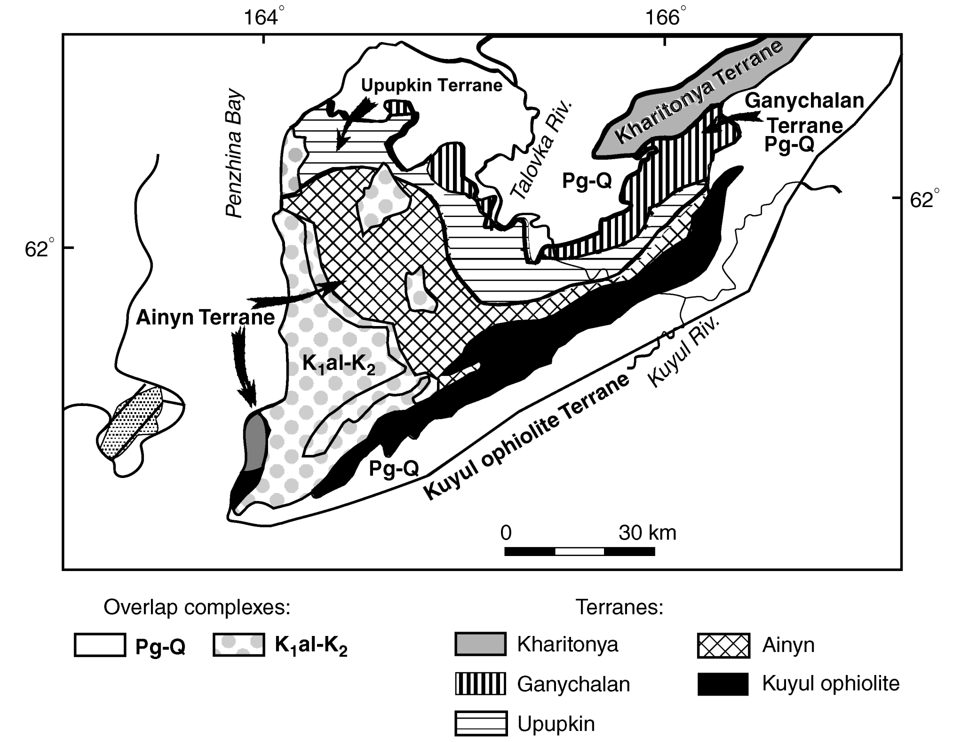

Fig. 13. Generalised terrane map of Penzhina Bay region (after Sokolov et al., 2003).

amphiboles average less than 10%. Magmatic magnetite, ilmenite, and chromite, up to 25–35%, also characterise the sandstones from the eastern part of the region. Magnetite, ilmenite, chromite, and clinopyroxenes predominate in samples from the Kuyul Terrane, but zircon, garnet, apatite, and epidote are also present (Fig. 15).

Heavy minerals from the Hauterivian-Albian sediments are very similar in the different sections (Fig. 16). Magmatic magnetite, ilmenite, clinopyroxenes and occasionally chromite dominate the deep-marine deposits of the three terranes. They are almost free of garnet and the stable/ultrastable group. Amphibole is present only in a few samples in the western part of Penzhina Bay (Yelistratov and southern part of Mametchinsky peninsulas). Epidote is, in most cases, a major constituent.

The Late Cretaceous shallow-marine deposits contain high percentages of zircon, apatite, ilmenite, epidote, tourmaline, and magnetite (Fig. 17). These suites are similar to those of Berriasian-Valanginian sediments, but in the Albian-Cenomanian and Turonian-Campanian part of the succession, abundances of magnetite, ilmenite, and clinopyroxenes increase in the western part of the region (Fig. 17).

The geochemical composition of the heavy minerals, shown in MF-MT-GM plots (Fig. 18), distinguishes, in general, two major heavy mineral suites: one is composed of stable minerals, whereas the second encompasses unstable, volcanogenic species. Complementing the two major groups, evidence of a minor, "exotic", suite is shown

