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OCEANOLOGY

Deposition Settings on the Continental Shelf of the East Siberian Sea

O. V. Dudarev[a], I. P. Semiletov[a, b], A. N. Charkin[a], and A. I. Botsul[a]
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The spacious continental shelf of the East Siberian Sea (ESS) is of particular interest primarily due to its formation in settings of periglacial lithogenesis. This region is characterized by the universal development of Pleistocene permafrost rocks (PFR) [1, 11]. The presence of thick veins of relict ice enclosed in these sequences determined the dependence of the coastal-shelf cryolithozone PFR on the thermal and hydrodynamic impact. Under the influence of these factors, the present-day coastal zone is advancing landward at an annual mean rate of 3–5 m. Consequently, the seawater occupies tens of square kilometers of the former coastal areas of maritime plains [2, 3, 6, 12]. Large volumes of mineral and organic material introduced into shelf waters become involved in sedimentary and biogeochemical cycles. The ESS shelf is known not only for such catastrophic natural processes. It hosts the largest explored and potential reserves of coastal-marine placers and is considered a part of the megabasin with hydrocarbon potential [10].

However, the ESS region is characterized by maximal ice development and very low accessibility among high-latitude sea basins of Russia. Therefore, peculiarities of sedimentation patterns and other natural processes are poorly known even for the continental shelf of the ESS, which is free of ice for only one or two months of the year. The present paper considers new oceanographic data that contribute to solution of the problem mentioned above. Our work is based on results of five Arctic expeditions carried out by the Il'ichev Pacific Institute of Oceanology. Complex sedimentological, biogeochemical, and hydrological studies were conducted at 205 stations (depths from 2 to 47 m) during the ice-free periods of 1999, 2000, and 2003–2005. The stations are located on the continental shelf of the ESS and southeastern shelf of the Laptev Sea located on the western side. The grain-size composition of sediments was examined using an Analysette 22 (FRITISCH Company) laser particle analyzer. Coarse-grained sediments were fractionated by the standard sieve method. In line with the three-component classification based on proportions of psammite (Ps) (1.0–0.1 mm), silt (S) (0.1–0.01 mm), and pelite (Pl) (<0.01 mm) fractions, we defined the following nine lithological sediment types with different associations of grain-size fractions(table): medium-grained (Ps_2) and fine-grained (Ps_3) psammites, silty (SPs) and pelitic (PlPs) psammites, pelitic silt (PlS), silty pelite (SPl), pelite (Pl), and psammitic (PsM) and (PlM) pelitic mixtites.

The distribution of sediments demonstrates that they sustain fine-grained texture in the major part of the continental shelf regardless of the distance from the shore (Fig. 1), e.g., in the western Yana–Kolyma and central Kolyma–Chaun shelf areas. This phenomenon is explained by the specific features of the coastal-shelf cryolithozone. The near-shore part of the sea is covered by ice approximately ten months of the year. The bottom is relatively flat and insignificantly inclined (~0.0001). The drainage area provides large volumes of fine-grained terrigenous material. According to our calculations, only two major sources—suspended particulates (SP) and thermal abrasion products of the coast—supply 21.4 and 15.0 Mt/yr of material, respectively. The study of the SP from the Indigirka–Alazeya river prodeltas and PFRs from thermal abrasion scarps located along the Dmitry Laptev Strait coast reveals that the content of Ps, S, and Pl fractions in these areas is 1–3, 21–36, and 61–77%, respectively. It is obvious that the grain-size composition of sedimentary material from its main sources is identical and is assigned to types PlS and Pl [5].

