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Geological Setting and Lithological Features of Cenozoic Sediments in Ebelyakh Bay (Laptev Sea)

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Abstract—Materials of bottom sampling and drilling on Ebelyakh Bay, the Cape Svyatoi Nos area, and southern part of the Dmitry Laptev Strait by researchers from VNIIOkeangeologiya during the past 60 years and data on the geological setting of the Chokhchur–Chokurdakh zone (Ebelyakh Bay included) were also examined. The geology and lithology of Cenozoic sediments in the water area of the bay and adjacent land were scrutinized to elucidate mineral resources in the Earth's interior in the study area. Analysis of the Upper Jurassic–Holocene summary section shows that terrigenous material was derived from (i) coastal zones composed of granitoid or contact metamorphic rocks, (ii) Quaternary friable sediments of marine terraces and beaches, (iii) submarine rises, and (iv) river discharge. It is shown that cassiterite is associated with the Pliocene–lower Pleistocene Serkino horizon and Holocene sediments. New promising cassiterite areas have been revealed. The results suggest that prospecting for tin placers should be continued at Ebelyakh Bay.

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Intensification of sedimentological processes during last decades primarily in the shallow shelf and coastal zones of the Arctic region due to climate warming required the comprehensive analysis of the available geological data on particular areas of this region.

The main purpose of the complex geological and geophysical investigations carried out on the Russian Arctic shelf over more than a half century was the prospecting for marine and coastal placers of cassiterite and other solid mineral resources.

Like investigations by V.A. Kosheleva (2013), study of the grain size, mineral, and geochemical compositions of friable sediments and their biostratigraphy was conducted to reveal peculiar features in the formation of tin placers in the high-latitude Arctic regions, specify the geological setting of the study area, and understand general regularities in sedimentation on the Arctic shelf. These works should serve as a basis for the further geological, sedimentological, ecological, geological engineering, cryological, and prospecting–exploration investigations for revealing combustible and solid mineral resources in the marine region under consideration.

GEOLOGICAL SETTING OF THE STUDY AREA

The Ebelyakh Bay is located in the southeastern part of the Laptev Sea between Cape Churkin of the Shirokostan Peninsula in the southwest and Cape Svyatoi Nos in the north (*Lotsiya ...,* 1977; *Atlas ....*,1980). The bay up to 11 m deep is opened in the northwesterly direction and intrudes as an arc into the continent for 26 km. In the Cape Svyatoi Nos area, the shore notably rises to the altitude of 394 m. At the boundary with the sea, Cape Svyatoi Nos is characterized by abrasion scarps, which represent active cliffs. The cape is composed of relicts of Early Cretaceous granitoids (*Geologiya* ..., 1970a, 1970b; *Geologicheskoe* ..., 1984).

The continental coastal part of the bay is located in the Yana–Indigirka lowland rising in a stagewise manner to the altitude of 180 m. In some areas of the coast, the lowland reaches the seashore as abrasion scarps (10–25 m high) composed of friable permafrost rocks fringed mostly by silty–clayey beaches. The shores of the bay and Dmitry Laptev Strait in outcrops of Cape Svyatoi Nos bedrocks are abrasive and steep up to >30 m high in some places. These shores are located behind the muddy–sandy (locally, pebbly) beaches. The remaining shores of the bay and strait are relatively low and muddy (*Lotsiya* ..., 1997, 1998). In addition to Cape Svaytoi Nos, smaller bedrock relicts tower above the lowland. The surface of the flat, terraced, highly waterlogged Yana–Indigirka lowland is covered by a dense system of lakes, rivers, and creeks. Some rivers and creeks, which incise the shores and flow into the bay and Dmitry Laptev Strait, supply them mainly with the silty–clayey material. Mouths of some rivers in the Cape Svyatoi Nos area are fringed by pebbly beaches. The eastern and southern parts of the bay are occupied by a spacious intermittently drained sandy–silty–clayey shoal extending along shores over >10 km. The bay shores dip gently under the water. The bottom topography of the bay represents a flat continental continuation with a spacious bank (up to 2.7 m deep) located in the middle of the bay entry.

MATERIAL AND METHODS

The coring and drilling samples obtained in Ebelyakh Bay, the Cape Svyatoi Nos area, and southern part of the Dmitry Laptev Strait by researchers from the Research Institute of Geology and Mineral Resources of the World Ocean, VNIIOkeangeologiya (A.I. Gusev, O.A Ivanov, V.I. Kaiyalainen, V.S. Lomachenkov, K.S. Ageev, D.V. Levin, A.I. Samusin, S.V. Beimart, N.P. Semenov, M.N. Blagoveshchenskii, V.A. Kosheleva, and others) during the last 60 years were used for this investigation. The works were conducted in cooperation with geologists from the Yakutian Geological Survey (V.K. Pokrovskii, A.Ya. Andrusenko, M.S. Kir'yanov, V.M. Mel'nikov, E.G. Savrasov, and others).

Assessment of the tin potential of Cenozoic sediments in the Ebelyakh Bay and Dmitry Laptev State areas was accompanied by geological and geophysical investigations.

Materials of the Sevmorgeo Scientific-Production Association obtained in Ebelyakh Bay and coastal part of the Dmitry Laptev Strait in 1974–1975 served as a basis for the work (Fig. 1). In total, 163 boreholes were drilled from the shipboard and 8 boreholes were drilled from the ice platform to a depth of 15 m. The results of analysis of the grain size and mineral compositions of bottom sediments sampled at 10 stations in the eastern part of the Laptev Sea and western part of the East Siberian Sea (Semenov et al., 1961, 1967) were also taken into consideration.

Bottom sediment sampling was accompanied by the seismic acoustic (1204 km), hydromagnetic (1236 km), ice-based magnetic (200 km), and ice-based gravimetric (50 km) surveys. Boreholes (70 mm in diameter) were drilled with the vibrodrill system to a depth of 4.5 m. Sites for vibrodrilling were chosen taking into consideration the results of seismoacoustic investigations including works by the Yana Geological–Exploration expedition (YanGRE) and Moscow Geological–Prospecting Institute (MGRI). Samples from vibrodrill core were with a spacing of 0.5–1.0 m. The following analyses were performed in laboratories of the Research Institute of Arctic Geology (NIIGA): identification of minerals in thin sections (189 samples) and useful components (120 samples), palynological analysis (35 samples), determination of the grain size composition (189 samples), mineralogical analysis, i.e., determination of the major, accessory, and heavy minerals (131 samples), X-ray structural (15 samples), approximate-quantitative spectral analysis (400 samples), and quantitative spectral analysis for Sn (74 samples) and Au (10 samples).

The analyses were conducted in line with standard techniques used for the study of bottom sediment composition and modified at NIIGA by N.N. Lapina (1977). The complex study of the composition of sediments recovered from Ebelyakh Bay and Dmitry Laptev Strait, their structure, and formation setting was performed in field and stationary conditions by V.A. Kosheleva (1975–1976).

The results of both previous and recent geological and geophysical investigations carried out by geologists from NIIGA and Sevmorgeo in the region under consideration along with the adjacent shelf and land areas were also taken into consideration. The geological and geophysical investigations of the region including Ebelyakh Bay, Cape Svyatoi Nos, and the Dmitry Laptev Strait were mostly performed by scientists from NIIGA, Sevmorgeo, and VNIIOkeangeologiya prior to 1990. The results are presented in classified reports. We also used the later data on the geology, lithology, and geomorphology of the study area (Kosheleva and Yashin, 1999; *Geologicheskaya* ..., 2004; Kosheleva, 2013).

HISTORY OF INVESTIGATION OF THE STUDY AREA

E.V. Toll (1899) and K.A. Volosovich (1902, 1930) were the first to obtain information on outcrops of the pre-Cenozoic basement in the Yana–Indigirka lowland, which includes the study area. The reconnaissance geological prospecting carried out by geologists from the Dal'stroi Trust in 1947–1949 under the supervision by B.V. Pepelyaev revealed the regional tin potential associated with Cretaceous granitoids in the Cape Svyatoi Nos area. In 1949–1952, these objects were investigated and explored by G.M. Zubkov, L.L. Dubovikov, A.S. Titkov, A.V. Gorelyshev, and other geologists from the Yana Geological-Mining Survey.

In 1955–1968, workers of NIIGA (A.I. Gusev, O.A. Ivanov, V.I. Kaijalainen, V.S. Lomachenkov, and others) conducted geological prospecting and exploration in some areas of the Yana–Indigirka lowland including the Cape Svyatoi Nos area. In 1962–1967, the aeromagnetic survey (scales 1 : 50000, 1 : 200000, and 1 : 500000) was carried out in the land area adjacent to Ebelyakh Bay by M.S. Samynskaya, V.P. Toropchinov, A.N. Orlov, and others from the Yakutian Geological Survey. These surveys made it possible to outline granitoid intrusions overlain by a cover of friable sediments.

In 1965–1973, S.M. Prokhorova, O.A. Ivanov, and S.I. Andreeva (NIIGA) specified the geological setting of the region. They also investigated the granitoid massifs and their relation with tin ore occurrences. In 1967–1969, scientists from the Russian State Geological-Prospecting University (RGGRU, former MGRI) studied bottom sediments of shallow coastal areas of Ebelyakh Bay and revealed their general contamination with cassiterite.