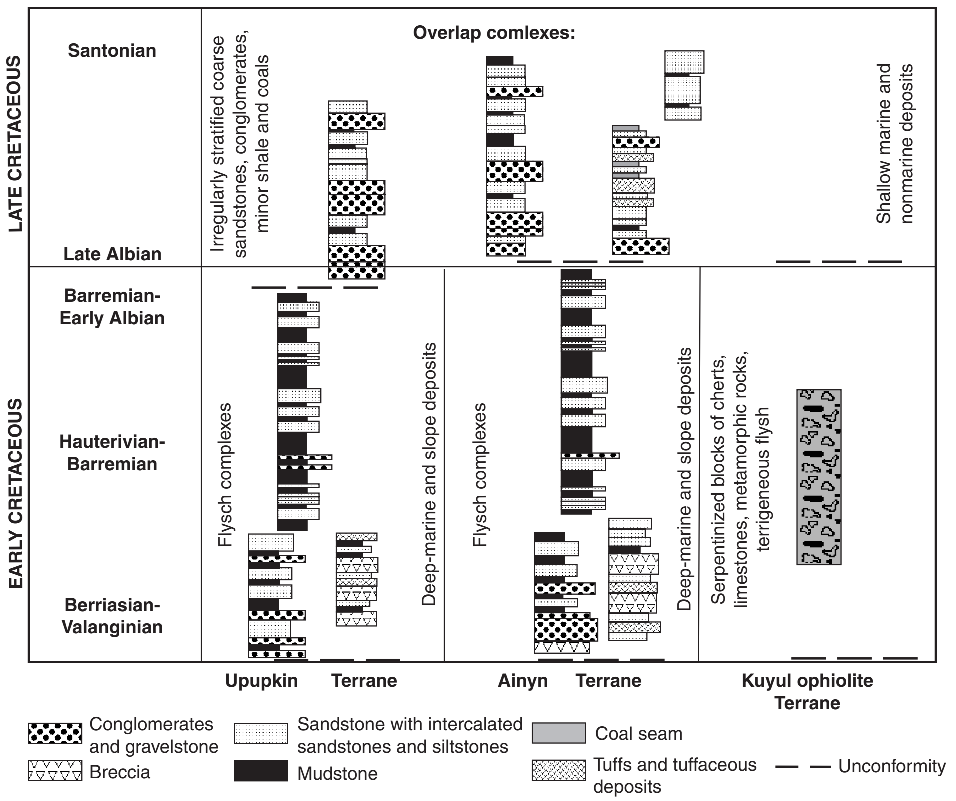

Fig. 14. Generalised lithostratigrapy of the Upupkin, Ainyn, and Kuyul ophiolite terranes.

by serpentinite-bearing sandstones, situated in the northeastern part of the Upupkin Terrane. Another suite, near the western part of the Kuyul Terrane, is distinguished by high abundances of chromite, magnetite, and ilmenite.

Analyses of two sections have enabled reconstruction of sediment provenance and tectonic evolution of the Penzhina area: (1) in the northern region, in the Dlinnaya Mountain of the Upupkin Terrane, ophiolite-derived serpentinite-bearing assemblages have been identified from Hauterivian sandstones (Fig. 16); (2) in the eastern part, chromite-dominated Barremian-Albian sandstones occur, derived from the northern Kuyul ophiolitic rocks (Ainyn Terrane, Vesyolaya river). Epidote is magmatic and is shed by the ophiolites.

Heavy mineral signatures point to two major source provinces for the sediments of the Penzhina area. The zircon, garnet, amphibole and epidote-bearing assemblages, found in Berriasian-Valanginian and Late Cretaceous deposits, were probably derived from the crystalline, medium grade metamorphic basement of the Upupkin and Ainyn terranes. A granitoid or granite-gneiss source, signalled by the abundance of zircon, sphene, and apatite, seems to have played an important role. The second province, associated with island arc volcanics, is indicated by magnetite, ilmenite, and clinopyroxenes in the Hauterivian-Albian formations. A high percentage of detrital chromite records the erosion of the ultramafic unit of an ophiolite body.