The average content of Ps, S, and Pl fractions in the most dispersed Pl sediments is 0.5, 16.2, and 83.3%, respectively (Figs. 1, 2; table). Their formation is determined by gravitational deposition of clayey particles in

[a] *Il'ichev Pacific Institute of Oceanology, Far East Division, Russian Academy of Sciences, ul. Baltiiskaya 43, Vladivostok, 690041 Russia*
[b] *International Research Center, University of Alaska, Fairbanks, USA; e-mail: dudarev@poi.dvo.ru*

Sedimentation areas and grain-size composition of bottom sediments on the East Siberian and southeastern Laptev continental shelves

Sediment type	Sedimentation area	Depth, m	Content of grain-size fractions in bottom sediments, %								
			1.0–0.1 mm (psammite)			0.1–0.01 mm (silt)			<0.01 mm (pelite)		
			min	max	*x*	min	max	*x*	min	max	*x*
Ps_2 (*n* = 7)	Summit of the Svyatoi Diomid Bank; UCSs in Blagoveshchenskii and Longa straits, Chaun Bay, and Shelagskii–Billings shelf	8–12	–	–	76.2	–	–	13.4	–	–	10.4
Ps_3 (*n* = 9)	UCS of the southeastern Laptev Sea and Chaun Bay	3–15	50.1	95.4	72.3	12.8	29.6	19.0	1.8	20.4	8.4
SPs (*n* = 5)	Yana–Indigirka shelf, UCS of the southeastern Laptev Sea and Kolyma–Chaun shelf	7–16	41.2	54.2	49.0	35.1	40.0	34.4	6.3	24.1	16.6
PlPs (*n* = 1)	UCS foothill in the Kolyma–Chaun shelf area	24	–	–	56.2	–	–	16.0	–	–	
PlS (*n* = 64)	Prodeltas of the Yana, Indigirka–Alazeya, and Kolyma rivers; thalweg and UCS of Dmitry Laptev and Sannikova straits; shelves of the southeastern Laptev Sea, eastern part of the ESS, and Indigirka–Kolyma; UCS of the Kolyma–Chaun shelf and Chaun Bay	3–31	0.0	16.4	2.5	50.6	80.5	61.0	16.5	49.7	36.5
SPl (*n* = 57)	Southeastern Laptev Sea; thalweg of the Sannikova and Longa straits; Yana–Kolyma, Shelagskii–Billings, and Kolyma–Chaun shelves, eastern shelf of the ESS; UCS of the Sannikova and Blagoveshchenskii straits and Chaun Bay; prodeltas of Alazeya–Indigirka and Kolyma rivers	7–47	0.0	11.8	1.3	25.0	47.3	39.9	50.8	75.0	58.8
Pl (*n* = 37)	Thalweg of Dmitry Laptev Strait; Yana–Kolyma, Kolyma–Chaun, and Shelagskii–Billings shelves, eastern shelf of the ESS; UCS of the Chaun Bay; prodeltas of the Kolyma and Indigirka–Alazeya rivers	9–41	0.0	21.6	0.5	0.0	28.8	16.2	71.2	99.9	83.3
PsM (*n* = 6)	UCS of the Dmitry Laptev Strait, Svyatoi Diomid Bank, and Shelagskii–Billings shelf; shelf of the southeastern Laptev Sea	2–38	37.0	48.0	43.8	22.0	37.3	32.4	23.5	37.0	23.8
PlM (*n* = 18)	Underwater Shelagskii–Billings shelf of the Dmitry Laptev Strait; Yana–Kolyma shelf, eastern and southeastern shelves of the East Siberia and Laptev seas, respectively; prodelta of the Kolyma River; Longa Strait	2–47	5.1	36.2	22.9	26.1	45.4	38.1	34.0	49.8	39.0

Note: (UCS) Underwater coastal slope. Sediment types: psammites: (Ps_2) medium-grained, (Ps_3) fine-grained: psammites: (SPs) silty, (PlPs) pelitic; (PlS) pelitic silt; (SPl) silty pelite; pelite (Pl); mixtites: (PsM) psammitic, (PlM) pelitic.