The long-term (1952–1977) investigation of the terrigenous mineralogical provinces of the Permian–

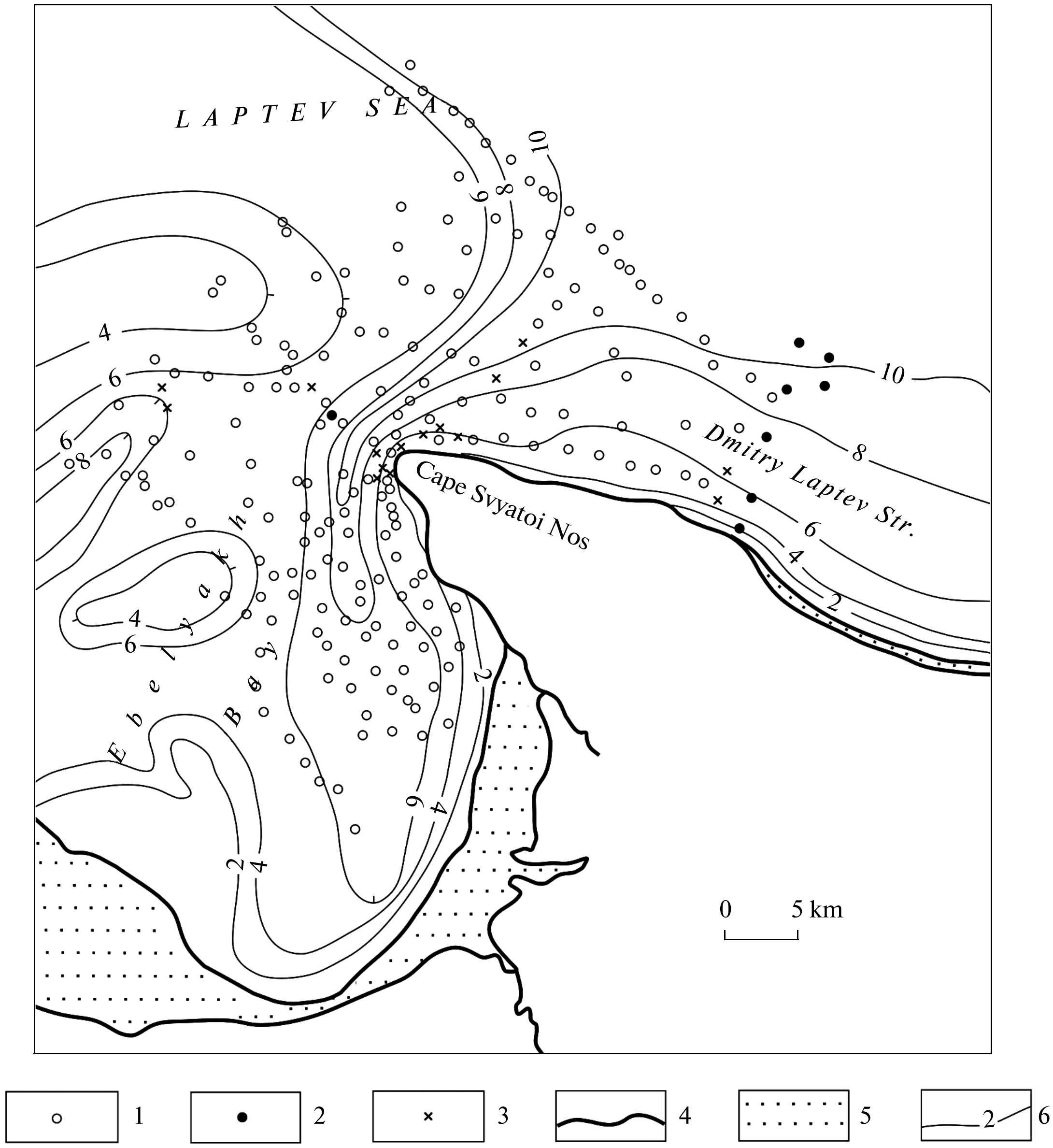


Fig. 1. Schematic location of boreholes and coring stations cores in Ebelyakh Bay. (1, 2) Boreholes: (1) vibrodrilling, (2) ice-based drilling; (3) coring stations; (4) shoreline; (5) coastal shoals, drained zone; (6) isobaths.

Mesozoic sequence in the northern part of Central Siberia were carried out by Z.Z. Ronkina and T.N. Vishnevskaya. They accomplished 4125 mineralogical analyses of rocks of the following ages: Permian (1117 analyses), Jurassic (1396), Cretaceous (1311), and Triassic (301). Figure 2 shows the paleogeographic setting of this region based on these results (Ronkina and Vishnevskaya, 1977).

In 1973–1976, V.I. Ushakov, V.K. Dorofeev, M.G. Blagoveshchenskii, and others accomplished exploration of the coastal zone in the western part of the East Siberian Sea (including the Dmitry Laptev Strait) for estimating the tin and gold potential of the region (Ushakov et al., 1976). In 1969–1975, scientists from Geological Institute of the Russian Academy of Sciences (V.V. Zinov'ev and others) provided the preliminary assessment of the tin potential of the shelf zone in the eastern part of the Laptev Sea including the Ebelyakh Bay and Cape Svyatoi Nos areas.

Special works were carried out in 1973–1976 in the Cape Svyatoi Nos area by geologists from NIIGA to specify the geological setting of the region and outline areas with promising cassiterite placers (Semenov et al, 1976). These works revealed that the Chokhchur–Chokurdakh zone (both land and shelf areas) is marked by development of the granodiorite–granite–leucocratic formation (Yana Complex). Igneous rocks, their host contact-metamorphic terrigenous

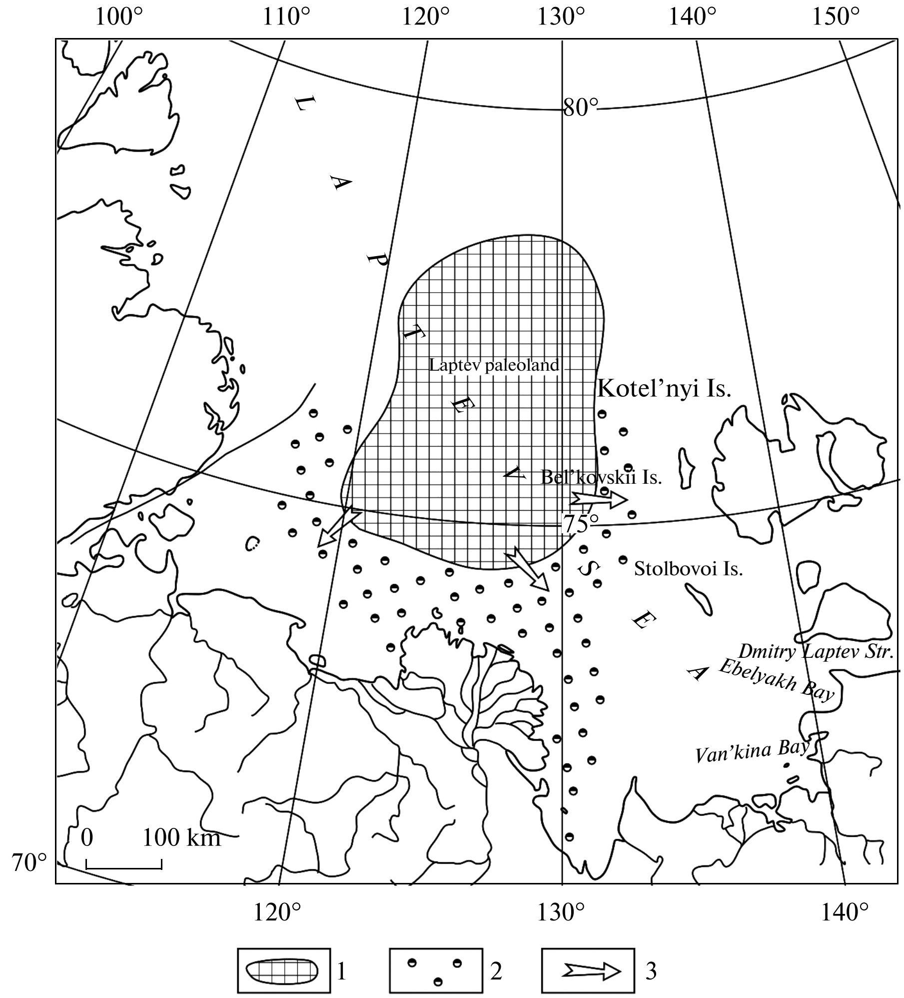


Fig. 2. Schematic paleogeography of northern Siberia in the Early Cretaceous, after (Ronkina and Vishnevskaya, 1977). (1) Laptev paleoland; (2) epidote–magnetite (hematite)–garnet terrigenous–mineralogical province; (3) direction of the terrigenous material transport.

sediments, and tectonic fractures with the endogenic tin mineralization are ore-bearing zones. They form several cassiterite deposits and occurrences belonging mostly to the cassiterite–silicate formation.

Ore occurrences are associated with cassiterite placers of usually Pliocene–Early Pleistocene age. Sandy–pebbly rocks of the Serkino horizon (Pliocene–lower Pleistocene), which are exposed on the coast of Ebelyakh Bay and spatially confined to outcrops of granitoid intrusions, can be promising cassiterite placers. Simultaneously, they represent the intermediate cassiterite reservoirs for the recent coastal-marine and marine sediments of the bay and southern part of the Dmitry Laptev Strait (Fig. 3). For example, the cassiterite content in bottom sediments of the coastal part of Ebelyakh Bay near Cape Svyatoi Nos exceeds 100 g/m^3 in one sample (Semenov et al., 1976). Workers of the All-Union Geological Fund (VGF) estimated the placer metal and petroleum potential of the Yana–Kolyma lowland and adjacent coastal-shelf zone (Balandin, 1983).

The shelf of the Laptev Sea is a promising object for the exploration of hydrocarbon pools (Kleshchev, 2007). The promising petroliferous structures of the second category (Stolbovoi horst and Shelonskaya terrace) are outlined on the shelf north and northwest of Ebelyakh Bay, respectively (Kim et al., 2007). During future exploration works on oil, gas, and solid mineral resources, Ebelyakh Bay should become an important object for geoecological monitoring.

GEOLOGICAL SETTING OF THE PRE-CENOZOIC BASEMENT AND BEDROCK SOURCES OF CASSITERITE

The Cape Svyatoi Nos area is an element of the Chokurdakh Sn-bearing placer cluster. Study of the geological setting of the pre-Cenozoic basement in the Chokhchur–Chokurdakh zone and the entire Yana–

Indigirka lowland is difficult because of the thick Cenozoic sedimentary cover. In the southeasterly direction, the pre-Cenozoic basement of the Chokhchur–Chokurdakh zone becomes shallower. The Svyatoi Nos mountainous massif is composed of the slightly deformed monoclinal sequence of Lower Cretaceous volcanogenic rocks intruded by a granodiorite pluton (Fig. 3). The volcanogenic rocks dip at 20°–45° NNE. It is conceivable that the basal part of the Lower Cretaceous sequence in the Svyatoi Nos massif is composed of the deformed Upper Jurassic terrigenous rocks as in the Mount Chokurdakh area located southeast of Cape Svyatoi Nos, where they are up to 1000 m thick (Prokhorova and Ivanov, 1973; Kosheleva, 2013).