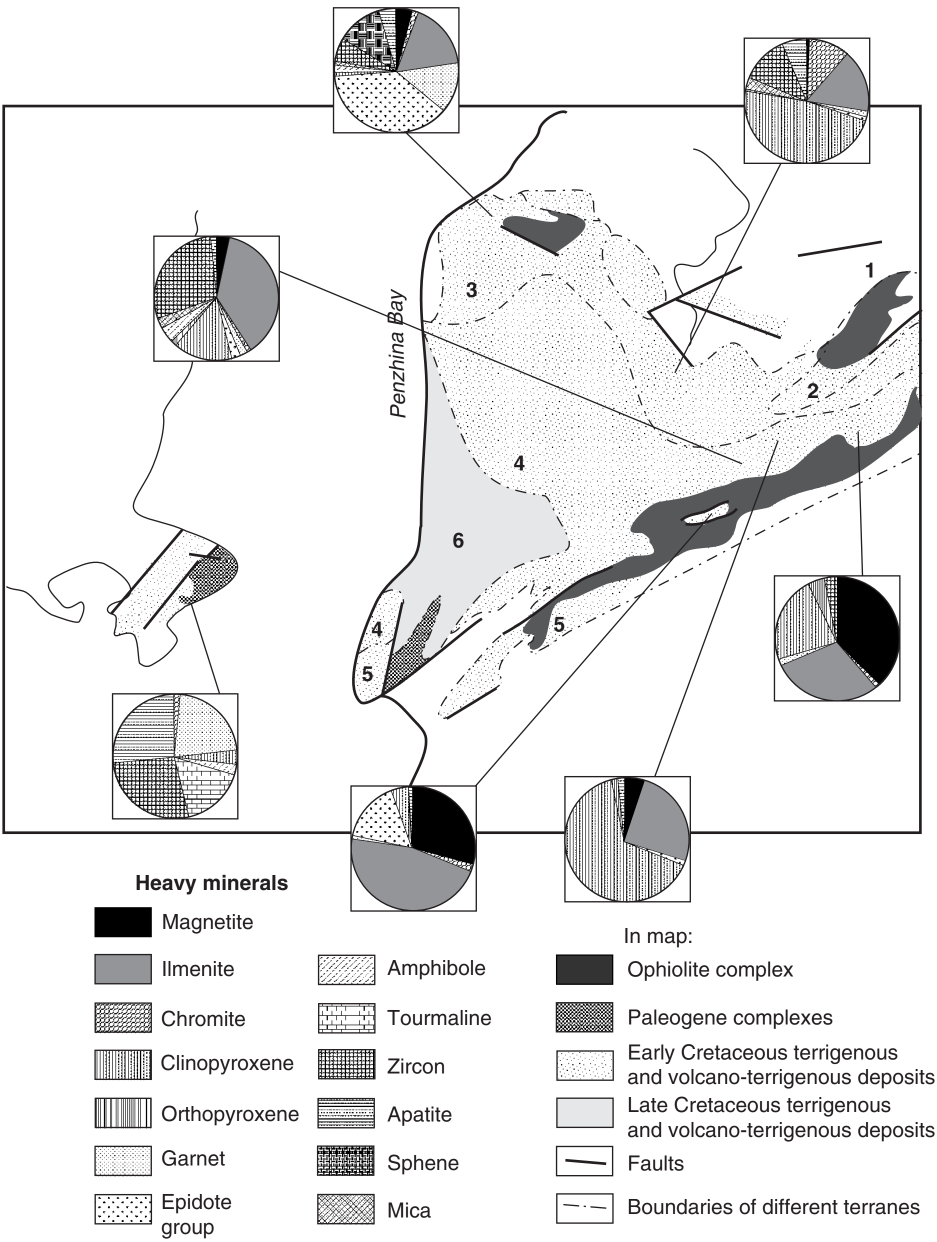

Fig. 15. Average heavy mineral associations in the Berriasian-Valanginian deposits. Numbers in map are the main terranes 1: Kharitonia; 2: Ganychalan; 3: Upupkin; 4: Ainyn; 5: Kuyul ophiolite; 6: Albian-Upper Cretaceous overlap complexes.

According to Sokolov et al. (1999) and Sokolov (2000) the accretionary prism of the Penzhina-Anadyr Terrane consists of Berriasian-Valanginian sediments, accumulated in the deep-seated zone of a forearc, bordered by the Uda-Murgal island arc to the west, and by the accretionary uplift of the Kuyul ophiolites to

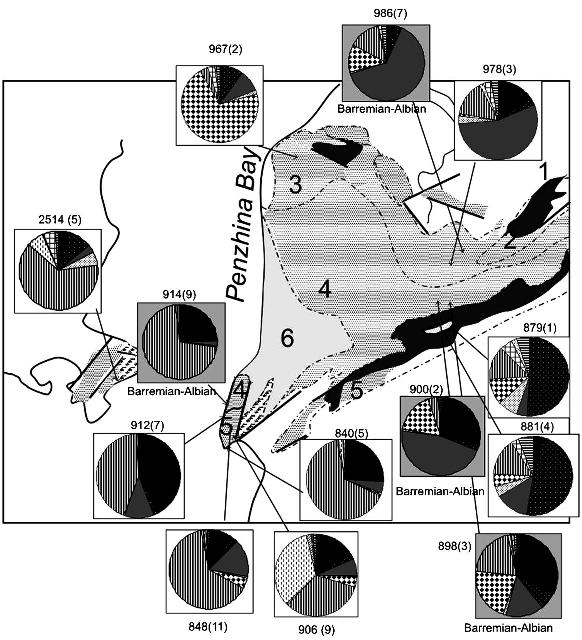

Fig. 16. Average heavy mineral associations in the Hauterivian-Albian deposits. Numbers in parentheses indicate the number of samples used at each location for calculating average heavy mineral compositions. Legend same as in Fig. 15.

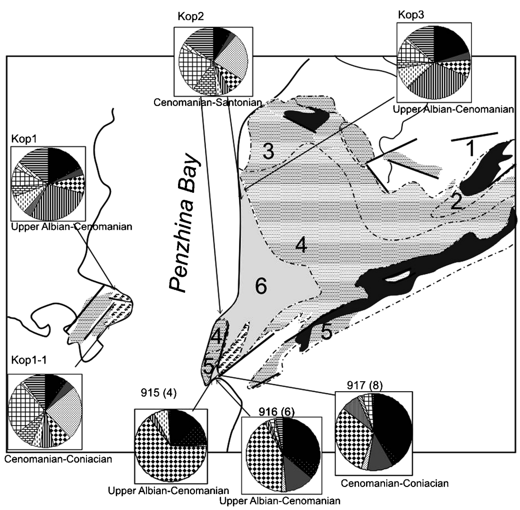

Fig. 17. Average heavy mineral associations in the Albian-Late Cretaceous deposits. Legend same as in Fig. 15.

the east. In the forearc segment of the Uda-Murgal arc, deep-water flysch-type sediments accumulated. They incorporate recycled detritus from the Ainyn and Upupkin terranes, which contain associations of metamorphic origin. In some areas of the Kuyul Terrane sediments predominantly from ophiolitic sources were

