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The Holocene Destruction of the Tumannaya River Delta and the Formation of Shallow Gas Accumulations along the Shelf in the Western Part of Peter the Great Bay (Sea of Japan)

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Abstract—This paper reports on results of bathymetric and seismoacoustic studies of the shelf in the western part of Peter the Great Bay. Five flooded coastlines, formed in the Late Pleistocene–Holocene, were revealed on the shelf. It was found that a significant part of the shelf is occupied by a zone of irregular sedimentation. This zone is underlain by an erosion surface buried under sediments of ebb–flood tidal deltas in the areas of active sedimentation and is exposed on the seafloor within the area of active modern erosion. The abrasion and formation of the irregular sedimentation zone on the shelf intensified about 11 500–11 700 years ago. Acoustic anomalies, associated with gas occurrences in sediments and gas plumes in the water column, were recorded on the shelf of the bay. Types of anomalies were classified, and a map of their areal distribution was compiled. It is concluded that the trigger mechanism that provides gas migration into sediments and to the water column is associated with a group of factors: the change of the postglacial sea level and abrasion processes, as well as the meteorological and hydrological regimes.

Keywords: shallow gas accumulations, Tumannaya River delta, Holocene changes of a sea level, Peter the Great Bay

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INTRODUCTION

Rivers are a major supplier of large quantities of sediment to the shelf, deep-water slope and seafloor. A river delta is formed at confluence of a watercourse with a marine basin as a result of the interaction of river discharge, sea swell, tides and currents. Delta sediments form a significant part of the sedimentary cover on the shelf and continental slope. Various near-surface gas accumulations are frequently observed in the shelf sediments (7, 24, 30). Their recognition is based on the presence of acoustic features such as acoustic "turbidity," "cover," "columns," "curtain," etc. (26, 29, 30). It is important to study and identify zones of increased pore pressure in sediments by seismoacoustic methods, when pore water contains dissolved gas under a pressure that is higher than the sum of hydrostatic and lithostatic pressures. It is assumed that these zones are column-shaped acoustic voids (26). Another indicator of an excessive pore pressure may be the presence of local highs of the seafloor above transparent zones. The stability of the near-surface gas accumulations in shallow waters, as well as their destruction and gas migration to the seafloor are influenced by the following factors: pressure in gas-saturated sediments (23), destruction of sedimentary sequence by moving fluids, excessive pore water pressure, and the effect of the so-called "hydraulic pump" on gas-bearing sediments [30]. Gas migration can be triggered by various external forces: earthquakes and tsunamis, storm waves and tides, atmospheric pressure fluctuations, and the activity of internal waves.

Information on near-surface gas accumulations on the shelf of the Sea of Japan is not abundant (24). Near-surface gas accumulations have been reported in muds of the Korean Peninsula shelf (25, 32, 33). Gas accumulations on the shelf of the northwestern part of the Sea of Japan began to be explored after the discovery of various near-surface acoustic anomalies of the gas origin in the Late Pleistocene–Holocene muddy sediments in the Amur Bay (northern part of Peter the Great Bay) during expeditions of the Il'ichev Pacific Oceanological Institute, Far Eastern Branch, Russian Academy of Sciences (30). In the western part of Peter the Great Bay, seismoacoustic profiles also indicated near-surface gas accumulations (12, 13), and echo sounder records showed gas plumes (6). The present work summarizes the available seismic and seismoacoustic data obtained during the expeditions of the Il'ichev Pacific Oceanological Institute in 2001–2022 to clarify the structure of the shelf of the western part of Peter the Great Bay, to identify and classify near-surface gas accumulations, to assess the state of the Tumannaya River sedimentary delta, and to analyze oceanological and meteorological data to determine the trigger mechanism of gas migration in the sediments.

THE GEOLOGICAL AND OCEANOGRAPHIC SETTINGS

Peter the Great Bay is located in the northwestern part of the Sea of Japan and is with a vast shallow shelf (Fig. 1a). There are no large rivers in the northwestern part of the Japan Sea region. Here, small rivers 50–150-km long flow from the slopes of the Sikhote-Alin, East Manchurian and North Korean mountains. Only the Tumannaya River stands out distinctly from these rivers. This river, also known as the Tumen River (Korean pronunciation: Tumangan), is a 550-km long watercourse originating on the slopes of Paektu Mountain. The river delta occupies extensive lacustrine and marshy coastal lowlands with numerous pools and lakes located at 2–8 m a.s.l.

In terms of the tectonic position, the western part of the bay and adjacent land belongs to the southern edge (called the West Primorskaya zone) of the Khankai massif [1]. The marginal parts of the massif in the West Primorskaya zone are intensively reworked, overlain by terrigenous-volcanogenic formations, and intruded by granitoids of the Paleozoic and Mesozoic stages of tectono-magmatic activation. The basement in the shelf area is presumably composed of sedimentary rocks (sandstones, siltstones, and carbonaceous siltstones with black coal lenses) of the Permian age, granitoids of the Late Permian and Early Jurassic, and volcanic formations of the Late Triassic and Eocene.

The western part of Peter the Great Bay is a basin open to the waters of the Sea of Japan. The sea level changes and water circulation in the bay are controlled by wind patterns, cyclonic/anticyclonic weather systems (rise/decrease in pressure by 1 hPa results in 1-cm rise/decrease in sea level), storm waves, and tides. Wind circulation is the main factor that controls the water dynamics in the bay. Northern and southern winds prevail over the bay [16, 27]. The maximum wind velocity is up to 26 m/s. There is no stable ice cover in the winter season; waves move from the north and west and their height can reach 5.8 m [15]. In summer, waves moving from the south prevail and their height reaches 9 m [18]. The height of tides in the bay is 0.2–0.5 m [16]. The atmospheric pressure varies throughout the year from 981 to 1039 GPa [27]. Wind, atmospheric pressure fluctuations, and tides can cause the local sea level to rise or fall, which can reach 0.6–1.0 m [16]. The waters of the bay are influenced by the cold Primorsky current, which moves from the northern part of the Sea of Japan [22]. Deep water from the Japan Basin periodically invades the bay under upwelling conditions. The combination of all these factors causes the formation of the seafloor currents with velocities of 0.3–1.0 m/s [15, 21].