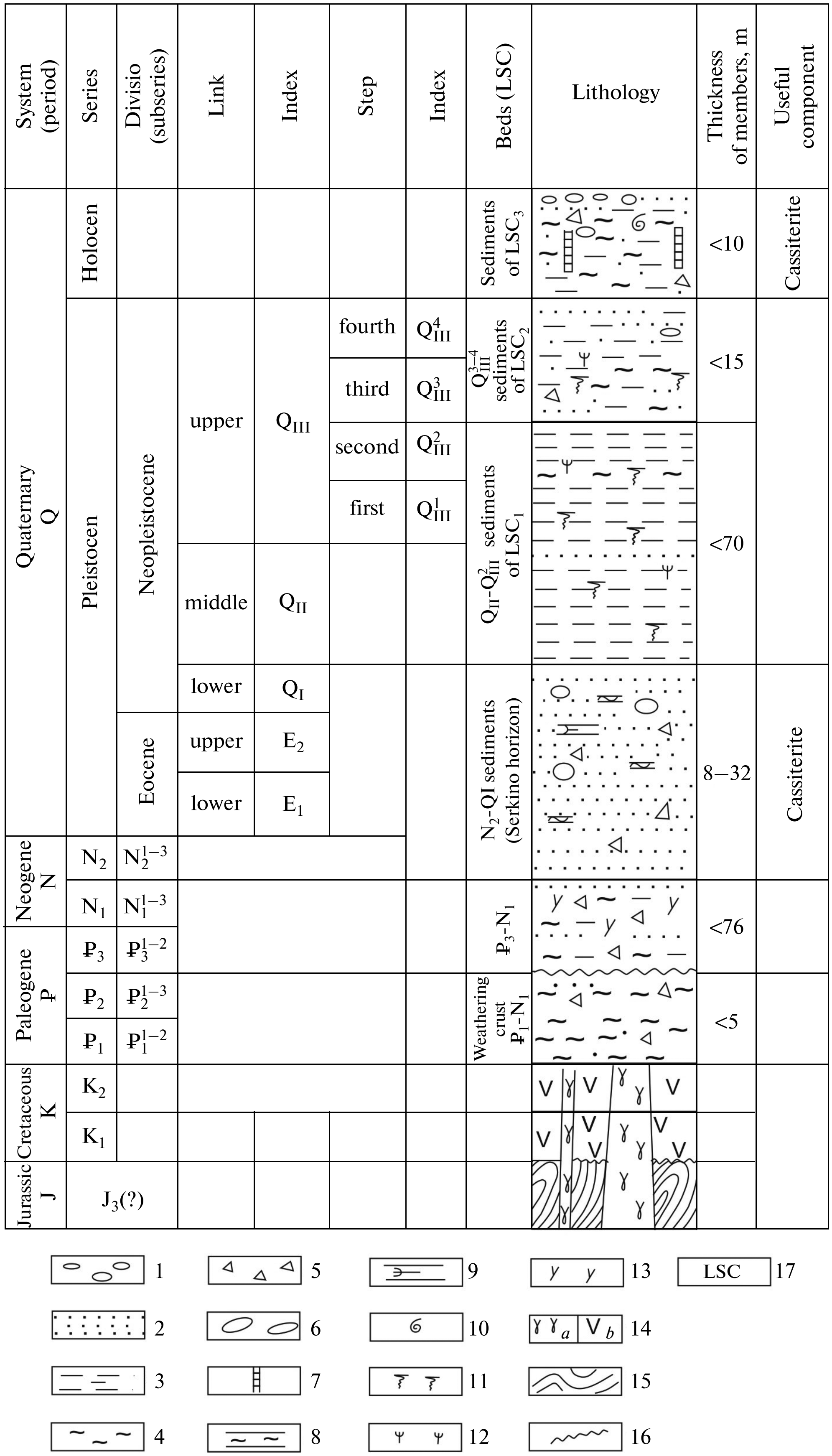
Such an assumption is indirectly confirmed by the geological setting of the Laptev paleoland (Ronkina and Vishnevskaya, 1977). The latter structure, which is likely characterized by the mountainous relief and composed of metamorphic sequences and acid volcanics, existed in the Permian–Early Cretaceous within the present-day Laptev Sea north of the Lena River mouth. The paleoland was subjected intermittently to intense erosion, resulting in the transport of accessory minerals of different associations to sediments (Ronkina and Vishnevskaya, 1977). In the terminal Early–initial Late Cretaceous, the Laptev paleoland experienced peneplanation with the formation of weathering crust in some areas, which supplied garnet, epidote, titanite, and ore minerals (ilmenite and magnetite) to sediments. The latter authors note that the main share of clastic material was transported into the Permian–Mesozoic basins from relatively proximal provenances. The presence of pyroclastic material in Triassic sequences of the Laptev paleoland explains its insignificant admixture in younger friable sediments of the eastern Laptev Sea. The Laptev paleoland and its erosion influenced undoubtedly sedimentation in the shallow coastal zone of the shelf in the eastern part of the Laptev Sea, including the Ebelyakh Bay and Svyatoi Nos areas as well (Fig. 2). It is conceivable that the Laptev paleoland and pre-Cenozoic basement beneath Stolbovoi Island and the Svyatoi Nos massif of the Chokhchur–Chokurdakh zone have a common origin. In structural–tectonic zoning maps of the Laptev Sea and its surrounding areas, the Laptev paleoland is interpreted as a buried block-arch uplift (with multistage structure in some places) fringed in the east and southeast by riftogenic trenches and grabens filled with sediments (*Geologicheskoe* ..., 1984). The geological setting of the Laptev Sea (*Geologicheskaya* ..., 2004) is consistent with this assumption. If this is correct, some Cenozoic sequences of the eastern Laptev Sea areas adjacent to the Laptev paleoland, which are characterized by relief variations and tectonic fractures, contain high concentrations of cassiterite or even its lenticular accumulations. Their formation is evidently related to transgressive-regressive processes and other neotectonic factors, which stimulate the natural panning of sediments derived from the metamorphic and acid volcanic rocks of the Laptev paleoland.

The volcanogenic section of Cape Svyatoi Nos is divided into four sequences. The lower (first) sequence is composed of alternating massive autoclastic basalts, their coarse- to medium-grained tuffs, and thin-bedded fine-detrital volcanic rocks. Its apparent thickness is 220–260 m. The second sequence is represented by alternating coarse- to medium-grained basalt tuffs with rare thin-bedded tuffaceous mudstone intercalations. The thickness is 320–360 m. The third sequence consists of thin-bedded tuffaceous mudstones, tuffaceous siltstones, and fine-detrital volcanic rocks with rare intercalations of detrital basalts. The thickness is 150–190 m. The upper (fourth) sequence is mainly composed of basic tuffs with large (up to 10–15 cm across) angular fragments of tuffaceous siltstones. Its recovered thickness is 220–280 m. Total thickness of the section is 1000–1100 m (Prokhorova and Ivanov, 1973; *Geologicheskoe* ..., 1984).

The granodiorite intrusion crops out on the western slope of the mountainous range hypsometrically below the summits composed of volcanogenic rocks (Fig. 4). The outcrops of intrusive rocks form a band (up to 4 km wide) extending southeastward over 18 km from Cape Svyatoi Nos. The land area occupied by the intrusive body is 56 km^2 in size and its whole size is approximately 400 km^2. Its surface dips (dip angle ranges from 40′ to 1°) under friable sediments of the bay and Dmitry Laptev Strait from a depth of ~60 m near the shore to ~200 m near the outer boundary of the bay. The gentle deep of the bedrock is observable up to an altitude of ~100 m. The offshore surface of bedrocks is bent, resulting in increase of the dip angle and friable cover. This bent likely marks an ancient shoreline. The intrusion exhibits systems of NW- and NE-oriented (younger) fissures.

In the aeromagnetic field, the intrusion is marked by the negative anomaly with intensity up to –130 γ, contours of which correspond to its boundaries at the present-day erosion surface. Contact-metamorphosed rocks fringe the intrusion as a narrow band (3–5 km) characterized by a positive anomaly zone with intensity varying from 150 to 520 γ. Intensity of positive anomalies varies from 300–500 γ near the northeastern contact of the intrusion to 120–130 γ along the southwestern periphery of Cape Svyatoi Nos. It is conceivable that such variations are determined by the plate-type shape of the intrusion, which dips toward northeast. Host rocks with the highest concentration of useful minerals are confined to the intrusion top. The intrusion extends along the strike of volcanogenic rocks.

With respect to its structure, Cape Svyatoi Nos and adjacent areas of Ebelyakh Bay and the Dmitry Laptev Strait make up the central part of the NW-oriented horst. In the southwest and northeast, the horst is bounded by graben-shaped troughs filled with Paleo-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Series
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Link
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Beds (LSC)
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Quaternary Q
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Pleistocen
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<15
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Q_{II}-Q_{III}^2 sediments of LSC_1
<70
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Q_{II}
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Eocene
upper
E_2
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N_2-QI sediments (Serkino horizon)
8–32
Cassiterite
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<76
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Weathering crust ₽$_1$-N_1
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Cretaceous K
K_2
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a
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Fig. 3. Summary section of Upper Jurassic (?)–Cenozoic sediments in the southeastern Laptev Sea (Ebelyakh Bay). (1–6) Sediments: (1) pebble gravel, (2) sand, (3) silt, (4) clay, (5) grus and rubble, (6) boulders; (7) Polychaeta tubes; (8) mud intercalations; (9) peat intercalations; (10) shelly detritus; (11) plant remain; (12) peat; (13) fragments of brown coal; (14) granitoids (*a*) and volcanogenic rocks (*b*); (15) deformed terrigenous rocks; (16) angular unconformities; (17) lithostratigraphic complex (Kosheleva and Yashin, 1999).

gene–Neogene friable sediments. The surface topography of bedrocks is crossed by valley-shaped troughs and uplifts with an amplitude up to 60 m. The axes of positive and negative structures of the buried relief are oriented in the fan-type manner from Cape Svyatoi Nos. Many negative morphostructures of the basement surface are located at the continuation of present-day water streams. Such areas of the bay may be favorable for the accumulation of heavy minerals (including cassiterite).