stable environments under ice, i.e., beyond the zone of waves. Pelites also constitute underwater fans of the Yana, Indigirka, Alazeya, and Kolyma rivers, where they fringe the peripheral part of the prodelta. The boundary of a spacious field of sediments deposited under ice in the eastern part of the sea reflects the annual mean position of the drift ice edge at depths of 25–30 m. In the Aion Island area, Pl sediments reach the coast. This can be explained by the formation of "shadow" sedimentation settings when the Aion pack

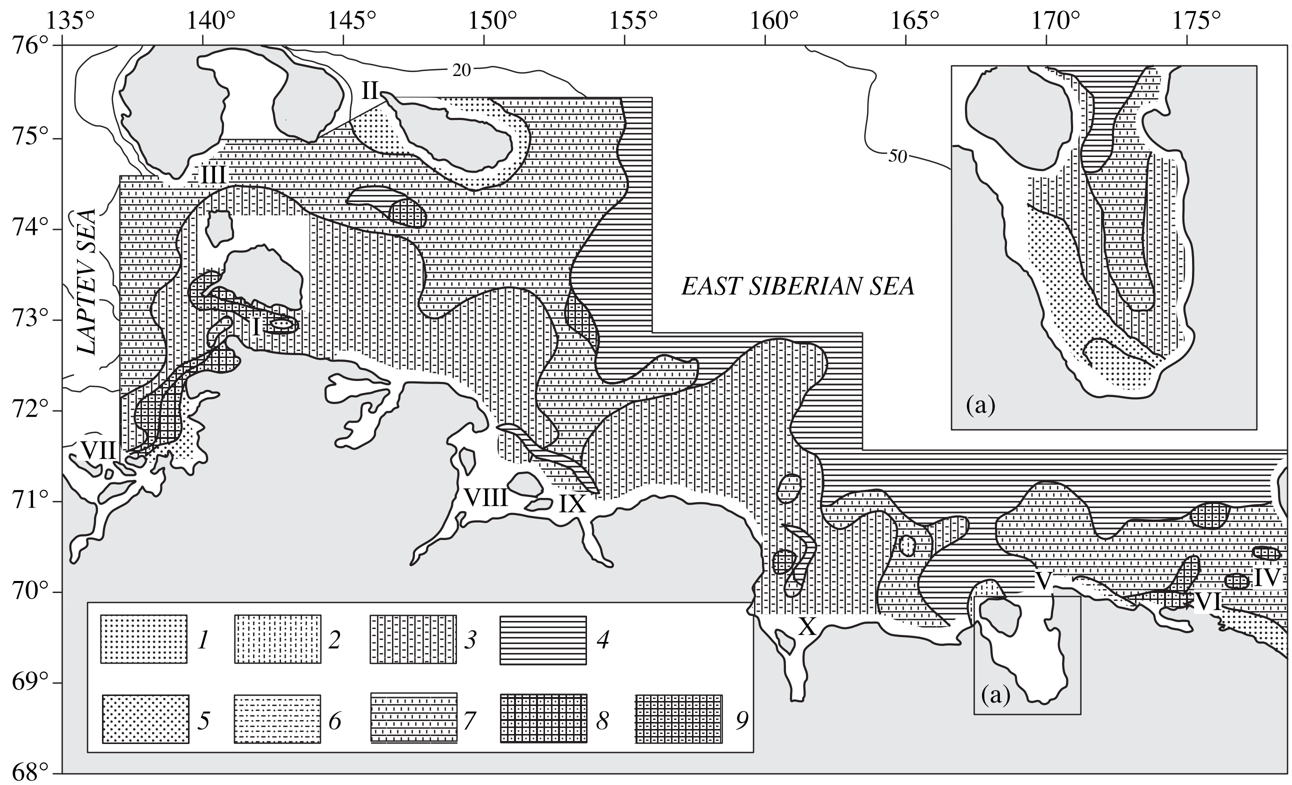

Fig. 1. Bottom sediments of the ESS shelf. Lithological types of sediments: (*1*) Ps_2, (*2*) Ps_3, (*3*) SPs, (*4*) PlPs, (*5*) PlS, (*6*) SPl), (*7*) Pl, (*8*) PsM, (*9*) PlM. Straits: (I) Dmitry Laptev, (II) Blagovshchenskii, (III) Sannikova, (IV) Longa; capes: (V) Shelagskii, (VI) Billings; river deltas: (VII) Yana, (VIII) Indigirka, (IX) Alazeya, (X) Kolyma. Inset (a) shows the Chaun Bay.