The structure of sea water in the bay is very variable. In summer, there are two layers of water with different salinities and temperatures. In the surface layer, the water is heated to a temperature of 20–24°C [5]. Below a depth of 50 m, the water temperature varies from +5°C to +1°C. In winter, the water column has a uniform temperature distribution and there is no distinct stratification of water. The presence of temperature and salinity extremes in summer, tidal activity, near-bottom currents and periodic deep-water invasions contribute to the formation of internal waves. The internal waves are usually formed near the shelf edge and have a wavelength of 1.5–2.0 km and an amplitude of 3–5 m [17]. As the sea depth decreases, the length of the internal waves decreases to 200–500 m and the amplitude increases to 5–10 m.

INITIAL DATA

The results of marine bathymetric, seismic, and seismoacoustic surveys were used in this study. Bathymetric data (Fig. 1b) were obtained with the use of single-beam and multibeam echo sounders. The single-beam echo sounders were GARMIN GPSMAP 420s, ELAC LAZ-72AV, and GEL-3 types. The multibeam echo sounder was a SeaBeam 3050 model. Seismic works were carried out by the method of continuous profile observations using a single-channel seismic streamer and a 3-liter pneumatic source [10]. Seismoacoustic studies were carried out according to the methodology with the "GeoPulse Subbottom Profilier" high-frequency profiler (Fig. 2). A signal with a frequency of 3.5 kHz was used.

RESULTS

The shelf of the western part of Peter the Great Bay is a surface inclined to the south that is complicated by separate depressions and rises (Fig. 1c). The shelf edge is located at depths from 125 to 135 m. In general, the width of the shelf increases in the northeastern direction from 8 to about 50 km. In the depth interval of 650–70 m, there is a scarp that divides the shelf into inner and outer parts. Extended depressions 30–40 m deep are located in Kitovy Bay and to the southwest of Furuhjelm Island. Another depression up to 75 m deep is located to the south of Gamov Peninsula. The width of the outer shelf increases in the northeastern direction from 2–3 up to about 22 km. This pattern is disturbed between Furuhjelm Island and Gamov Canyon, where the local expansion of the outer shelf is up to 18 km. Several canyons cross the continental slope. The largest of them is Gamov Canyon. Another large system of canyons is located on the slope near 131°50′ E. There is also a large canyon located near the mouth of the Tumannaya River. The upper parts of the