The intrusion is composed of the medium-grained pyroxene, hornblende–pyroxene, and pyroxene–biotite granodiorites. At the contact of the intrusion with volcanogenic host rocks, granodiorites are characterized by a finer structure. They often contain schlieren of melanocratic granodiorites, quartz dior-

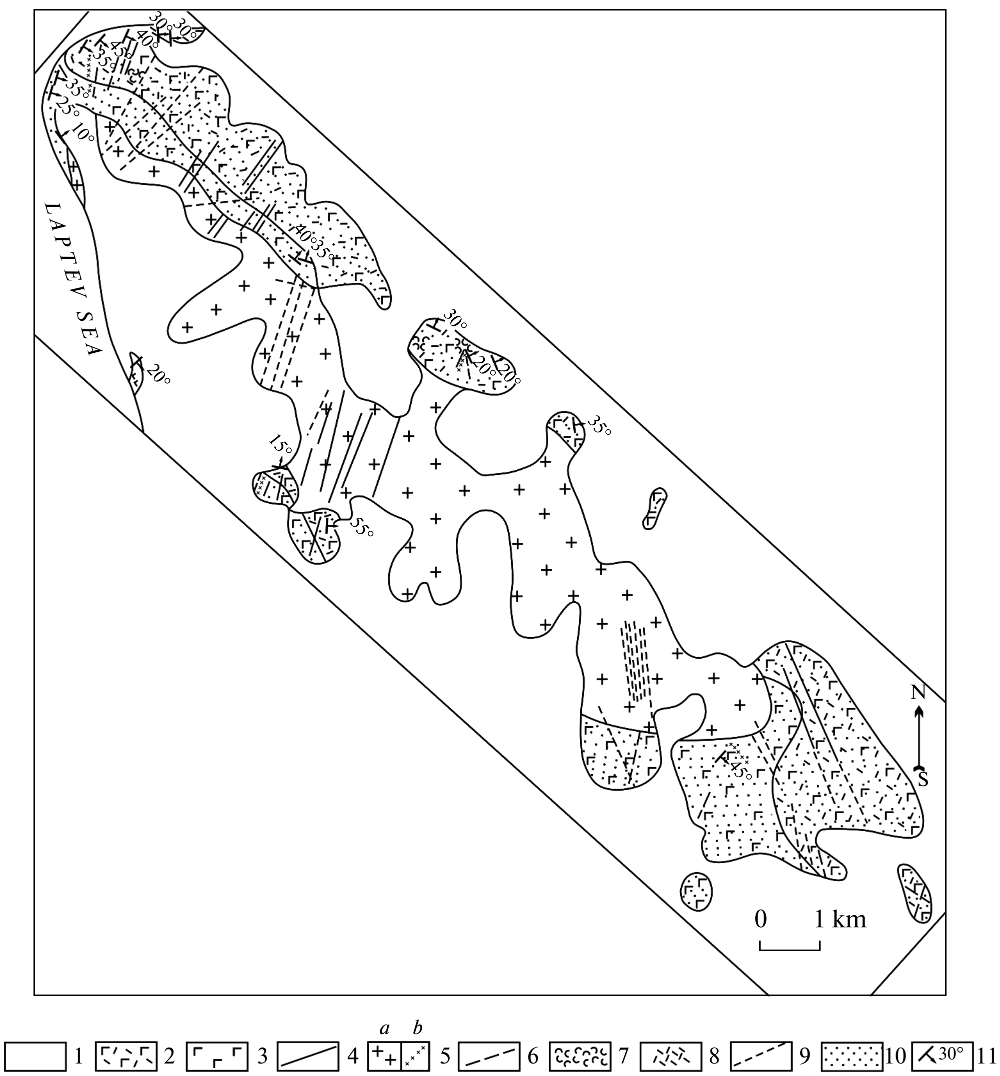

Fig. 4. Schematic structure of the Svyatoi Nos intrusion, after (Prokhorova and Ivanov, 1973). (1) Quaternary sandy loam; (2, 3) Cretaceous (?) rocks: (2) basic tuffs, (3) autoclastic basalts, their tuffs, and intercalation of volcanic rocks; (4–6) Lower Cretaceous intrusive complex: (4) quartz porphyry and granite porphyry dikes, (5) bipyroxene, hornblende–pyroxene, pyroxene granodiorites (*a*) and granodiorite porphyry dikes (*b*), (6) diorite porphyry dikes; (7) quartz and quartz–feldspar veins and their fragments; (8) quartz–tourmaline veins and their fragments; (9) faults; (10) hornfelsization zone; (11) attitude elements.

ites, and xenoliths of host rocks. At the contact with the intrusion, autoclastic basalts are enriched with biotite and amphiboles, while volcanogenic detrital rocks are transformed into cordierite, pyroxene–scapolite–plagioclase, quartz–plagioclase–chlorite, or plagioclase–hypersthene–biotite hornfels.

Dikes are represented by diorite porphyries preceding the intrusion emplacement, granodiorite porphyries synchronous with the formation of the granodiorite massif, and younger granite porphyries and quartz porphyries. Diorite porphyry and quartz porphyry dikes occur in both host rocks and intrusion. All of them are oriented mostly in the northeasterly direction. Thickness of dikes varies from 0.5 to 7.0 m (up to 15 m in some cases).

Pneumatolytic-hydrothermal and hydrothermal mineralization is relatively intense with postmagmatic minerals being most widespread in the host volcanogenic rocks.

In terms of mineral composition, vein and veinlets are represented by the quartz–feldspar, quartz–tourmaline, quartz, carbonate, axinite, and chlorite varieties.

The quartz–feldspar veins 5–20 cm thick are recorded among volcanics. One can also see quartz–muscovite–feldspar, quartz–amphibole–feldspar, quartz–pyroxene–feldspar, and quartz–prehnite–feldspar veins. Accessory minerals in them are represented by the bipyramidal-prismatic cassiterite crystals, platy allanite crystals, arsenopyrite, pyrrhotite, chalcopyrite, pyrite, and galena.

The widespread quartz–tourmaline veinlets 1–10 mm thick are associated with the granite porphyry and quartz porphyry dikes. They also occur in the host granodiorites and volcanogenic rocks. The quartz–tourmaline veinlets contain rare sulfides, axinite, and cassiterite. The quartz veins up to 30 cm thick crosscut all rocks of Cape Svyatoi Nos and are the youngest among the veins. Accessory minerals in them are represented by feldspars and axinite associated with the subordinate galena, pyrite, and secondary minerals, such as pyromorphite, Fe-hydroxides, prehnite, and calcite. Cassiterite occurs as rare crystals 0.1–0.2 mm across. Axinite, chlorite, and carbonate veinlets are rare and barren of cassiterite. Single cassiterite grains were recorded in panned samples from quartz–feldspar rocks, quartz veins, and quartz–tourmaline veins, which also include arsenopyrite, pyrite, galena, chalcopyrite, and pyrrhotite. As a whole, the Sn content in granite porphyries, quartz porphyries, and quartz veins never exceeds 0.01%. Taking into consideration some prospecting features (abundant granite porphyry and quartz porphyry veins and tourmaline veinlets) and the presence of cassiterite in fluvial sediments of the coast near Cape Svyatoi Nos, these intrusions are of certain interest.

DESCRIPTION OF SEDIMENTS AND WEATHERING CRUSTS

In the study area, Paleogene, Neogene, upper Pliocene–lower Pleistocene (Eopleistocene), and Quaternary sediments are definable. The Paleogene and Neogene sediments are observable in rare outcrops, which are confined to uplifted areas of the Mesozoic basement. The upper Pliocene–lower Pleistocene sediments are represented by marine and fluvial facies in the Yana–Indigirka lowland and its surrounding mountainous structures, respectively. The Quaternary sediments are widespread. According to the geophysical (seismic and gravimetric exploration) data, thickness of the friable Cenozoic sediments in the bay and Dmitry Laptev Strait varies from a few meters near Cape Svyatoi Nos to 100 m at a distance of 3–8 km (general variation from 60 and 200 m). On the adjacent land, they are ~130 m thick.

Before discussing Cenozoic sediments in the study area, let us describe the weathering crusts.

The *Upper Cretaceous–Neogene weathering crust* was recovered by drilling in the Ebelyakh Bay, Dmitry Laptev Strait, and adjacent areas, suggesting its wide distribution. On the land, the weathering crust crops out on cliffs and slopes of Cape Svyatoi Nos. It was also recovered in pits on the slope of the Svyatoi Nos massif.

In the area under consideration, the weathering crust was formed during several stages. Some researchers (Kim and Slobodin, 1991) define two stages in the crust formation: Late Cretaceous–Eocene and early Miocene–Pliocene. Recently, scientists from VNIIOkeangeologiya (A.N. Smirnov) analyzed crust formation conditions on the Arctic shelf of Russia and concluded that it is more correct to discriminate two types of weathering crusts depending on the formation in different climatic environments: Late Cretaceous–Eocene chemically weathered crust and early Miocene—Pliocene physically weathered crust.

The *chemically weathered crust* started forming in the Late Cretaceous. This epoch corresponds to the earliest stage of the crust formation on shelves of the Laptev and East Siberian seas. This weathering crust is developed on a relatively flat surface (relative topography amplitude up to 100 m) of Mesozoic granitoid intrusions, as well as on terrigenous and volcanic rocks (Prokhorova and Ivanov, 1973; *Geologicheskoe* ..., 1984). It was formed in hot humid climatic environments. It is conceivable that similar weathering crust was also developed on the Laptev paleoland. The crust formation epoch corresponded to relief peneplanation (Kim and Slobodin, 1991).

Thickness of the Late Cretaceous–Eocene chemically weathered crust varies usually from 0.5 to 7.0 m. Its maximum values (10–17 m) are recorded in reference boreholes drilled in the Dmitry Laptev Strait, north of Cape Svyatoi Nos, and on Bol'shoi Lyakhovskii Island located northeast of the cape (Samusin et al., 1974, 1986).

The Late Cretaceous–Eocene weathering crust is represented by variegated hydromica–kaolinite clays and silts with an admixture of chlorite, smectite, and Fe-hydroxides, as well as grus and rubble of the underlying weathered Cretaceous volcanics and hornfels.

In the Dmitry Laptev Strait, the chemically weathered crust is composed of clays, sands, and silts with pollen characterizing mostly Paleogene plants: Betulaceae, *Tricolpopollenites*, Pinaceae, subordinate *Castanea*, and other broad-leaved taxa. The sediments also contain single grains of *Rhus, Nyssa, Ilex*, and Taxodiaceae pollen and Polypodiaceae, *Osmunda*, and *Sphagnum* spores. Judging from the pollen composition, the weathering crust is of the Late Cretaceous-Paleogene age (Samusin et al., 1974, 1986).

The coarse silt fraction is largely represented by quartz (29–39%) and silica–quartz aggregates (44–53%) with the subordinate K-feldspars, plagioclases, and rock fragments. The content of the heavy fraction is usually below 0.9%. The main accessory minerals in clays are ilmenite (45 to 46%), tourmaline (15–17%), and zircon (7–10%) (Prokhorova and Ivanov, 1973).

The weathering crust of the linear type developed on granitoid intrusive bodies is associated with mineralized shear zones in the hornfelsized rocks. It is conceivable that this crust serves as an accumulator of placer cassiterite.