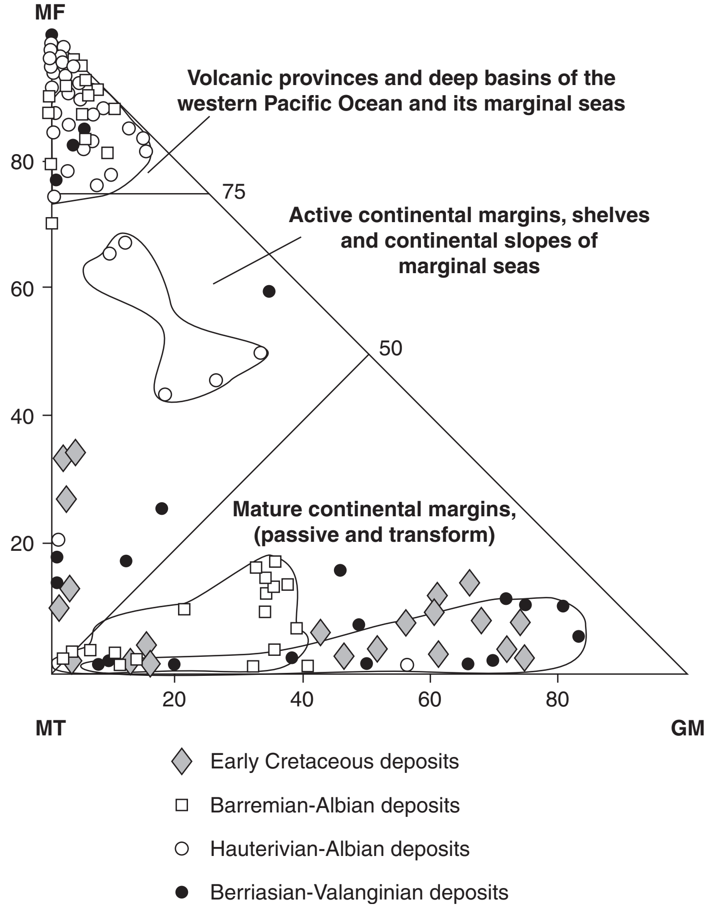

Fig. 18. Correlation of heavy mineral associations from the Penzhina area (sandstones from Upupkin, Ainyn, and Kuyul terranes) and modern sediments from various geodynamic setting on MF-GM-MT diagram (after Nechaev and Isphording, 1993). Legend same as in Fig. 3.

deposited. Hauterivian and Barremian-Albian successions accumulated in similar basins (Fig. 19).

During Albian accretion, Cretaceous sedimentation of the Penzhina Basin changed from deep-marine flysch to a shallow-marine facies. Parallel with the shift in the depositional environment, heavy mineral associations also changed, denoting provenance from continental granitic–metamorphic and basic rocks; one or the other of these lithologies became dominant at different times during the Cretaceous.

Systematic variations in the heavy mineral associations through time reflect the *tectonic evolution* of the region. Tectonic development of the Asian continental margin and of the West Koryak fold belt, which includes the studied region, was related to the sequential accretion of various lithotectonic units to the Asian continent (Sokolov, 2003). Terranes of the Penzhina segment accreted in two stages: (1) pre-Late Albian and (2) during the Late Albian. In the earlier stages (Berriasian-Valanginian), the continental margin acted as the main sediment source. Metamorphic complexes were