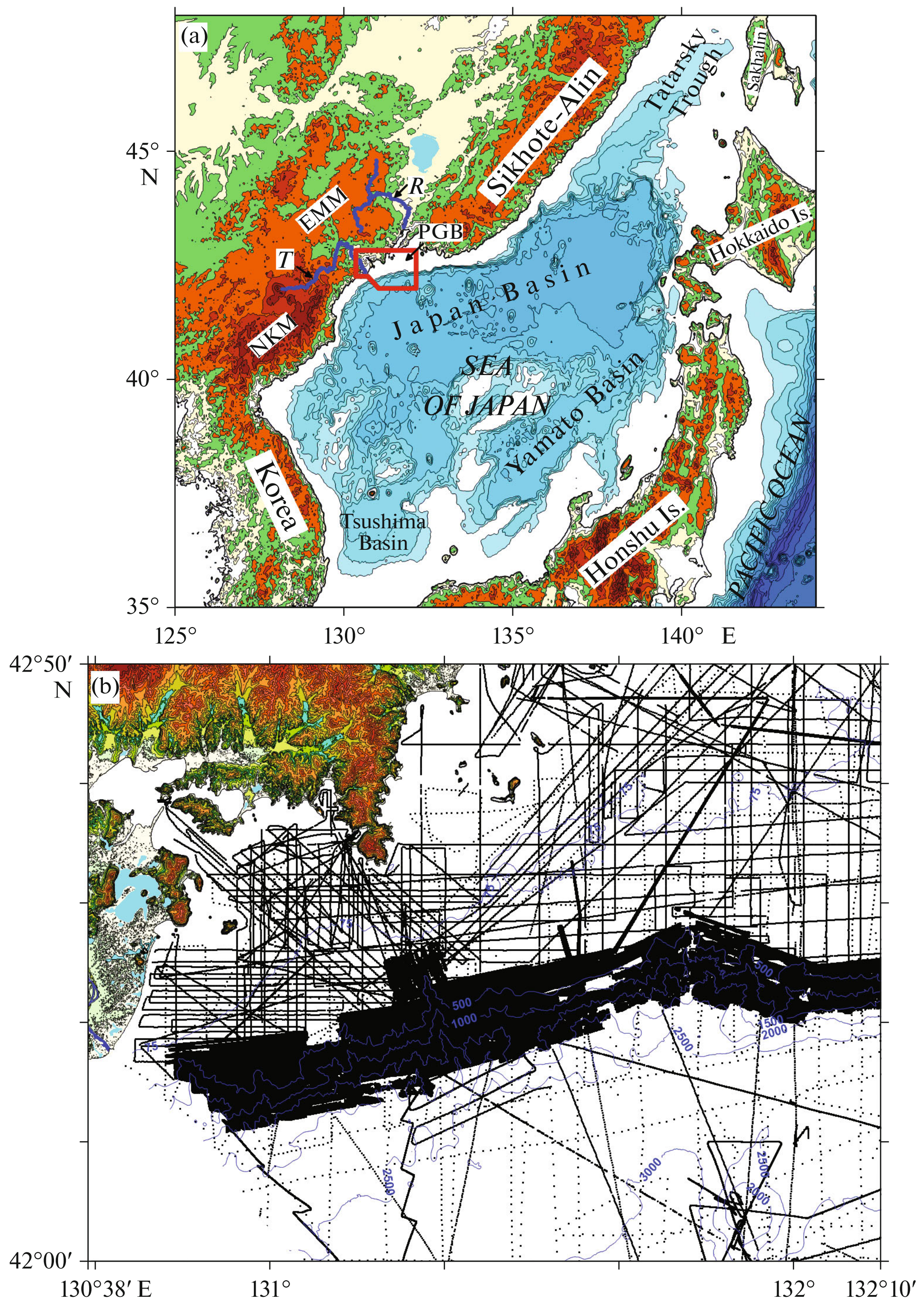


Fig. 1. The work area in the Sea of Japan (shown in red outline) (a) and the bathymetric profiles in the western part of Peter the Great Bay (b). 1a: PGB—Peter the Great Bay. EMM—East Manchurian Mountains. NKM—North Korean Mountains. T—Tumannaya River. R—Razdolnaya River 1b: profiles with a single-beam echosounder are shown with solid black and dashed lines. The work areas with a multibeam echosounder are marked with black areas. Fig. 1. A map of seafloor relief (0.1' grid) of the western part of Peter the Great Bay and the adjacent part of the Japan Basin (c). In the depth range of 5–100 m, isobaths are drawn at 5-m intervals. Deeper than 200 m, isobaths are drawn at 100-m intervals. Between depths of 100 and 200 m, isobaths of 110, 130 and 150 m are shown. Red rectangles show the dredging stations of mudstone sequence (4). Red asterisks show the oceanological stations (14, 20). TB, Trinity Bay; VB, Vityaz Bay; LB, Lebediny Bay; NS, Nazimova Spit.

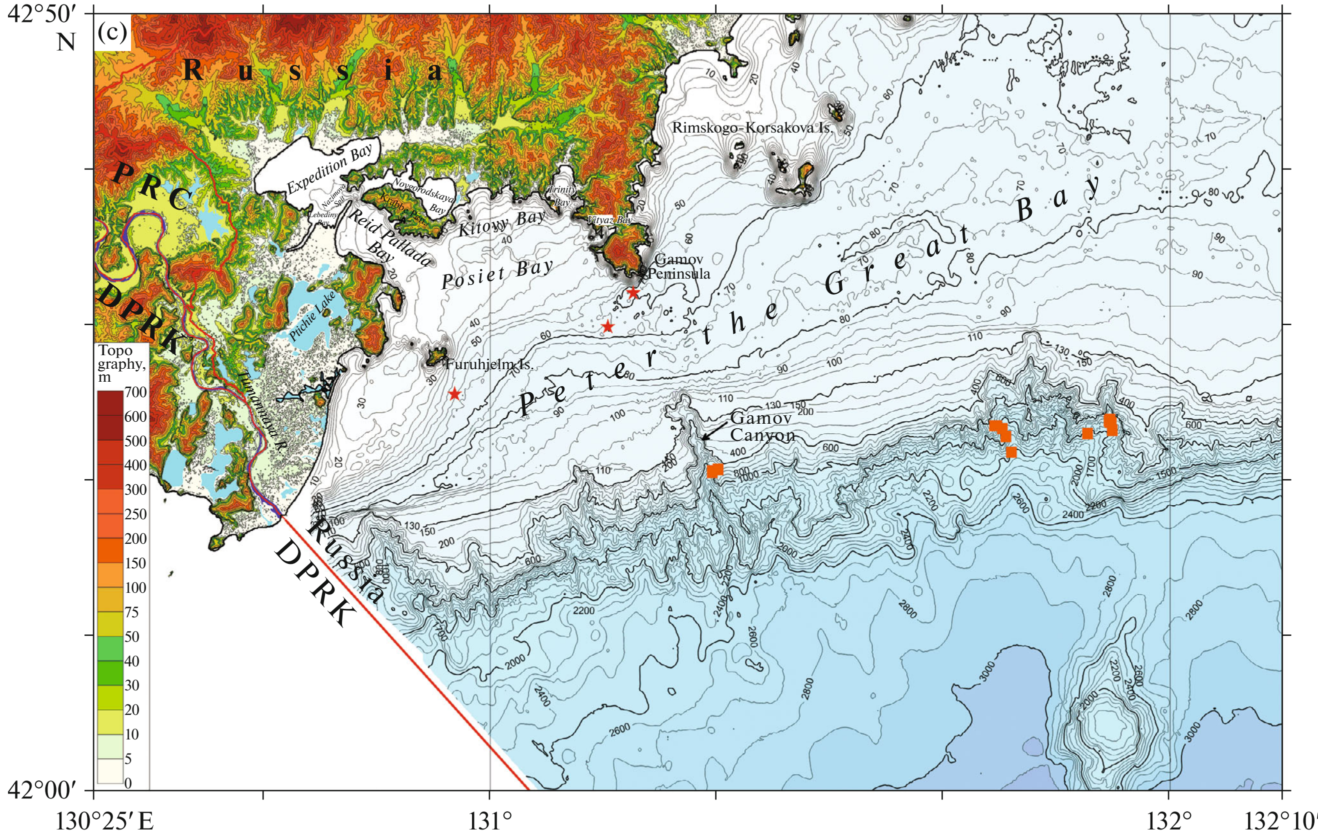


Fig. 1. (Contd.)

canyons begin to form at depths of 90–105 m. The part of the Japan Basin adjacent to Peter the Great Bay has an extensive continental foot. The foot is located in the range of sea depths from 2200 to about 3300 m; its width is 50–90 km. The foot is well-manifested in the part of the basin adjacent to the mouth of the Tumannaya River and Gamov Canyon.

The acoustic basement (AB) of the shelf dips in the direction of the Japan Basin (Figs. 3, 4). The AB surface within the inner shelf is relatively flat and is usually located at depths of 0.2–0.4 s (the double wave propagation time is given here and below). The AB surface of the outer shelf has a dissected relief and is located at depths of 0.4–1.4 s. Several narrow depressions with depths up to 1.1 s are distinguished here. A notable feature of the basement structure is the presence of a chain of local rises in the area of the shelf edge and the upper part of the slope. In the upward direction, these rises are adjacent to the broad tilted block of the AB. These distinctive features of the basement structure of the bay shelf determine the characteristics of the distribution of a sediment thickness. The thickness of sediments in the upper part of the continental slope reaches 1.5 s. In most of the shelf, the sediment thickness is about 0.2–0.7 s, rarely up to 1.0 s.