In sections located southwest of the study object on the right side of the Selennyakh River, a left tributary of the Indigirka River in the Chokhchur–Chokurdakh zone, Popova (1970) defined Eocene palynological assemblages with angiosperm pollen prevailing over the gymnosperm plants. They are characterized by the diverse pollen of subtropical taxa and the presence of typical terminal Cretaceous–initial Paleogene vegetation: *Gleichenia* sp., *Gleicheniidites* sp., *Leiotriletes* sp., *Leptolepia fossilis* Chlon., *Camptotriletes* sp., Cyatheaceae, *Sphagnum putillum* var. *tenuissimum* Drozh. et. Purt., and pollen of *Triatriopollenites* sp., *Triporites* sp., *Membranosphaera maastrichtica* Samoil., *Ericipites* sp., and *Tilia vescipites* Kremp (Popova, 1970). It is conceivable that these sediments represent a chemically weathered crust developed after Mesozoic rocks (*Geologicheskaya* ..., 2004).

The lower boundary of the chemically weathered crust coincides with the weathered surface of Cretaceous granitoid intrusions and older host rocks, while its upper boundary is determined by the age of the overlying sediments. It should be taken into consideration that many plant taxa in the Cenozoic section are represented by transit forms. Intense weathering in stable tectonic settings with hot humid climatic conditions lasted from the Late Cretaceous to early Oligocene (*Geologiya* ..., 1970b; Ronkina and Vishnevskaya, 1977).

The *lower Miocene–Pliocene physically weathered crust* started forming during the Oligocene cooling, which also continued in the Neogene. It is likely that the crust was formed after the late Oligocene cooling event noted in (Kartashova et al., 1987). The climate became gradually colder and drier at that time. The general cooling trend was repeatedly interrupted by rhythmic temperature oscillations when warmer humid conditions gave way to colder and drier environments and vice versa. In the terminal middle–late Miocene, cooling was accompanied by intense aridization and, probably, intense formation of the physically weathered crust.

The early Miocene–Pliocene physically weathered crust is documented in the Cape Svyatoi Nos and Van'kina Bay areas and represented by variegated kaolinite or kaolinite–hydromica clays with inclusions of clastic material. Its maximum thickness is 7 m.

In the upper part of the weathering crust, allochthonous terrigenous material contains the palynological assemblage dominated by Amentaceae: *Alnus* sp., *Betula* sp., *Corylus* sp. and coniferous pollen: *Picea* sp., *Pinus* (subgenus *Diploxylon*) sp., *Pinus* (subgenus *Haploxyon*) sp.). They are accompanied by representatives of broad-leaved plant, Cupressaceae, and Taxodiaceae pollen. Spores are dominated by ferns from the family Polypodiaceae and peat mosses *Sphagnum* sp. Pollen of *Osmunda* sp. occur in some places. Such a composition of the assemblage indicated the Pliocene (N_2^{1-2}) age of the uppermost sediments in the weathering crust (*Geologiya* ..., 1970a; Prokhorova and Ivanov, 1973; Semenov et al., 1976).

Rock-forming minerals of the physically weathered crust in the Cape Svyatoi Nos area are represented by biotite and oligoclase aggregates. Accessory minerals of the coarse silt fraction are represented by amphiboles (37–64% of the terrigenous material), biotite (32–56%), carbonate (~10%) and oligoclase. The authigenic component of clays is characterized by the high content of Fe-hydroxides and carbonates (up to 25%).

The late Pliocene age of the crowning part of this weathering crust is based on its stratigraphic position and paleontological data. The sediments overlying the physically weathered crust were deposited mostly in the Eopleistocene. The Miocene–lower Pliocene sediments were deposited in physical weathering conditions favorable for the crust formation: weakened neotectonic movements and mainly cold dry climate.

Analysis of the paleontological material from sediments of the chemically and physically weathered crusts developed after Cretaceous granitoid intrusions revealed that they are heterochronous products formed in different climatic environments by different processes. The terminal Late Cretaceous–Paleogene in the Dmitry Laptev Strait (Samusin et al., 1974) and Eocene in Ebelyakh Bay (Popova, 1970), were marked by the formation of the weathering crust because of intense chemical weathering due to the humid and hot climate. In the Pliocene, the formation of the crust in the Cape Svyatoi Nos area and, probably, in the Dmitry Laptev Strait was determined by physical weathering of bedrocks (*Geologiya* ..., 1970a; Prokhorova and Ivanov, 1973; Semenov et al., 1976).

It is probable that the formation of weathering crusts by chemical and physical processes in some areas of the region under consideration (Cape Svyatoi Nos, Dmitry Laptev Strait) was gradual. Transition between different crust formation conditions during the Late Cretaceous–Pliocene period was interrupted only by long periods of climate changes and neotectonic movements.

Oligocene–Miocene sediments (P_3–N_1) rest upon the Late Cretaceous–Eocene weathering crust or Mesozoic bedrocks. They are spread at the bay bottom north of Cape Svyatoi Nos and in the Dmitry Laptev Strait, where they are overlain by Pliocene strata (Samusin et al., 1974, 1986; *Geologicheskoe* ..., 1984). The incomplete thickness of these sediments on the northern shore of Cape Svyatoi Nos amounts to 76 m. They are represented by intercalating silts, clays, sands, and brown coals with fragments of coalified wood and coal debris. The coal seams yielded remains of *Ulmus* (Ulmaceae), *Trochodendroides* (Magnoliaceae), *Patanus* (Platanaceae), *Liquidambar* (large deciduous trees), and *Acer platanoides*. Age of these sediments is based on the composition of palynological spectra dominated by pollen of thermophilic forms of arboreal Betulaceae, *Tricolpopollenites*, and Pinacae taxa, as well as on the stratigraphic position and lithology of sediments. It is conceivable that they were partly formed as weathering crust on Mesozoic bedrocks.

Pliocene sediments (N_2) overlie the Oligocene–Miocene sediments and are overlain by the Pliocene–lower Pleistocene strata. According to drilling data, the Pliocene sediments are widespread in the bay and strait. They are represented by light gray, brown, and dark brown fine-grained sands and silts with small pebbles. The sediments contain the palynological assemblage dominated by Amentaceae: *Alnus* sp., *Betula* sp., and *Corylus* sp. The coniferous pollen are represented by *Picea* sp., *Pinus* (subgenus *Diploxylon*) sp., and *Pinus* (subgenus *Haploxyon*) sp. They are accompanied by representatives of broad-leaved plants, Cupressaceae, and Taxodiaceae pollen. Spores include Polypodiaceae and *Osmunda* sp. representatives with single *Leiotriletes* sp. and *Sphagnum* sp. (*Geologiya SSSR* ..., 1970a; Kosheleva and Yashin, 1999). Diatoms are represented both by marine and freshwater taxa. The freshwater diatom group is dominated by extinct Neogene species of the genus *Aulacoseira* (*A. praegranulata, A. praedistans, A. praeislandica, A. jouseana*). Marine diatoms are represented by taxa typical of the Arctic seas (*Thalassiosira bramaputrae, T. bramaputrae* v. *septentrionals, T. gravida*, and others) and extinct Neogene species (*Pyxidicula zabelinae, Thalassiosira mocenica*). These sediments were deposited in the coastal marine zone. Some microfossils were likely redeposited. On the basis of organic remains and position in the section, the sediments are of the Pliocene age (N_2^{1-2}).

The cassiterite potential of the Upper Cretaceous–Eocene chemically weathered crust and the Pliocene physically weathered crust is rather high.

Pliocene–lower Pleistocene sediments (N_2–Q_1) of the Serkino horizon are established by drilling in the bay and Dmitry Laptev strait, where they are developed on submarine rises and land in the Cape Svyatoi Nos area. They rest on the eroded surface of the Late Cretaceous–Neogene weathering crust and are overlain by the Middle–upper Pleistocene sediments. The Pliocene–lower Pleistocene sediments are represented by the fine-grained sands with silt intercalations, peat lenses containing plant remains, and thin lenticular intercalations of coarse-grained sand and gravel. Their thickness varies from a few meters to 23 m.

On the Cape Svyatoi Nos coast, the Serkino horizon observable in outcrops is characterized by the two-member structure. The basal part of the lower member is composed of the lacustrine–boggy and coastal-marine sands overlain by silts with lenticular intercalations of inequigranular sands and pebble gravel with inclusions of peat and tree trunks. Paleobotanical remains in these sediments are represented by *Epipremnum crassum* (family Araceae or Monocotyledones), thermophilic *Picea* and *Pinus* species, as well as Pleistocene and Neogene marine diatom algae. The palynological spectra include piney–deciduous, coniferous, and exotic broad-leaved plants. Thickness of the subhorizon amounts to 12 m (Prokhorova and Ivanov, 1973; Semenov et al., 1976).

The upper Serkino subhorizon in the Cape Svyatoi Nos area is generally composed of the coarser material: coastal-marine pebble gravel, small boulders submerged into loam, inequigranular sands with pebble and gravel, lacustrine–boggy silts, and peat. The sediments are characterized by remains of diatom algae including relict Neogene forms, the alder–birch palynological assemblage with rare coniferous pollen, and tests of benthic foraminifers *Elphidium clavatum* Cushman and *E.* cf. *orbiculare* (Bredy). Thickness of the subhorizon in this area is approximately 20 m. In other areas, it is represented by the coarse-grained sand with Fe-hydroxides and pebbles and boulders. Its Pliocene age is based on the position in the section and rare fragments of marine mollusks *Portlandia arctica* (Gray), *P. intermedia* (M. Sars), and *Astarte* sp. The Serkino horizon is characterized by elevated cassiterite concentrations.

The middle–upper Pleistocene sediments (Q_{II}–Q_{III}) constituting the lower lithostratigraphic complex (LSC_1) rest upon Pliocene–lower Pleistocene strata and are overlain by upper Pleistocene or Holocene sediments (Kosheleva, 2002) (Fig. 3). They are widespread in the bay and strait and on land as the lagoonal–deltaic, lacustrine–fluvial, and marsh–deltaic plains. These sediments are represented by gray or brown silts with plant remains. Thickness of the middle–upper Pleistocene sediments is ~10–32 in the bay and up to 70 m on the adjacent land. Their age is substantiated by faunal remains, palynological spectra, and position in the section. Organic remains are represented by shelly detritus, diatom algae, spores and pollen, in addition to microfaunal fossils. The microfaunal assemblage includes poorly preserved tests of the dwarfish benthic foraminifers represented by the shallow-water eurybiont species *Ammotium cassis* (Parker), *Reophax curtus, Haynesina orbicularis, Eggerella advena* (Cushman). The Far East taxa are represented by *Reophax micuceus, Glabratella beringovensis*, and *Buccella limpida*. The Chukotka species is represented by *Petroelphidium anaabarense*. These silty sediments contain, in addition to mollusks *Portlandia arctica* (Gray), *P. intermedia* (M. Sars), and *Astarte* sp., the assemblage of marine brackish- and freshwater diatoms bonging to the orders Centrales and Pennales. Among them, the marine species are often Tertiary (reworked) varieties. Marine sediments with faunal remains contain a notable admixture of freshwater diatom forms. The palynological spectra are dominated by coniferous pollen: *Pinus silvestris* (L.) and *P. sibirica* (Rupr.) Mayr. They are accompanied by the subordinate *Picea* sp. and *Abies* sp., as well as rare *Betula* sp. and *Alnus* sp. According to seismoacoustic data, the sediments were deposited in a shallow basin with depths up to 30 m in the Arctic–Boreal climatic environments during the Kazantsevo transgressive stage (lower lithostratigraphic complex LSC_1) (Kosheleva, 2002).