ice field reaches the shoreline. The influence of this ice barrier is reflected in several features: (a) limitation of the eastward distribution of freshened Kolyma River waters and the consequent increase in salinity of surface waters from 24 to 29‰; (b) discharge of the SP (we established a fourfold decrease in the SP content in water near the eastern edge of the ice field relative to the western edge); (c) the facies replacement of sediments to the east and west of the barrier according to the Pl→SPl→PlS succession. In the clayey fraction, the illite content increases eastward by several percent, while the chlorite content decreases by a similar value in the same direction. The sharp turbidity reduction and westward ingression of water masses enriched in biogenic elements enhance photosynthesis, which increases the total concentration of marine planktonogenic C_{org}. The average C_{org} is 21% in sediments of the Kolyma–Chaun shelf west of the ice barrier and only 7% in sediments of the Yana–Kolyma shelf dominated by the contribution of terrestrial C_{org} from river runoff and products of thermal coast abrasion. East of the barrier, the contribution of planktonogenic and terrestrial sources becomes similar. The role of the former source prevails farther toward the Chukchi Sea. The $\delta^{13}C$ value in the terrestrial and mixed (terrestrial–planktonogenic) sources increases in this direction to 27 and 25–23‰, respectively [13, 14].

Depending on the intensity of storms, the boundary of the wave influence zone can fall to a depth of 25 m, above which the drift ice edge is usually located. This zone of alternating lithodynamic processes involves the entire near-continental shelf, including shoals around the New Siberian Islands. In the ice-free shelf area, hydrodynamic processes provide transport of terrigenous material from the coast and erosion and redeposition of sediments of the active layer. Wave roiling of the SP promotes the existence of the bottom nepheloid layer, which is the main factor responsible for the formation of the sedimentary cover during periods of low-energy hydrodynamics. Sediments of the erosion–accumulation sedimentation settings are represented by the SPl→PlS→PlPs→SPs series, which reflects the increase in grain size, and mixtite varieties PlM→PsM.

Figure 1 demonstrates that PlS and SPl sediments are second in abundance after Pl varieties. The spatial distribution of these sediment types is inconsistent with the circumcontinental zoning of the marginal sea sedimentation. As is evident from Fig. 2 and the table, nearshore shoals are covered by SPl sediments (average content of Ps, S, and Pl fractions is 1, 40, and 59%, respectively), which replace less dispersed PlS varieties with an average content of Ps, S, and Pl fractions equal to 3, 62, and 35%, respectively, in distal parts. This fact suggests changes in sedimentation settings, probably,