The seismoacoustic profiles on Figs. 5–9 demonstrate the general structure of the Pliocene-Holocene sediments in the western part of the Peter the Great Bay shelf. Our profiles show that five stages, which resulted from the sea level fluctuations in the Late Pleistocene and Holocene, are distinguished on the shelf. Their identification is based on the features of the seafloor relief and sediment structure. The steps manifest the main elements of submerged ancient coastlines: a coastal bar (barrier), lagoon, lower coastline (refers to that part of the seafloor and sedimentary media below the base of the daily wave), and relict mainland coast. The nomenclature of the main coastal barrier systems is given according to (35). The first coastline is located at depths of 105–108 m, the second at 67–87 m, the third at 53–63 m, the fourth at 27–43 m, and the fifth at 17–25 m. The fourth line is the best preserved. Its barrier is indicated in the depth interval of 25–40 m and can be traced from the mouth of the Tumannaya River through Furuhjelm Island to Vityaz Bay. The seafloor surface in the lagoons is usually flat or slightly hilly. This specific feature is distinctly disturbed in the part of a lagoon of the third line located to the south of Gamov Peninsula (Fig. 9). The lagoon is connected to the outer shelf through a narrow channel at a depth of about 65 m. The bottom surface in the lagoon is complicated by troughs and hills

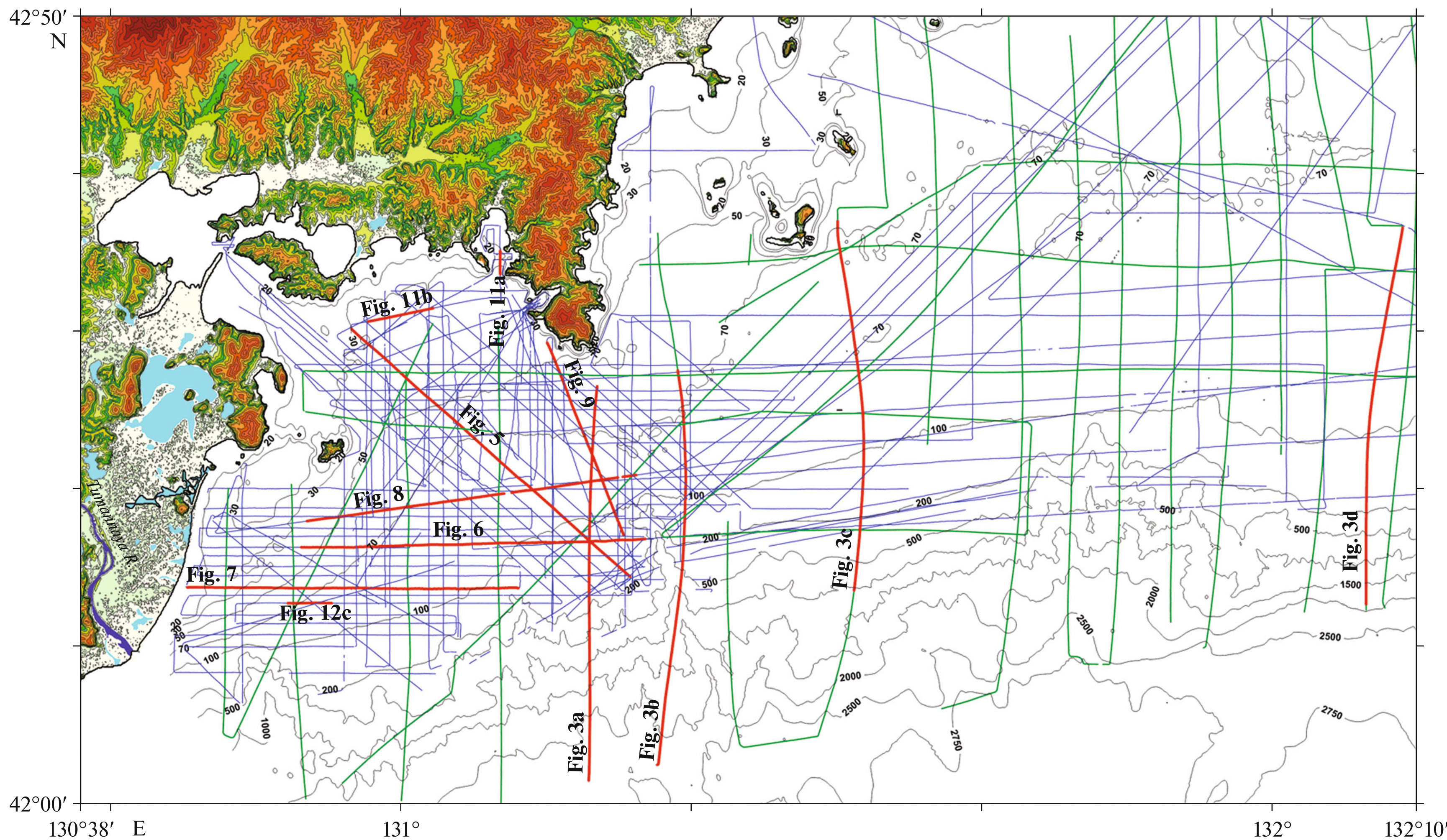


Fig. 2. A map of seismoacoustic profiles obtained with a high-frequency profiler (thin blue lines). Profiles of single-channel continuous seismic profiling with a pneumatic source are shown by thick green lines. Examples of profiles are indicated in Figs. 3, 5–9, 11, and 12 by thick red lines.