The *upper Pleistocene (Q_{III}) sediments*, which represent the middle lithostratigraphic complex (LSC_2) according to V. Kosheleva, are developed through the entire region under consideration: on the land and in the bay and Dmitry Laptev Strait (Fig. 3). On the land, they are represented by the terrestrial or marine facies resting on the eroded surface of the Kazantsevo marine, Zyryanka terrestrial or pre-Quaternary sediments. Their basal layers crop out in some coastal areas. The sediments were deposited during the Kargino interglacial (Q_{III}^3kr) when the entire Arctic region was subjected to marine transgression (*Geologicheskoe* ..., 1984; Kim and Slobodin, 1991; Kosheleva, 2002). They are usually overlain by Holocene or Recent sediments (Hl), which were formed during the last postglacial transgression corresponding to LSC_3 (Kosheleva, 2002) and by sediments deposited during the Sartan glaciation (Q_{III}^4st) in some areas. They are represented by sands and silts with an admixture and lenses of peat and plant remains or by lacustrine–boggy alas facies (on land): silts and peat with ice wedges constituting a system of lacustrine terraces in spacious depressions and plains. Thickness of these sediments varies from a few centimeters to 15 m.

Organic remains in the upper Pleistocene sediments are more abundant as compared with the middle–upper Pleistocene sequence. They are represented by shelly detritus, diatom algae, benthic foraminifers, spores, and pollen. As a whole, their composition is similar with that in the middle–upper Pleistocene sediments. However, they are distinguished by a better preservation of small detritus and higher diversity of bivalves and benthic foraminifers. Sediments in the open part of the bay contain detritus of euryhaline and brackish-water bivalves: *Portlandia arctica, Astarte borealis placenta, A. sibirica, F. Montaqui fibula*, and *Lyonsia arenosa*. In the mouth areas of the bay, their assemblage includes *Portladia aestuariorum* and *Cyrtodaria kurriana*. Sediments of the bays enclose Arctic forms: *Astarte acuticostata, Macoma moesta, M. torelli, M. calcarea*, and others.

Foraminifers are represented by species capable of tolerating significant water desalination: *Reophax curtus, Ammotium inflatum, Eggerella advena* (Cushman), and others. In mouth areas of rivers, the sediments contain Arctic bivalve forms *Portladia aestuariorum* and *Cyrtodaria kurriana*. The foraminiferal assemblage in these sediments also includes rare *Elphidium clavatum, E. orbiculare, Buccella frigida, Eggerella advena, Proteonella atlantica, Cunlata arctica*, and others. Thus, judging from the composition of floral and faunal assemblages, the upper Pleistocene sediments were deposited in a shallow-marine, probably, intermittently drained basin with depths up to 15–20 m and Arctic–Boreal environments. They constitute the middle lithostratigraphic complex (LSC_2) and correspond to the Kargino transgressive stage of the study region (Kosheleva, 2002).

According to the grain size composition, the upper Pleistocene sediments of the bay and Dmitry Laptev Strait are represented by silts, clayey silts, sands, silty sands, and sandy–silty–clayey mictites (sediments containing 25–50% of each fraction). The sediment varieties frequently alternate with each other. Thickness of layers varies from several centimeters to 1 m. The sediments are mostly characterized by the bimodal grain size distribution with maximums in the following fractions: silty and clayey, silty and sandy, or clayey and sandy (>25% of one of these fractions and >50% of another). The sandy–silty–clayey mictites are characterized by the trimodal grain size distribution with peaks in the sandy, silty, and clayey fractions (>25% of each fraction).

The rock-forming minerals in these sediments are represented by quartz and feldspars. The contents of quartz and feldspar are ~20–30 and ~30–40%, respectively, in sediments of the coastal part of the bay and 30–40 and 50–60%, respectively, in sediments of the bay. Carbonates, micas, and rock fragments are present as admixture. In coastal sediments of the Cape Svyatoi Nos area, clastic material frequently exceeds 10%.

Accessory minerals in the upper Pleistocene sediments of the bay and strait are dominated by ilmenite and magnetite (~10–15%), minerals of the epidote–zoisite group (~12–15%), and ordinary hornblende (20–40%). They also include (up to 10%) pyroxenes, garnet, zircon, and Ti-minerals (titanite, brookite, anatase, leucoxene). Rare minerals are andalusite, kyanite, sillimanite, chloritoid, and staurolite. The accessory mineral assemblage includes rare grains of apatite, tourmaline, rutile, spinel, Fe-chlorites, barite, siderite, and pyrite. The heavy fraction contains occasional volcanic glass, olivine, allanite, axinite, prehnite, monazite, and cassiterite (from single grains to a few percent).

Clay minerals in the sediments under consideration are dominated by hydromica (60–80% of the clayey component). The chlorite content is as high as 20–30%. There are also smectite and kaolinite. It is conceivable that smectite originated partly from the eroded older rocks.

Holocene sediments (Hl), which represent the upper lithostratigraphic complex (LSC_3) according to V. Kosheleva, are universally spread in the bay and Dmitry Laptev Strait (Figs. 3, 5). They are also developed on the adjacent land. The bay represents a shallow basin with depths up to 10–15 m. The southwestern part of the Dmitry Laptev Strait is also shallow with water depths never exceeding 14 m (Fig. 1). At the bay and strait bottom, the Holocene sediments are mostly represented by pebble gravel, sands, silts, and clayey silts (Fig. 5). They overlie the upper Pleistocene strata almost everywhere in the study area. In some areas, the basal part of the section is composed of sediments deposited during the Sartan glaciation (Q_{III}^4st). They are overlain by Holocene or Recent sediments (Hl) accumulated during the last postglacial transgression (LSC_3). In areas occupied by bedrock outcrops and sediments of the Serkino horizon, the Holocene layers contain the coarse-grained material with rubble and gravel. The friable Holocene sediments are represented by silts and clays near the shore. On the land, coeval sediments are composed of the residual and talus-solifluction facies. Thickness of the Holocene sediments is maximum (up to 10 m) in depressions and often less than 1.0 m on elevations. Organic remains in the Holocene sediments are represented by species characteristic of the Arctic shallow-water zone. Sediments of the bay and strait enclose a high Arctic fauna with the prevalence of euryhaline and brackish-water species similar to taxa from the upper Pleistocene marine sediments. Shells of Quaternary mollusks are well preserved. The microfaunal assemblage includes *Egerella advena, Ammotium inflataum*, and other species of the agglutinated benthic foraminifers accompanied by taxa characteristic of the shallow-water Arctic basin: *Proteonella atlantica, Reophax curtus, Cunlata arctica*, and others (Kosheleva, 2002). The palynological spectrum is dominated by the pollen of arboreal plants and tundra vegetation. The sediments constitute the upper lithostratigraphic complex (LSC_3) and correspond to the current Holocene transgressive cycle (Figs. 3, 5). In the shallow coastal zone of Ebelyakh Bay southeast of Cape Svyatoi Nos, the Holocene sediments contain cassiterite (up to 10–20 g/m^3) and gold colors (*Rossypnye* ..., 1997). These minerals likely originate from the hydrothermally altered granodiorites of the intrusion, their weathering crust, and Pliocene–lower Pleistocene sediments of the Serkino horizon, which rest with erosion on the weathered crust. Single cassiterite grains are also documented in the sandy and sandy–silty sediments in the coastal part of the Cape Svyatoi Nos.

The undivided Holocene sediments recorded only on the land adjacent to the bay are represented by the residual and talus–solifluction facies that are mostly composed of material from the eroded intrusive and dike bodies. Such sediments are developed in mountainous massifs including Cape Svyatoi Nos. Residual sediments are confined to the mountain summits and watershed surfaces. They are represented by boulders, rubble, and grus in the sandy–silty–clayey material. Their thickness never exceeds a few meters. The talus–solifluction sediments cover the medium-, low-angle, and flattened slopes. They are represented by the sandy–silty–clayey material with an admixture of bedrock grus and rubble. They can be as thick as 10 m at foothills. The residual and talus–solifluction sediments can serve as collectors of cassiterite and, thus, deserve the attention of prospectors (Semenov et al., 1976).

The Holocene sediments of the bay and Dmitry Laptev Strait are represented by the coarse-grained and clayey sands, sandy silts, silts, and silty clays with angular fragments of the granitoid or metamorphic rocks. In terms of the grain size composition, the Holocene sediments are close to the sandy–clayey or silty–clayey mictites formed in the Arctic environment.