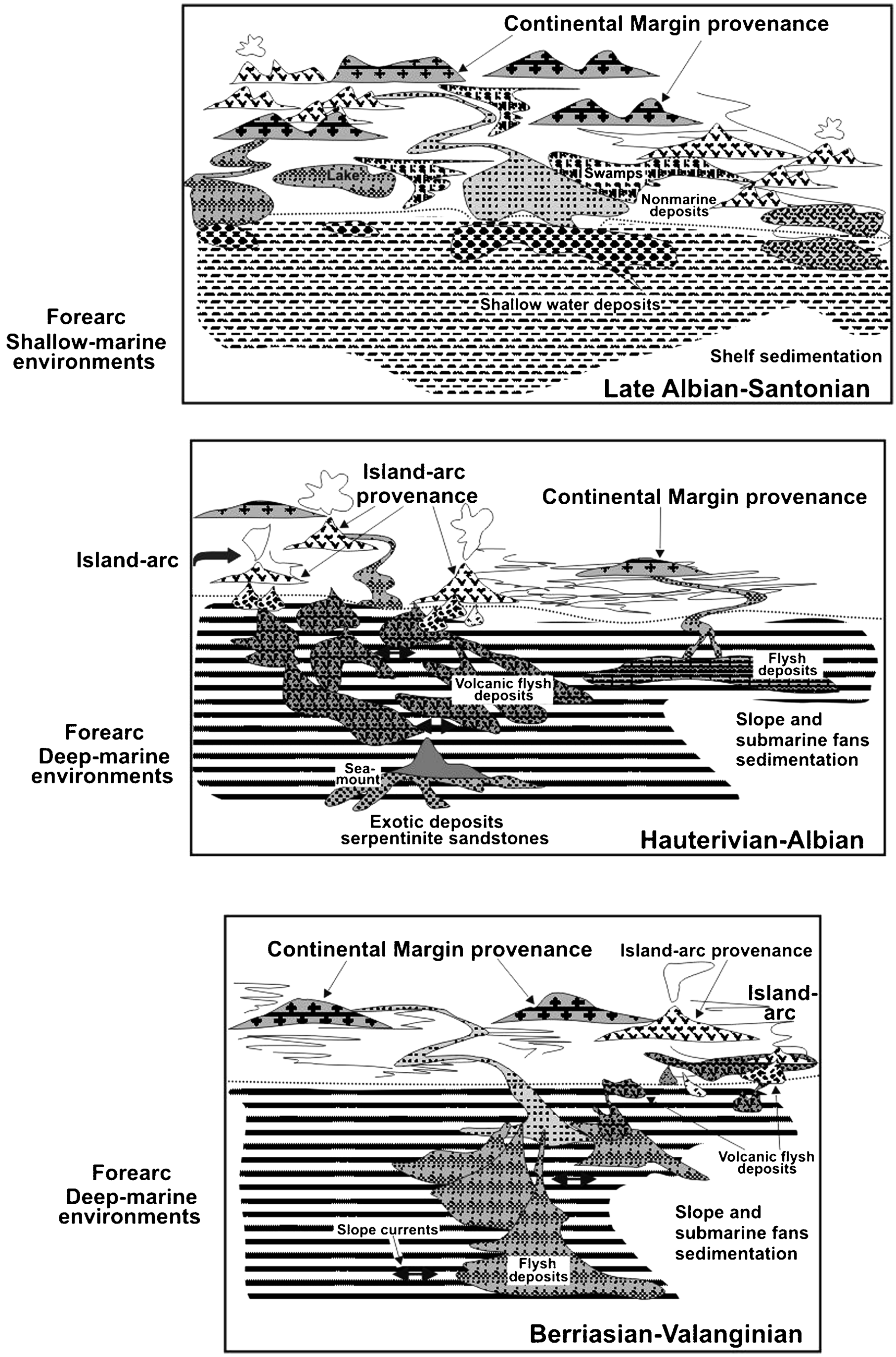

Fig. 19. Model of the Cretaceous sedimentary evolution of the Penzhina Basin, from deep-marine deposits during the Berriasian-Valanginian and Hauterivian-Barremian to shallow-marine—during the Late Albian-Santonian.

eroded and their detritus was delivered to the sedimentary basin by gravity flows and deposited in submarine fans. The low abundance of magnetite and ilmenite indicates a minor influence of island arc volcanism. This was ascertained by the associated volcanic rock fragments and by bulk chemical composition. The dramatic enhancement of volcanism in the Uda-Murgal island arc in the Hauterivian and the erosion of adjacent volcanic edifices resulted in a change of provenance. Heavy mineral associations from volcanics became predominant, whereas the supply of stable minerals from the continental margin declined. The influence of volcanic sources continued in the Barremian and Albian. Following the first stage of accretion, before the Late Albian, the Kharitonia, Ganychalan, and Upupkin terranes had been accreted to the Asian continental margin (Fig. 19). This Middle Cretaceous tectonic rearrangement, caused by the disappearance of the Uda-Murgal island-arc system, changed the environment of sedimentation in the Penzhina Basin. Subsequently, a new subduction zone developed which governed the evolution of the Okhotsk-Chukotka volcanic belt and related sedimentation. During the Late Albian, the second stage of accretion resulted in the accretion of Ainyn and Kuyul Terranes to the Asian continental margin. After the Late Albian, following the disappearance of the Uda-Murgal island-arc, the Okhotsk-Chukotka volcanic belt became the source of volcanogenic detritus to the forearc basins. Following the second stage of accretion, Albian-Cenomanian marine, terrigenous, and Turonian-Early Senonian coal-bearing sequences were deposited in the Penzhina forearc trench of the Okhotsk-Chukotka volcanic belt via numerous fan deltas. Heavy mineral associations from the Upper Cretaceous deposits contain both stable and unstable minerals. Local volcanism of the Okhotsk-Chukotka volcanic belt was active in Albian-Cenomanian and Turonian-Campanian times, reflected by the increasing proportions of volcanic minerals in the Early Albian-Cenomanian deposits.

2.3.2. Olyutorsky Terrane.

The Olyutorsky Terrane is a constituent of the Mesozoic-Caenozoic Olyutorsky-Kamchatka fold belt (Malinovsky, 1993, 1996). The Terrane is situated in the southern part of the Koryak upland region (Figs. 1 and 19), extending toward the northeast along the Bering Sea coast. In the north, it is separated from the Anadyr-Koryak fold belt by the Vatyn Thrust. The Olyutorsky Terrane (Figs. 20 and 21) is a composite of juxtaposed sedimentary units that were once deposited in different environments, probably some considerable distance from their present position. The successions include: Aptian (?)-Turonian volcano–cherty, Coniacian-Palaeocene volcano–sedimentary, Eocene-turbidite, and Oligocene-Pliocene molasse complexes.

The volcano–cherty complex consists of basalts, lava-breccia, tuffs, radiolarian jaspers, and cherts and their clayey alteration products. Mudstones, sandstones, and limestones are rare. The *volcano–sedimentary complex* contains intercalated basalts, tuffs, tephra, volcaniclastic sandstones, cherts, siliceous tuffs and mudstones, mudstones, and cherty-clay. In the upper part of the succession, gravels and conglomerates occur. The turbidite complex encompasses thick, rhythmically alternating sandstones and siltstones, sometimes interrupted by horizons of siltstones, sandstones, gravelstones, basalts, tuffs, tuffaceous-breccia, and mixtites. The molasse complex includes mudstones, sandstones, gravelstones, and conglomerates.

In the Olyutorsky Terrane, detrital heavy mineral signatures define two heavy mineral provinces: Northern and Southern (Fig. 20) (Malinovsky, 1993, 1996).