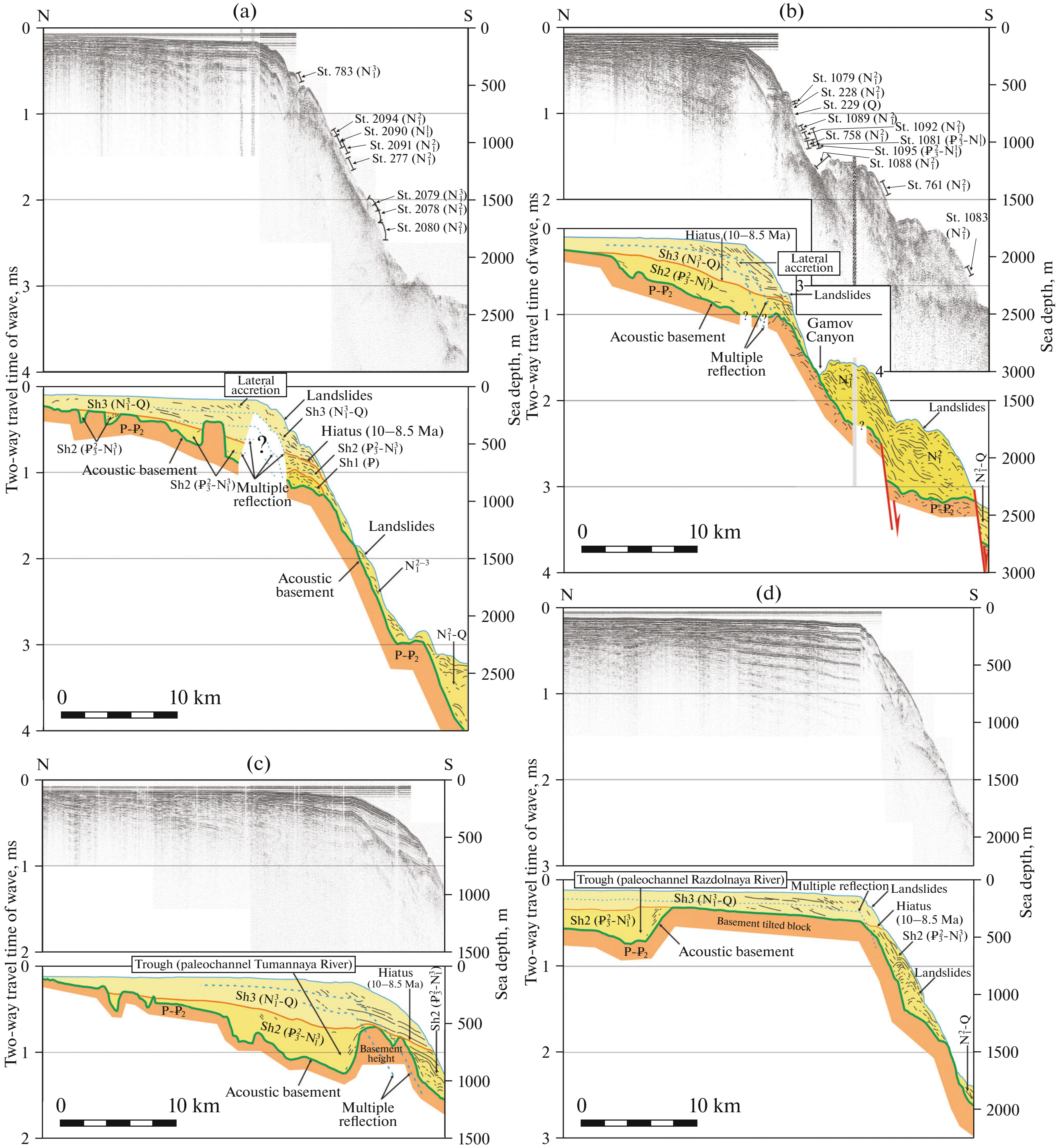


Fig. 3. Examples of seismic profiles with a pneumatic source illustrating the general structure of Paleogene(?)–Pleistocene sediments and the acoustic surface of the western part of Peter the Great Bay and the adjacent part of the continental slope. Sh1, Sh2, Sh3, seismic complexes. P-₽$_2$, Permian–Eocene, ₽, Paleogene, ₽$_3^2$, N_1^3, Late Oligocene, the beginning of Late Miocene, N_1^3–Q, the end of Late Miocene–Pleistocene, N_1^2 – Middle Miocene; N_1^2–Q, Middle Miocene–Pleistocene.