The yellowish gray coarse-grained sands with pebbles, rubble, and silty and clayey material are developed in coastal areas of the bay and Dmitry Laptev Strait near Cape Svyatoi Nos mostly at depths down to 2 m. They were produced by rewashing of the sedimentary inequigranular material of beach deposits of Cape Svyatoi Nos and erosion of the adjacent shores composed of middle–upper Pleistocene silty–clay sediments and ice (Semenov et al., 1976). Reworking due to the tidal and wave activity is evident from the mineral composition of sediments characterized by high concentrations of the most stable and heavy minerals (the heavy fraction often exceeds 9.0%) and from the presence of heterogeneous different-size fresh or intensely disintegrated minerals in the same samples. Sands with the silty–clayey material are distributed at the bottom of the shallow-water coastal part of the Dmitry Laptev Strait at depths down to ~4 m east and southeast of Cape Svyatoi Nos and at similar depths in

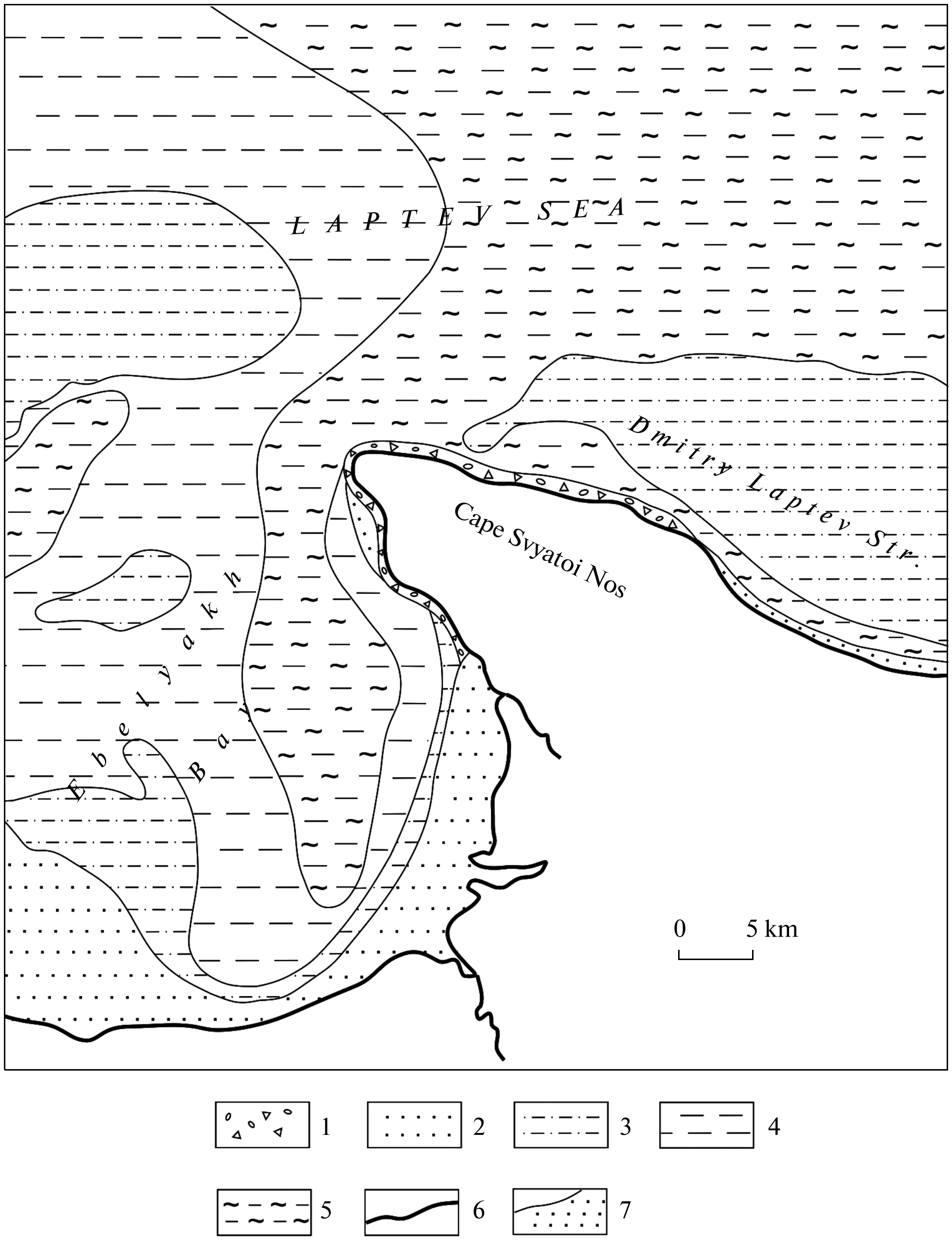

Fig. 5. Distribution of Holocene sediments in Ebelyakh Bay. (1–5) Sediments: (1) sand, pebble, and rubble, (2) sand, (3) sandy silt, (4) silt; (5) clayey silt and silty clay; (6) shoreline; (7) coastal shoal, drained zone.

the intermittently drained areas of the bay in the southern and southeastern parts (Fig. 3).

The coastal sands are gradually replaced seaward by the sandy silts, silts, clayey silts, and silty clays. The sandy gray silts with small plant remains and rare grus are confined to the southern part of the Dmitry Laptev Strait. They fringe the drying zone of the bay and occur on some elevated bottom areas at the entry into the bay and away from the shore. They are characterized by the bimodal grain size distribution with maximums in the sandy and silty fractions. Their bimodal patterns are determined by the activity of bottom currents and deposition of sedimentary material from ice during its melting. Their grain size coefficients correspond to the formation of sediments under the influence of bottom hydrodynamic motions complicated by ice rafting, i.e., free precipitation of diverse sedimentary material from ice during its melting (table).

The greenish gray silts with thin intercalations of plant remains (a few millimeters) are frequently marked by H_2S odor. They are spread at the bay bottom east of the sandy silt zone and in the outer zone of

Grain size composition of Holocene sediments in Ebelyakh Bay and the Dmitry Laptev Strait

Sediment	Grain size, mm	Sorting coefficient	Asymmetry coefficient
Sand	1.65–1.88 / 1.78	1.32–1.55 / 1.4	0.64–0.82 / 0.73
Sandy silt	0.058–0.1 / 0.084	1.93–4.37 / 3.15	0.39–0.61 / 0.5
Silt	0.032–0.099 / 0.047	1.16–1.94 / 1.48	0.54–1.085 / 0.94
Clayey silt	0.025–0.047 / 0.03	1.55–3.94 / 2.03	0.17–1.06 / 0.51

The numerator and denominator designate variation limits and average value, respectively.

the bay, on the western and northwestern sides of Cape Svyatoi Nos, and in the Dmitry Laptev Strait (Fig. 5). The silty sediments are characterized by the bimodal grain size distribution with maximums in the coarse silt and fine silt fractions. They are moderately sorted with approximately equal proportions of the silty and clayey particles.

The clayey silts are observable in depressions in the southern part of the Dmitry Laptev Strait and the central part of the bay with depths exceeding 6 m.

Thus, the grain size composition and sorting coefficients of bottom sediments in the bay and Dmitry Laptev Strait indicate their deposition in high-energy hydrodynamic environments. By the grain size composition, the Holocene sediments are similar with their middle–upper Pleistocene and upper Pleistocene counterparts.

The main rock-forming minerals of the coarse-grained fraction in the Holocene silty–clayey sediments of the bay and Dmitry Laptev Strait near Cape Svyatoi Nos are represented by feldspars (24–40%) and quartz (30–80%). They are accompanied by the subordinate muscovite, biotite, chlorite, rock fragments, single calcite and zeolite grains, and siliceous–quartz aggregates. In deeper areas away from the seashore, the content of quartz in sediments increases and the content of feldspar decreases, which is explained by their influx after the erosion of Quaternary sediments on the coast and the multiple reworking of sedimentary material (Kosheleva, 2002).

The contents of minerals in the heavy fraction of sediments governed by their grain size composition: 9.19–11.48% in sands, 0.67–3.36% in sandy silts, 0.2–2.0% in silts, and 0.2–1.0% in clayey silts.

Accessory minerals in bay sediments include epidote–zoisite (5.2–16.3%), ilmenite, magnetite (8.1–17.2%), pyroxenes (8.3–21.0%), amphiboles (31.7–53.5%), garnet, and zircon. Pyroxenes are represented by the monoclinic and orthorhombic grains (7.1–15.4 and 0.4–5.8%, respectively); amphiboles, by ordinary hornblende (Kosheleva, 2002). The sediments in the coastal part of Cape Svyatoi Nos contain epidote (5–15%), ilmenite (10–25%), and pyroxenes (15–35%). Concentrations of monoclinic and orthorhombic pyroxenes in Holocene sediments are as high as 7.1–15.4 and 0.4–5.8%, respectively. The content of garnet (almandine) amounts to 0.7% in sands and 5.4% in silts. The leucoxene concentration in silts varies from 1.0 to 4.98% of the heavy fraction. Minerals characteristic of granitoids or contact metamorphic rocks, such as zircon, titanite, aegirine, allanite, xenotime, anatase, brookite, staurolite, spinel, and sillimanite, occur as single grains. The presence of prehnite, pyrite, brookite, and anatase in sediments implies the supply of minerals from the hydrothermally altered granitoid rocks, while rutile, xenotime, allanite, and monazite originated from pegmatite veins. Authigenic minerals are represented by Fe-hydroxides, glauconite, chert micronodules, pyrite, and newly formed calcite crystals (Kosheleva, 1999, 2002).

Clay minerals in Holocene sediments of the bay and Dmitry Laptev Strait are dominated by hydromicas (60–70%) and chlorite (20–30%) accompanied by the subordinate kaolinite and smectites. Kaolinite is of terrigenous origin. Smectites resulted probably from the decomposition of volcanic glass in marine environments. The glass was most likely eolian material and some of its part could be yielded by the erosion of older sediments. Rare particles of volcanic glass are frequently observed in the light fraction. The sediments also contain mixed-layer minerals of the hydromica–smectite type (5–25%).

Pleistocene–Holocene sediments of Ebelyakh Bay and the southern Dmitry Laptev Strait demonstrate distinct zoning patterns. The content of the heavy coarse silt fraction in them decreases notably seaward from 11.48% in sands to 0.2% in clays. It also increases clearly although less significantly along the section from the surface downward (from <1 to 3%). The elevated content of heavy minerals in the coastal surface sands of the bay and Dmitry Laptev Strait, as well as on a spacious bank with water depths up to 2.7 m in the open part of the bay is determined by the relatively high-energy hydrodynamics, which results in the removal of fine silts, clay particles, and light minerals to deeper zones of the bay. Insignificant variations in the composition of rock-forming and accessory minerals in bay sediments are likely explained by the intensity and range of their transport.

Analysis of the grain size and mineral compositions of sediments revealed that intense abrasion of seashores in the Cape Svyatoi Nos area led to the destruction of rocks without notable material sorting. Subsequently, the clastic material becomes sorted in deeper environments and enriched with heavy minerals due to the activity of alongshore currents and waves. The composition of panned concentrates becomes more diverse and includes rare cassiterite grains and single gold colors.

Terrigenous material of Holocene sediments originated from the erosion of seashores composed of granitoid or contact metamorphic rocks, friable Quaternary sediments of marine terraces and beaches, and, probably, Laptev paleoland located northeast of the bay (Ronkina and Vishnevskaya, 1977) (Fig. 2). At present, the paleoland is recorded in the bottom topography as a slightly (up to a few meters) elevated area in the open part of the bay at depths shallower than 4 m.

The main collectors of cassiterite are the weathering crust, Serkino horizon, and Holocene sediments. Sites with promising cassiterite placers are preliminarily defined in the Ebelyakh Bay and Cape Svyatoi Nos areas (Fig. 6).

Friable Cenozoic sediments characterized by the significant thickness in Ebelyakh Bay, around Cape Svyatoi Nos, and in the Dmitry Laptev Strait are distributed along the periphery of granitoid (frequently buried) intrusions. These sediments are metalliferous units due to repeated erosion of the chemically and physically weathered productive rocks and redeposition of their material.