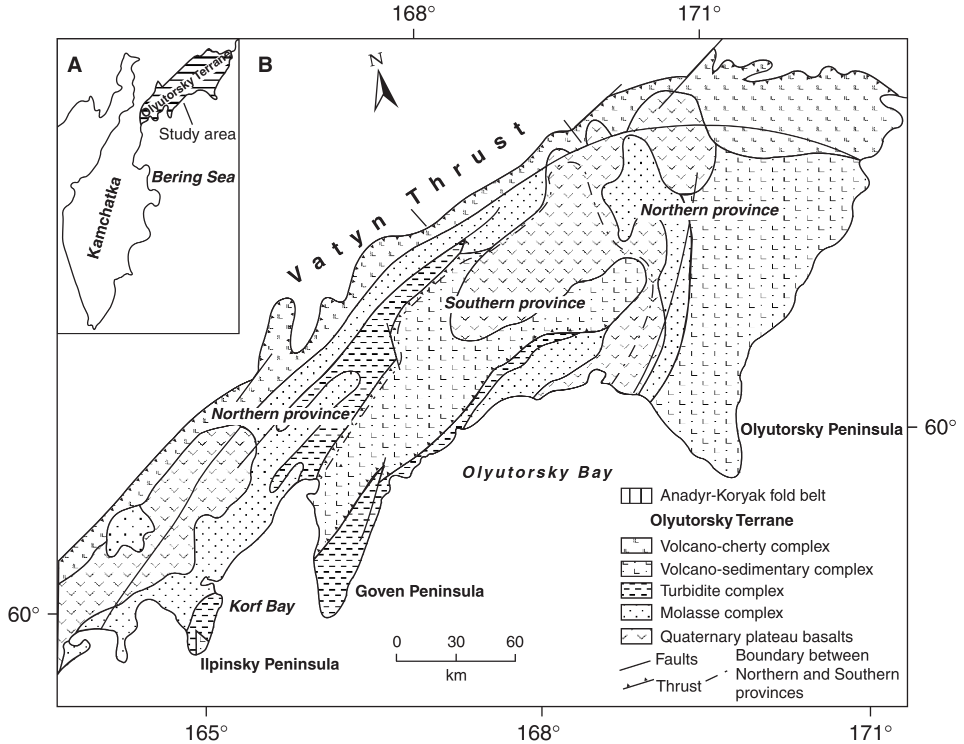

Fig. 20. The location (A) and schematic geologic map (B) of the Olyutorsky Terrane (after Malinovsky, 1996).

In the Northern Province, volcaniclastic, island arc type minerals, such as clino- and orthopyroxenes, magnetite and hornblendes predominate, forming not less than 90% of the total detrital assemblage. Minerals with island arc affinities are dominantly clinopyroxene (with an average of 40–70%, but in one individual case it contains 100% of the heavy mineral suite). Magnetite is less common (average contents in the analysed samples range between 15 and 55%), hornblende makes up 2–30%, and orthopyroxene 1–7%. The high proportion of minerals of the volcanic association, present in the Northern Province, testifies to the erosion of a prominent volcanic hinterland that also contributed synchronous pyroclastic material.

In the Southern Province*,* the role of the volcanic island arc association was also important. Similarly to the Northern Province, clinopyroxene dominates, although with much lower percentages, viz. ranging from 24 to 40%. Magnetite varies from 10 to 35% and chromite from 6 to 14%, but the content of hornblendes and orthopyroxenes is distinctly lower in *the Southern Province* (3% and 5%, respectively). Sialic minerals (10–39%) are, however, more significant; these include zircon, tourmaline, sphene, apatite, rutile, and garnet, the source of which could be sialic magmatic and older sedimentary rocks. Metamorphic and metasomatic corundum, vesuvianite, anatase, allanite, brookite, sillimanite, staurolite, andalusite, kyanite, and fluorite (as aggregates—up to 8%) are also found. These are absent in the