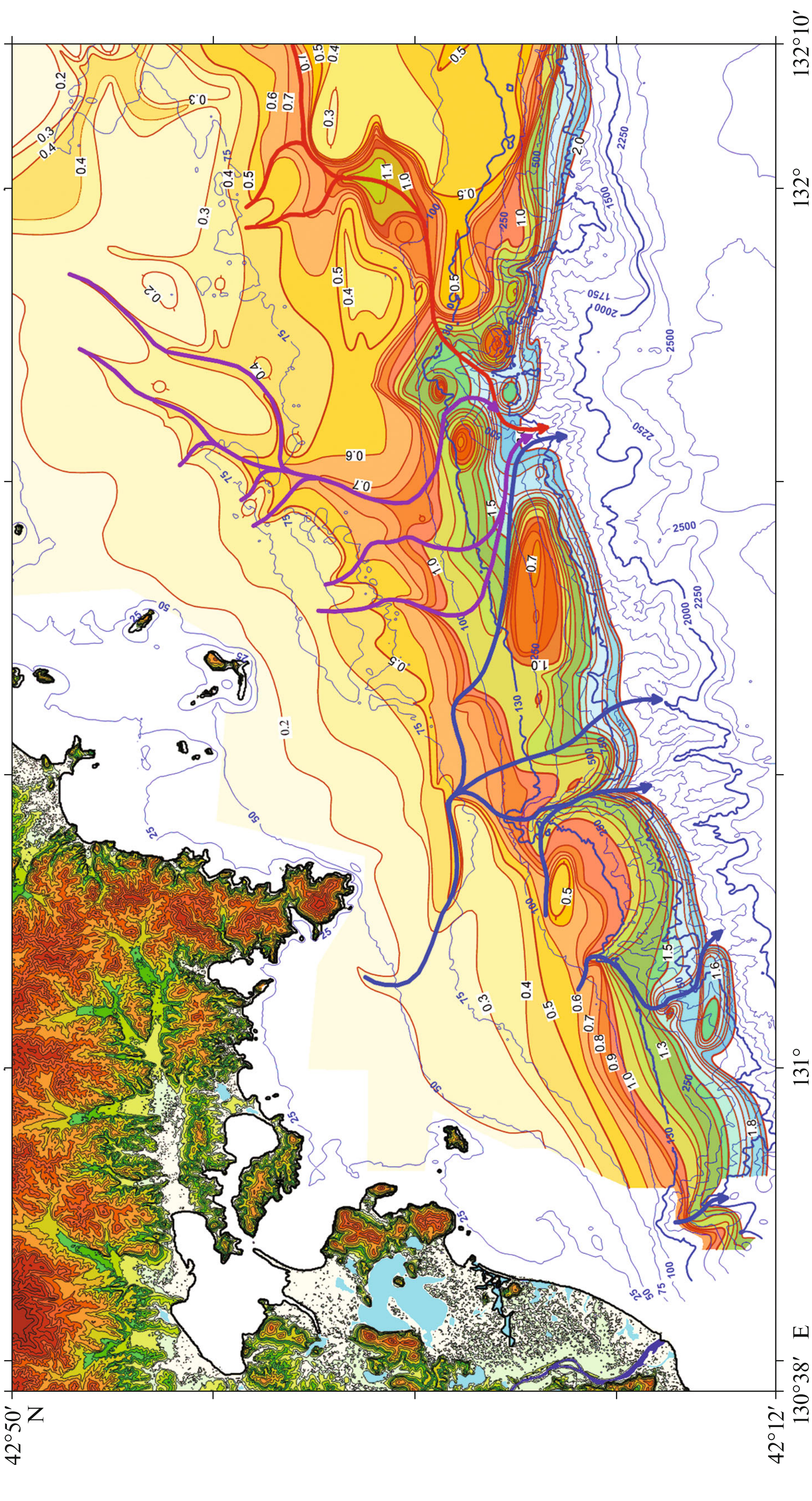


Fig. 4. A map of the acoustic basement surface of the western part of the Peter the Great Bay shelf and the adjacent continental slope. Elevation lines are drawn at 0.1 s intervals (two-way travel time of a wave). Blue and red lines indicate the paleochannels of the Tumannaya and Razdolnaya rivers, respectively. Purple lines illustrate the paleovalleys of local rivers.

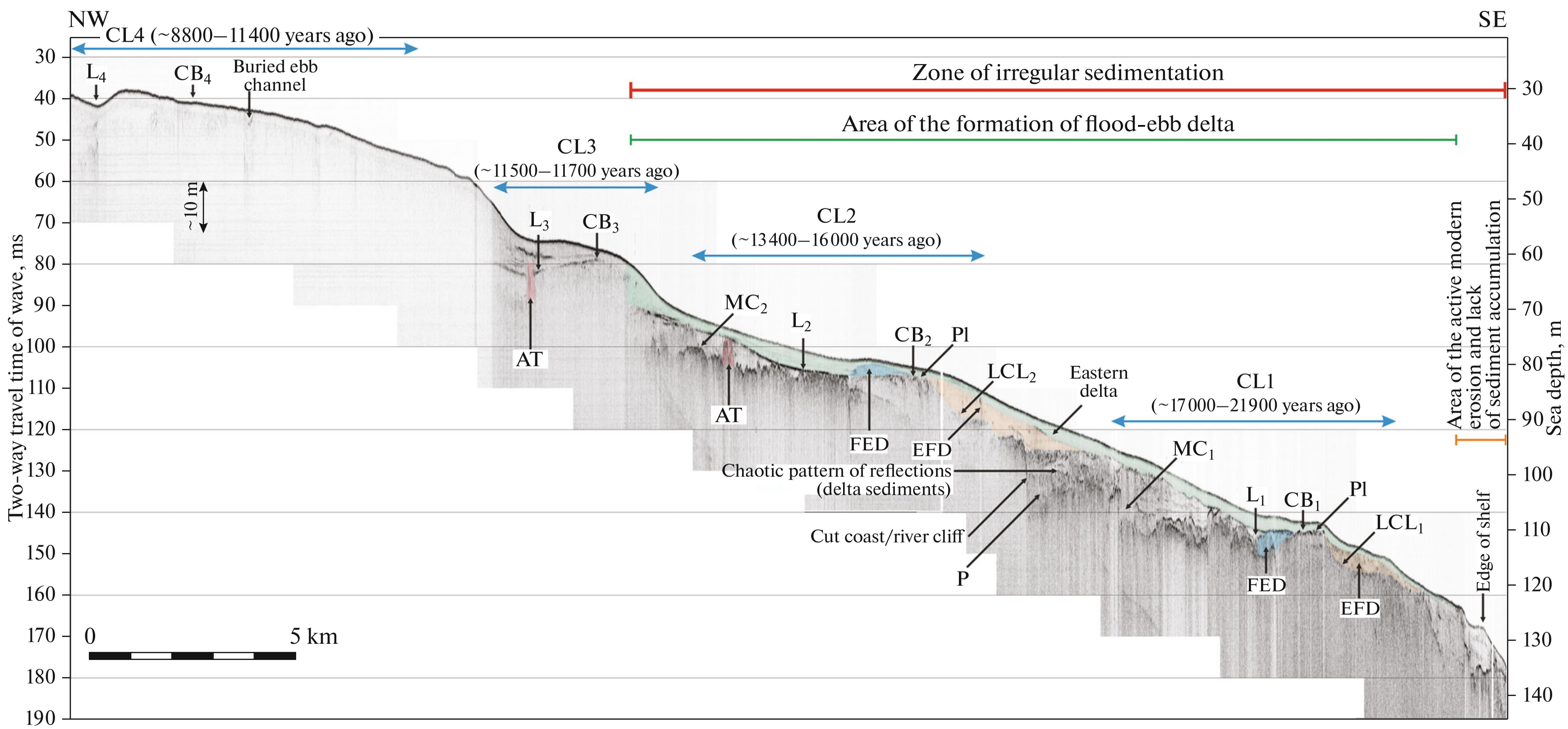


Fig. 5. The seismoacoustic profile illustrating the general structure of the shelf of the western part of Peter the Great Bay and the structure of the main elements of the submerged coastlines. Here and in Figs. 6–9: CL, coastline; CB, coastal bar; L, lagoon; LCL - lower coastline; MC, relict mainland coast; Pl, platform (buried under sediments or manifested in the modern seafloor relief) with a flat top formed due to subaquatic wave-surge abrasion; FED, flood-ebb delta; EFD, ebb-flood delta; P, buried tributary/stream of the Paleo-Tumannaya River; AT, acoustic turbidity.

up to 6-m high, indicating an active hydrological setting at the present time.