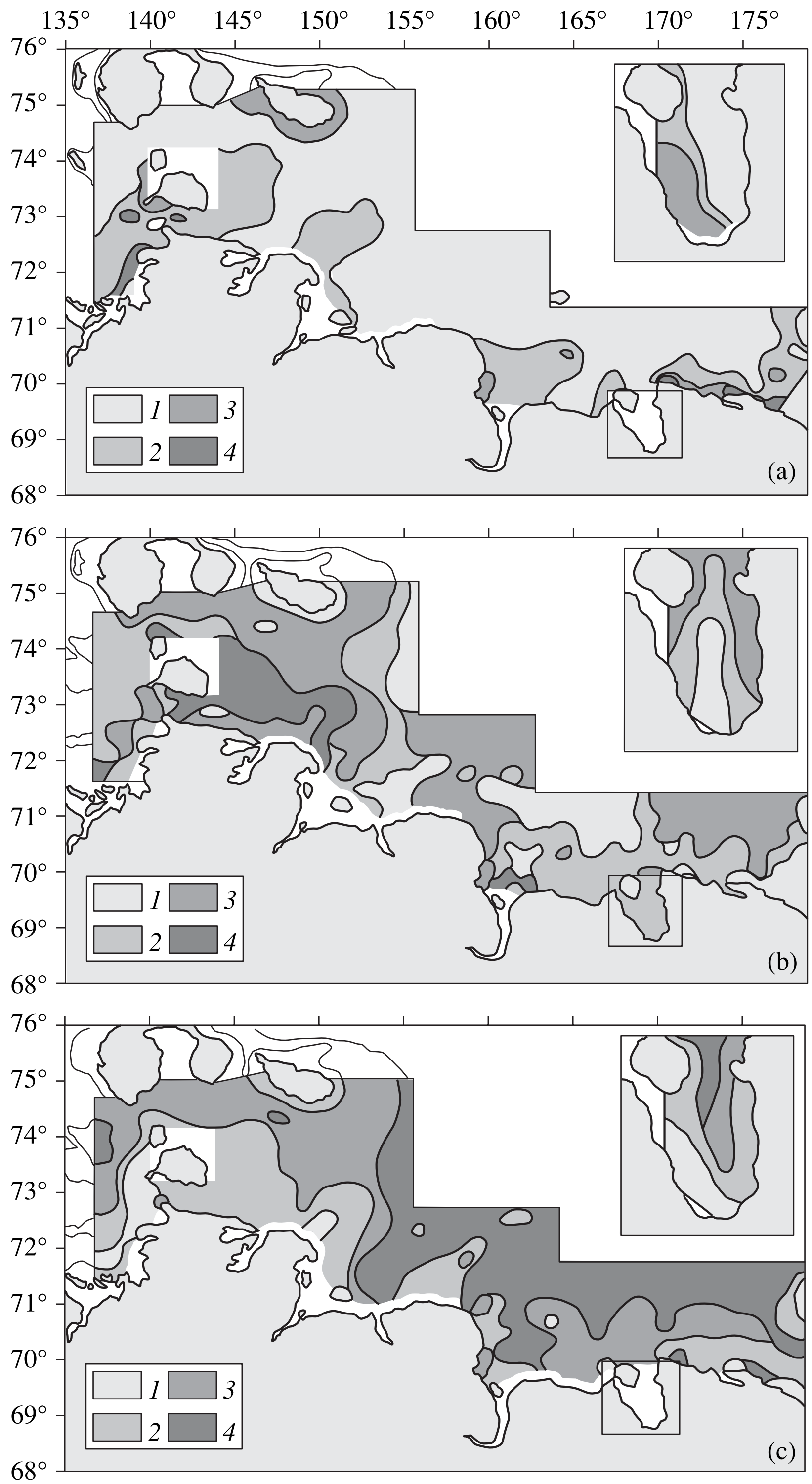

Fig. 2. Spatial variations in the content of the main sediment-forming fractions. Fraction content (%). (a) Psammite: (*1*) 0, (*2*) 1–25, (*3*) 25–50, (*4*) >50; (b) silt: (*1*) <20, (*2*) 20–40, (*3*) 40–60, (*4*) 60–80; (c) pelite: (*1*) <25, (*2*) 25–50, (*3*) 50–75, (*4*) >75.

due to the influence of the Siberian Coastal Current, which flows from west to east. The front of this alongshore current, which is formed along the distal periphery of this current owing to its interaction with waters of the outer shelf, hampers the heat and mass exchange processes. In addition to changes in grain-size composition of sediments, differences in the C_{org} content (almost a factor of two decrease on the northern side of the front) and $\delta^{13}C$ values (heavier by 1.5–2.0‰ north of the interface) are also observed on both sides of the hydrological front. This provides grounds to consider this front as a biogeochemical and sedimentation barrier. Waters discharged by large rivers can distort the established distribution of SPl and PlS sediments.