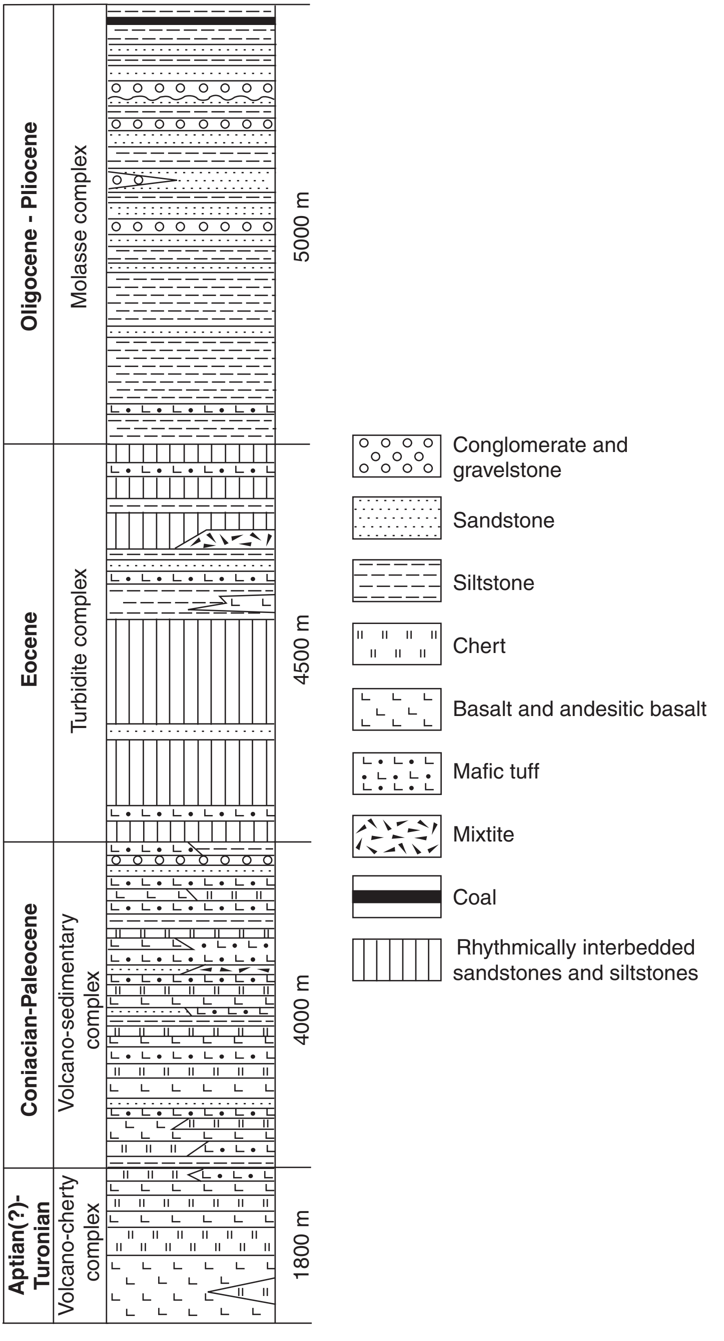

Fig. 21. Generalised lithostratigraphic column of the Olyutorsky Terrane.

Northern Province. The main silicic heavy mineral is zircon (5–25%, occasionally reaching 73%). Apatite (up to 22%), garnet (up to 13%), and rutile (up to 5%) are also present. Other minerals are much rarer. Relatively abundant silicic heavy minerals in the Southern Province suggest granitic–metamorphic continental sources, which made a small but noticeable contribution to the sedimentation.

The evaluation of geochemical data of detrital heavy minerals on the MF-MT-GM and Cpx-Opx-Hb plots (Fig. 3) (Nechaev and Isphording, 1993) allows us to distinguish heavy mineral provenances of both oceanic and island arc origin. The latter resulted from the destruction of an island arc with either an oceanic or a continental foundation. On the MF-MT-GM diagram, all data points of the Olyutorsky Terrane are close to the MF apex, corresponding with sediments of the deep-water depressions of the West-Pacific marginal seas whose main sources of detritus were the island arc volcanics. In the basins of the Southern province, the latter were mixed with continental detritus. The Cpx-Opx-Hb ratios for all points of the Olyutorsky Terrane correspond with an oceanic arc with a small convergence angle of the plates, as suggested by the low content of Opx and Hb (Nechaev and Isphording, 1993).

The nature of the volcanic source of the Olyutorsky Terrane sediments can be identified by the chemical composition of diagnostic detrital heavy minerals. Fig. 4A shows that clinopyroxenes from both provinces of this terrane are diopside and augite. Their origin can be determined on the discriminant diagrams, thus allowing us to distinguish between pyroxenes of basalts from different tectonic settings. In Fig. 4B (after Nisbet and Pearce, 1977), most of the clinopyroxenes correspond with those of island arc basalts but, in part, also with clinopyroxenes from ocean-floor basalts, constituting, probably, some portion of the island arc foundation. This interpretation is supported by the close chemical composition of the Olyutorsky Terrane clinopyroxenes to those from the Vanuatu Trench, which were sourced from the Vanuatu oceanic island arc volcanics. On discrimination diagram 1 in Fig. 5, all pyroxenes cluster near the line demarcating the pyroxenes of alkaline intercontinental basalts and the basalts of the oceanic islands (A) from all other non-alkaline basalts (T). Formally, they would be alkaline basalts, but their low titanium and sodium content prevent them to be confidently related to that group. Diagram 2, which divides non-alkaline basalts into MORB (D) from calc-alkaline and tholeiitic basalts of continental margins and of volcanic island arcs (O), the majority of the Olyutorsky Terrane pyroxenes cluster in the island arc area. In diagram 3, which differentiates island arc pyroxenes into calc-alkaline (C) and tholeiitic types (I), it is apparent that the pyroxenes were derived from tholeiitic basalts.

In Fig. 6 the majority of detrital chromite data points are in the field of volcanic island arcs, whereas the remainder correspond with chromites of intraplate and MORB basalts. The island arc character of the hornblendes is demonstrated by the Ti-Al-Fe diagram (Nechaev, 1991). Their low titanium content suggests they are amphiboles of basic and intermediate island arc volcanics (Fig. 6B). All detrital garnets are almandine (19.49–22.36% Al_2O_3; 22.10–37.27% $FeO + Fe_2O_3$). The garnets (Fig. 6C) most probably originated from acid plutonic and effusive rocks (Kazachenko, 2001) and/or metamorphic sources. This is most likely for the garnets of the Southern Province, which are noticeably different in composition from garnets of the Northern Province, and are associated with sialic minerals.