A specific feature of the shelf structure is the existence of a broad zone of irregular sedimentation in the parts of the shelf where sea depths exceed 45–60 m (Figs. 5–9). This zone is characterized by the presence of both areas of the active sedimentation and formation of flood-ebb tidal deltas, as well as areas of modern erosion and lack of sediment deposition. The unifying feature for both areas is the presence of a common broad erosion surface that underlies the areas of active sedimentation and is exposed on the seafloor in the areas of modern erosion. The amplitude of the erosion cut at the boundary between these areas reaches 8–10 m (Figs. 6, 8). In the direction of the continent, the outer boundary of the irregular sedimentation zone approximately corresponds to the base of the third coastline. The southwestern and northeastern edges of this zone are covered by sediments of flood-ebb tidal deltas up to 11-m thick (a sound velocity in the sediments is assumed to be 1600 m/s). Between them, in the outer shelf area between Gamov Canyon and Furuhjelm Island (Fig. 10), the erosion surface is exposed on the seafloor. In the Holocene, sediment deposition did not occur here, but sediment cover destruction and sediment redeposition prevailed. The flooded ancient coastlines were completely destroyed and are not detected.

Ebb–flood tidal deltas are recognized on the slopes of coastal bars facing the sea; flood–ebb tidal deltas are distinguished on the slopes facing the land. These objects are up to 5-m thick and 1—2-km wide. Sometimes, a pattern of lateral accretion is observed on the ocean side of the barrier (Figs. 5, 6), indicating successive growth/extension of the sedimentary sequence in the lateral direction. Narrow valleys up to 10-m deep and the first hundreds of meters wide are recognized on the tops of the barriers and on their slopes (Figs. 5, 6). We believe that these structures correspond to buried flood–ebb tidal channels. Sometimes narrow hollows up to 8-m deep and 1-km wide are found at the base of the lagoons of the first and second coastlines (Figs. 6–9). These structures probably correspond to buried tributaries or branches of the Paleo-Tumannaya River. These troughs are often adjoined by 8–12-m high scarps on the shore side, which may correspond to river cliffs.

In the western part of Peter the Great Bay, numerous near-surface gas accumulations have been discovered in seafloor sediments. These accumulations have been classified into several types based on their acoustic appearance, shape, and size: “cover,” “columns,” “turbidity,” and “pillars” (Figs. 5–8, 11). Their acoustic appearance was thoroughly described in [12, 13, 31]. Seismic data also indicate zones of high pore pressure and vertical gas migration. These zones are characterized by “curtain” type anomalies, columnar acoustic voids, and small seafloor highs above the acoustic “pipes” (Figs. 11, 12). Downward concave reflections (pull-downs structures) are often observed near the edges of the anomalies. As well, the results of the water column survey during multibeam echo sounder operations showed the presence of numerous acoustic anomalies in the water column in the form of gas plumes.

The acoustic “cover”-type anomalies range from 100 to 2000 meters in cross-section. This type of anomaly is usually found in the lower and middle parts of sedimentary sequences. Column-type anomalies are often located next to them and are usually grouped in clusters of 5–10 anomalies. The size of clusters varies from 50 to 1200 meters in cross-section. “Columns” are widely distributed in the upper and middle part of the sedimentary cover at depths of 1–12 m below the seafloor. Acoustic “turbidity” is manifested at depths of 1–8 m below the seafloor; it is characterized by subvertical boundaries in the sections, and reaches several kilometers in cross-section. Acoustic “pillars” with a cone-shape are a particular case of this type of anomaly. A diameter of the base of the “pillars” is 70–200 meters; their height is up to 22 meters. The depth, at which the tops of the “pillars” are located, is 1–9 meters below the seafloor. Another specific feature of the “pillars” is the presence of a significant downward slope of the reflecting horizons (pull-down structures) on the sides of the anomaly. This occurs because the round-trip time of the acoustic pulse increases due to decrease in a sound velocity in gas-saturated sediments, even though the sediments lie horizontally [36]. If the gas-filled zone is thick enough, this effect gives the impression that the sediments are subsiding (Figs. 11, 12).

An acoustic “curtain” has a typical, clearly distinguishable convex or chevron-shaped upper boundary with high-intensity reflections. The inner area of the “curtain” is usually acoustically transparent. The downward concave reflections are also observed near the “curtain.” The tops of the anomalies are located at a depth of 1–4 m below the seafloor. The width of the anomalies is 70–100 m. Pillar acoustic voids are a special case of this type of anomaly; they are very narrow needle-shaped transparent zones (Figs. 11, 12). Their width varies within 10–20 m. The tops of the acoustic voids are located at a depth of 1–3 m below the seafloor. There are examples of these anomalies reaching the seafloor surface (Fig. 11). At these locations, there is a localized increase in the intensity of the seafloor reflections.

An acoustic “pipe” is identified as a flower-shaped structure that typically expands upward and divides into several sloping arms (Fig. 12). Although their internal appearance of the “pipe” is similar to acoustic “turbidity,” it is on the basis of the upward expansion that we separate these anomalies. Above most of the “pipes” there are highs of the seafloor surface in the