Small fields of SPs, PlPs, PsPl, PsM, and PlM sediments mark areas of cryosol melting in the course of drift and degradation of pack ice fields. Such fields are mainly observed in the eastern part of the sea dominated by abrasion–denudation shores. Depending on the type of sediments, the content of Ps, S, and Pl fractions varies in the range 12–56, 16–45, and 6–50%, respectively (Figs. 1, 2; table).

The locally developed low-deposition lithodynamic settings (Ps_2 and Ps_3 sediments) are confined to areas of high-energy hydrodynamics, such as underwater banks (relicts of subaerial topography), erosional trenches in straits (with relict Ps_2 sediments), and present-day Ps_2 and Ps_3 zones characterized by wave-induced fractionation of sediments on the underwater coastal slope (UCS) (Figs. 1, 2; table).

Based on the SP content, the quantity of sedimentary material simultaneously dispersed in waters on the continental shelf of the ESS is estimated at 46.1 Mt, which is almost 10 Mt more than the total annual influx of solid sedimentary material by rivers and the calculated contribution of the coastal PFR destruction. Such a discrepancy could result from the combined influence of two processes: (i) removal of terrigenous material by surges or tidal waters away from the coast and (ii) remobilization of bottom sediments. The distribution of the above-mentioned quantity of SP is as follows: ~60% (27.5 Mt) is contained in waters of the Indigirka–Kolyma shelf, 33% (15.4 Mt) in waters of the Kolyma–Chaun shelf, and only 7% (3.2 Mt) is confined to waters of the Shelagskii–Billings shelf.

The calculated annual sedimentation rate decreases in the eastward direction from 0.2 mm on the Yana–Kolyma interfluve shelf to 0.15 mm on the Kolyma–Chaun shelf and 0.06 mm on the Shelagskii–Billings shelf. The absolute sediment mass decreases from 352 to 270 and 107 g/(m^2 yr), respectively, in the same direction. For example, the sediment flux measured by sedimentation traps on the UCS of the Dmitry Laptev Strait was as high as 37 g/(m^2 day) [5]. This value is comparable with estimates of the sediment flux at biogeochemical barriers of the tropical Mekong River estuary or Arctic Yenisei River estuary [4, 7]. Inasmuch as the influence of the drainage of the Lena and Yana rivers is largely manifested in water freshening, high values of sediments fluxes in these areas can be explained by the proximity of other provenances (shores subjected to thermal abrasion) and by additional saturation of waters with SP due to its remobilization.

The low sedimentation rate (close to zero) on the periglacial shallow shelf of the ESS is another important feature of recent sedimentogenesis, in addition to spatial uniformity of its sediment lithology. This lithogenetic peculiarity of the eastern Arctic has also been noted in [1, 9]. The sedimentation rates mentioned above indicate relative equilibrium between erosion and accumulation on the ice-free shelf, when influx and settling of sediments are volumetrically comparable. The calculated rates correspond to subglacial sedimentation settings with a low influx of sedimentary material.

The boundary between opposite lithodynamic sedimentation settings is governed by the position of the edge of drift ice fields. This edge simultaneously plays the role of a complex hydrodynamic, sedimentological, and biogeochemical natural barrier.

Hydrological fronts that form between genetically different and interacting water masses control fractionation of sedimentary material by its grain size and, hence, influence the spatial distribution of bottom sediments in the ice-free shelf area.

Terrigenous material is removed from the flat shoal by surge currents and gravity flows of sediments concentrated to the state of "liquid mud." The downward movement of these flows is controlled by bottom topography.

Stable accumulation of the SP begins after the blocking of shelf waters by ice cover. In the absence of turbulent perturbations, the dominant silty–pelitic fraction characterized by the hydraulic parameter of 0.01 cm/s (at a depth of 25 m or less) has a settling period of no more than four days. In addition, some suspended matter from the surface layer is transferred to the cryosol of young ices even at the ice formation stage.

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