Heavy mineral associations and the chemical composition of individual heavy minerals identify two principal source regions for the forearc basin sediments of both provinces of the Olyutorsky Terrane. Their lithologies persisted from the Late Cretaceous to the Neogene, throughout the geological history of the terrane. The prominent source for both provinces of the Olyutorsky Terrane was the Cretaceous-Palaeogene oceanic island arc and products of associated synsedimentary volcanism. The second source included an external continental, silicic complex that played a subordinate role, sourcing mainly the Southern province. Concluding from granitic–metamorphic heavy mineral signatures in the Southern province, the continental source formed a significant high that was exposed south of the Olyutorsky Terrane in the current Bering Sea.

2.3.3. Peculney Mountains.

From the Peculney Mountains Ordovician to Early Cretaceous sandstones have been studied. Ordovician sandstones are highly tuffaceous and contain almost exclusively pyroxenes, originating from synsedimentary volcanism. In Silurian and younger sandstones, there are two heavy mineral associations: (1) a dominant mafic suite, including chromite, magnetite, ilmenite, leucoxene, pyroxenes, hornblendes, and epidote and (2) a sialic suite, comprising zircon, sphene, tourmaline, apatite, rutile, and garnet. In the Lower Silurian and Carboniferous sections of the succession, abundant chromite indicates a typical ultramafic source, postulated as an ultramafic, ophiolitic oceanic rise. The Permian and, especially, the Lower Cretaceous sections, have low abundances of chromite, coinciding with increased amounts of ilmenite and magnetite. This may indicate mainly gabbroic source rocks. In the upper part of the Lower Cretaceous, the quantity of the heavy minerals with ultrabasic and mafic signatures diminished. The remaining part of the heavy mineral spectra is occupied by the mafic suite, with abundant pyroxenes, resembling the Ordovician associations. Parallel with temporal changes in the distribution of the mafic associations, a clear trend with a progressive decrease of the sialic component can be detected from the Silurian to Permian. In the upper part of the Lower Cretaceous the sialic continental influence is virtually absent. The chemical composition of chromites from the Silurian sediments shows affinities with the ultrabasic and basic pre-Silurian rocks of the Kuyul ophiolite Terrane (Fig. 13), and therefore, it can be considered as the source of the detritus.

3. SUMMARY OF SEDIMENTATION AND TECTONIC RECONSTRUCTIONS

The north-western part of the Circum-Pacific orogenic belt, spanning the Phanerozoic of the Russian Far East, incorporates a series of lithologies from a lower, ophiolitic pile, through flysch to molasse. These constitute, as a whole, two main zones within this belt: an inner one, situated to the east of volcanic island arcs, and an outer zone which is sialic and rests on Precambrian continental crust. Marine sedimentary basins were situated in different settings adjacent to an active continental margin. These include foreland, borderland, and backarc basins. The inner zone is oceanic, and developed as an island arc, with prolonged intensive volcanic activity. It supplied large amounts of juvenile mafic material to the sedimentary basins, with sediments accumulating as a series of volcaniclastic greywackes.

The Circum-Pacific orogenic belt comprises two principal sedimentary complexes: arkosic and greywacke. The arkosic complex is characteristic of the outer zone of the north-western part, situated between the Siberian and Chinese cratons. It also occurs as isolated fragments, the Bureya and Khanka massifs, and extends into the Late Cretaceous–Caenozoic East Asia volcanic belt. This complex constitutes the Mesozoic orogenic fold belts and includes the Sikhote-Alin system. It consists mainly of arkosic terrigenous and volcaniclastic rocks, intruded by granitoids of different dimensions, extending to thousands of kilometres. This zone becomes young progressively toward the east from the Palaeozoic to late Early Cretaceous. The mineralogy of the arkosic sediments indicates that the provenance of material in the Mesozoic sedimentary basins was the continental (granitic and metamorphic) crust of the Siberian and Chinese cratons. These contributed sialic heavy mineral associations comprising mainly zircon, sphene, apatite, tourmaline, garnet, sillimanite, rutile, anatase, and brookite.

The greywacke complex is peculiar to the inner zone, situated to the east of the East Asia volcanic belt. Its detrital heavy mineral assemblage is in stark contrast to that of the arkosic complex, and contains associations derived mainly from basic and ultrabasic plutonic and volcanic crustal rocks. The greywackes also incorporate products of volcanic island arc activity. During the initial stages of development, ultrabasic, ophiolite-derived material was the primary sediment constituent. Typical heavy minerals are pyroxenes, chromite, olivine, ilmenite, leucoxene, and hornblendes. Common in both the arkosic and greywacke rocks are magnetite, various garnets, and epidote.

The provenance of the Sikhote-Alin sediments has been interpreted as being the continental Siberian and Chinese cratons, complemented, at the beginning and the close of the Phanerozoic, by minor input from contemporary volcanics. In the Koryak-Kamchatka region sedimentary forearc basins were fed almost entirely by basic rocks amongst which the products of island arc volcanism played a dominant role throughout the Phanerozoic.

Distinctive heavy mineral suites characterise particular plate tectonic settings and indicate provenances, whereas geochemical analysis of individual heavy mineral species serves as a useful tool to define source lithologies and their settings in a plate tectonic context. For example, in our research we used magnetite and chromite compositions to identify, and differentiate between, associations sourced from different types of ophiolites, while the chemistry of detrital pyroxenes identified the main types of volcanic arc sources.

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