The tin potential of Cenozoic sediments in Ebelyakh Bay and the Dmitry Laptev Strait was estimated using the results of panning and geochemical sampling of core from boreholes drilled from ice-based platforms, vibrodrilling core, and bottom sediments. According to the panning Pleistocene–Holocene sediments, they contain single particles of cassiterite in all grain size types with a weak tendency for its landward increase. The elevated Sn contents (from 23 to 75 g/m^3) are recorded in some samples from the coastal Holocene sediments distributed along the northeastern coast of the bay and Cape Svyatoi Nos in areas with the elevated concentrations of heavy minerals. Single cassiterite particles are recorded in some samples from the coastal Holocene sediments along the entire shore of the bay and Dmitry Laptev Strait. No sustained zones with the elevated cassiterite content are established along the lateral and vertical directions in the study area. The size of cassiterite grains deceases from 0.2–0.5 mm in the coastal coarse-grained sediments to <0.1 mm in the deeper fine-grained varieties. The cassiterite grains are dark brown and characterized by irregular crystalline shape. As a whole, the elevated cassiterite content (up to 49 g/m^3) in recent sediments of the study area and its presence in the Pliocene–lower Pleistocene Serkino sediments indicate its potential concentration in the accumulative coastal-marine facies.

CONCLUSIONS

Analysis of the mineral composition of Pleistocene–Holocene sediments in Ebelyakh Bay, Cape Svyatoi Nos, and the southern Dmitry Laptev Strait areas revealed that they were deposited in uniform geological and physicogeographical settings similar to depositional environments in Van'kina Bay (Kosheleva, 2013). Terrigenous material was derived from granitoids or contact metamorphic rocks of Cape Svyatoi Nos and friable Quaternary sediments on the marine terraces and beaches. It is conceivable that material from the abraded submarine rises (primarily, a spacious submarine bank in the bay) and the sedimentary ice-rafted, river-transported, and eolian material contributed to the formation of bottom sediments (Kosheleva, 2002).

By their composition and attitude, the bottom sediments recovered by coring and ice-based drilling in the bay and Dmitry Laptev Strait are subdivided into beds. According to the ice-based drilling data, thickness of Pleistocene–Holocene sediments is 13 m in the southeastern part of the Laptev Sea and varies from less than 50 to more than 76 m in the study area.

Sediments on the land, bay, and Dmitry Laptev Strait contain remains of Pliocene, Pleistocene, and Holocene foraminifers, diatom algae, and bivalves accompanied by their poorly preserved Mesozoic species. The Holocene sediments include Polychaeta tubes, well-preserved shelly detritus, and algal remains.

The middle–upper Pleistocene sediments are mainly represented by silts with the rubble–gravel material of bedrocks. Peat lenses and ice veins occur on the land. The upper Pleistocene sediments contain a large amount of sands, clays, and sandy–silty–clayey mictites. The Holocene sediments are characterized by the diverse grain size composition. They are represented by sands, silts, clayey silts, and silty clays. The content of clastic material represented by the igneous and metamorphic rocks is insignificant.

The Pleistocene–Holocene sediments in the bay and Dmitry Laptev Strait were deposited during transgressive epochs: Kazantsevo (Q_{III}^{1}kz), Kargino (Q_{III}^{3}kr), and Holocene (Hl). This pattern is consistent

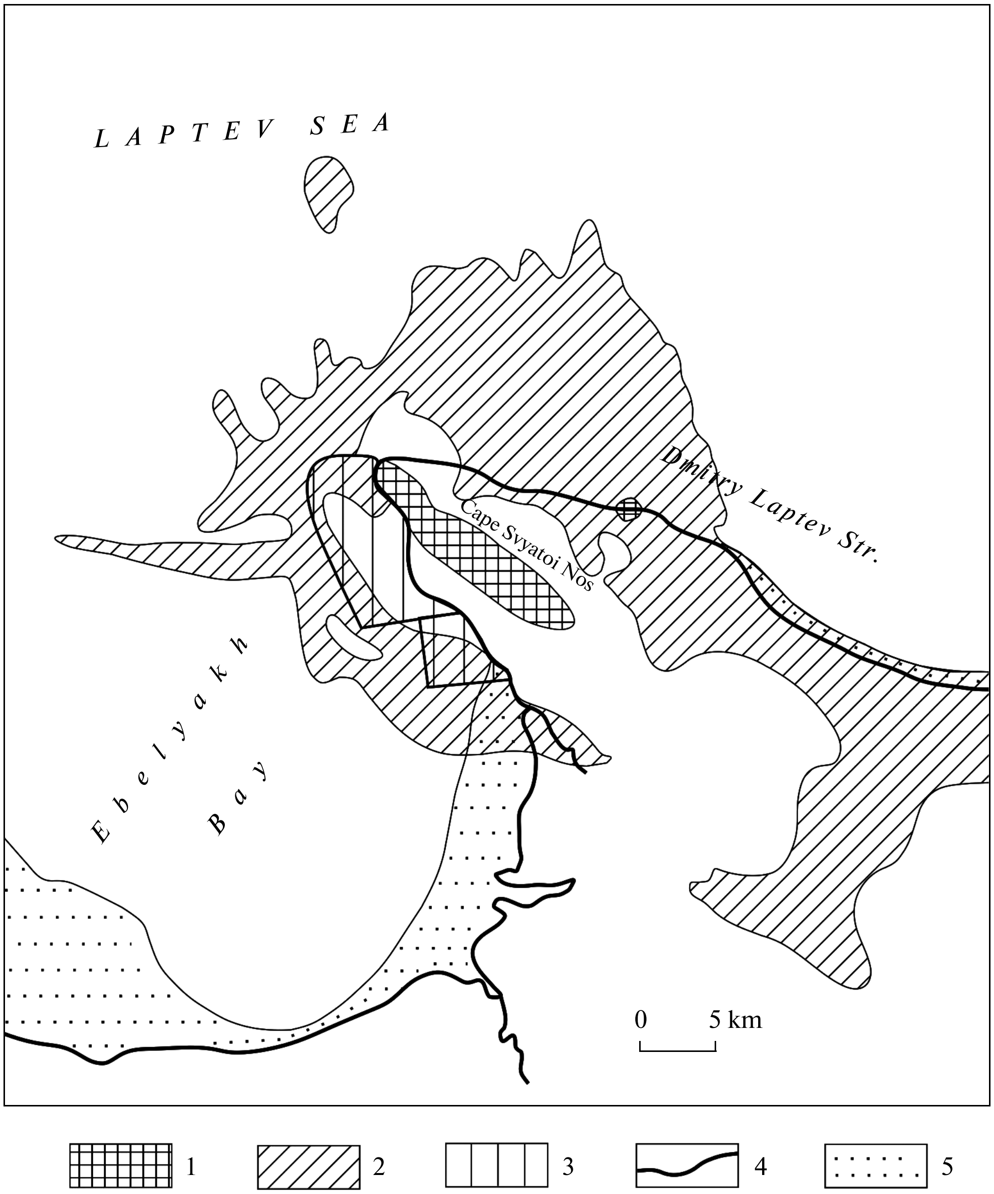

Fig. 6. Promising cassiterite sites in the Cape Svyatoi Nos area. (1, 2) Granitoid intrusions according to geological (1) and geophysical (2) data; (3) sites with the Sn content up to 20 g/m^3; (4) shoreline; (5) drained zone.

with the general Quaternary evolution of the Arctic region (Kosheleva, 2002). The Quaternary age of sediments developed in the bay, Dmitry Laptev Strait, and adjacent area is derived from the microfaunal (foraminifers), palynological, and diatom fossil assemblages.

By their geological, geomorphological, stratigraphic, and lithological features, the sediments of Ebelyakh Bay and the Dmitry Laptev Strait (elements of the Yana–Indigirka lowland and its coastal shallow-water zone) are favorable for the formation of ores typical of the entire region (Ushakov et al., 1976). This ore potential is partly determined by the presence of granitoid intrusion in the coastal zones of the bay, Cape Svyatoi Nos, and adjacent part of the Dmitry Laptev Strait. Fragments of this intrusion and contact-metamorphosed rocks are observable in natural outcrops of the cape, which demonstrate several cassiterite occurrences. The results of complex investigations of the mineral composition of the Pleistocene–Holocene sediments suggest that placers were formed here in the Pliocene, Early Pleistocene, and Holocene epochs. The chemically and physically weathered crusts served as a source of cassiterite in the sedimentary cover, primarily in the Pliocene–lower Pleistocene Serkino horizon resting upon rocks intensely weathered by chemical processes. The presence of cassiterite in Holocene sediments is likely determined by its dominant transport from the physically weathered crust along with the reworked and redeposited older sediments, which received cassiterite from the chemically weathered crust. Geomorphologists have revealed the presence of ancient buried elements of the subaerial relief: river valleys and shorelines in the fields of intrusive bodies. These elements can serve as prerequisite for the placer formation (Prokhorova and Ivanov, 1973). The valley-shaped differentiation of the submarine relief and its spatial relation with the present-day water streams on the land is likely determined by the development of an ancient river network within the submarine relief. The presence of the shallow granitoid intrusion overlain by friable sediments, as well as the development of ancient river valleys and shorelines, indicated that the coastal zone of the bay and Cape Svyatoi Nos (primarily, the basal part of its Pliocene–lower Pleistocene section) is a sufficiently promising area for cassiterite placers. This shelf area with a shallow location of bedrocks (up to 100 m) can be recommended for further prospecting investigations. Inasmuch as the granitoid intrusion is exposed on the basement surface in the coastal zone of the Dmitry Laptev Strait, the tin potential of this area should be higher than in areas adjacent to Ebelyakh Bay. Hence, prospecting works should first be conducted in this zone (Fig. 4).

According to the spectral analysis, the maximum Sn concentration in hand specimens from the hydrothermal veins amounts to 0.01–0.05%. The content of Cu and Zn is 0.1%. Some specimens exhibit elevated As, Sb, Co, W, and Bi concentrations. High contents (from 0.01 to 1%) of La and Ce are recorded in some autoclastic basalt samples from the exogenic zone of the intrusion (Prokhorova and Ivanov, 1973).

The global warming trend in the Arctic region, rise in tin prices, experience in the detection, assessment, and extraction of placer minerals, and presence of the Chokurdakh coastal cassiterite deposit in the neighboring (Van'kina) bay, and detection of several ore occurrences on the land provide ground for continuation of the geological, geophysical, and prospecting works aimed at the discovery of tin placers in coastal areas of Ebelyakh Bay, Cape Svyatoi Nos, and the Dmitry Laptev Strait.

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