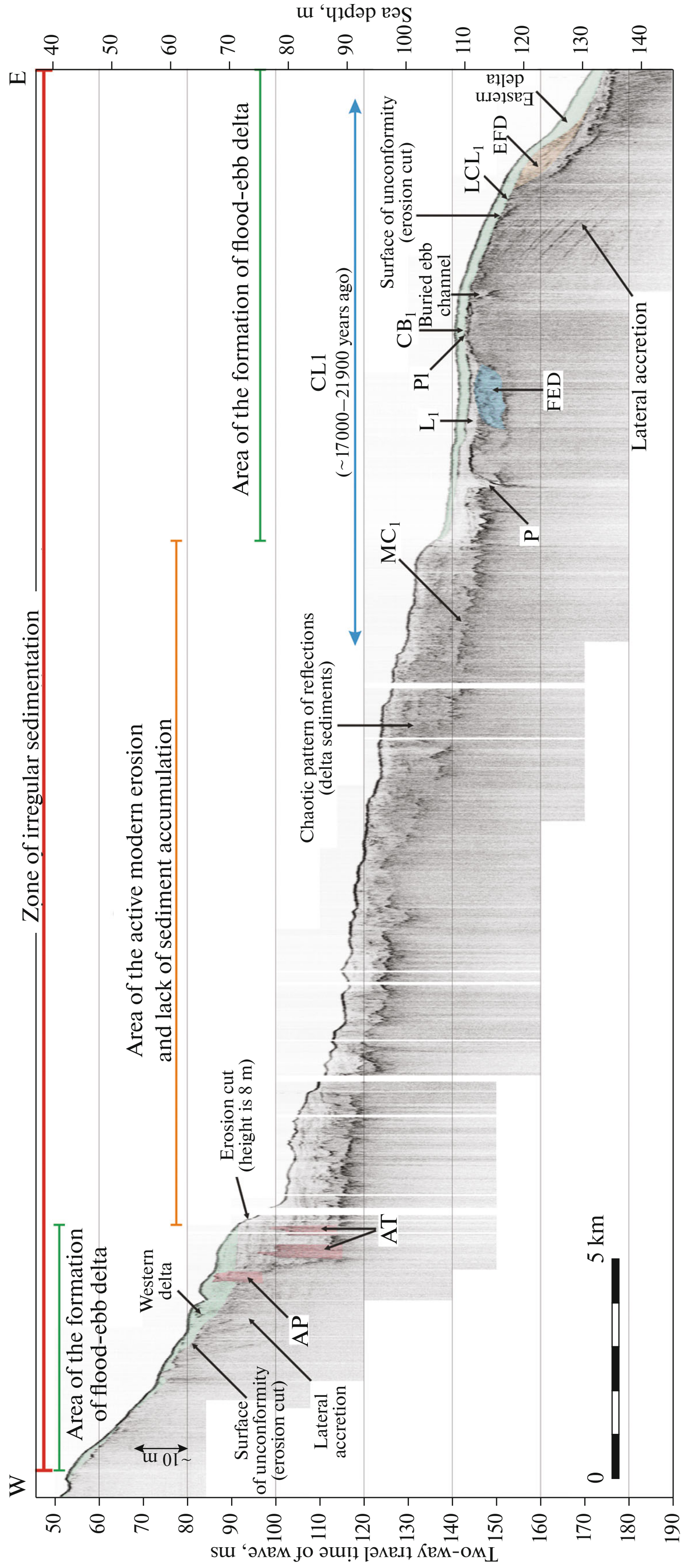


Fig. 6. The seismoacoustic profile explaining the structure of the irregular sedimentation zone, the structure of the active sedimentation areas (western and eastern flood-ebb deltas) and the appearance of the area of the active erosion and lack of sediment accumulation. Note the presence of the 8-m high erosion cut at the western edge of the erosion area. Here and in Fig. 12: AP, acoustic pipe. Other symbols are in Fig. 5.

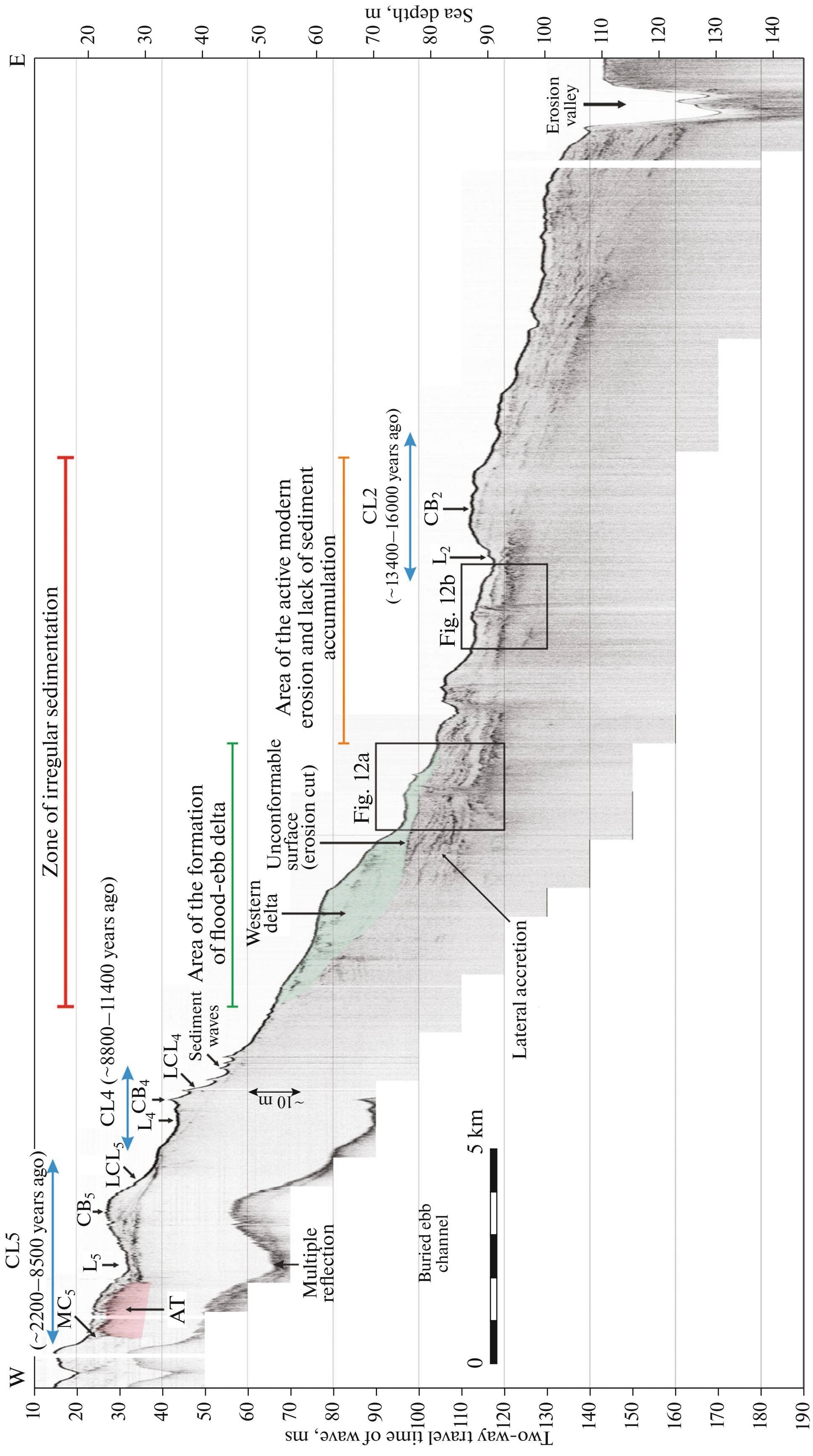


Fig. 7. The seismoacoustic profile illustrating the structure of the sedimentary layer on the shelf of the bay in the area of the modern mouth of the Tumannaya River. The legend is in Fig. 5.

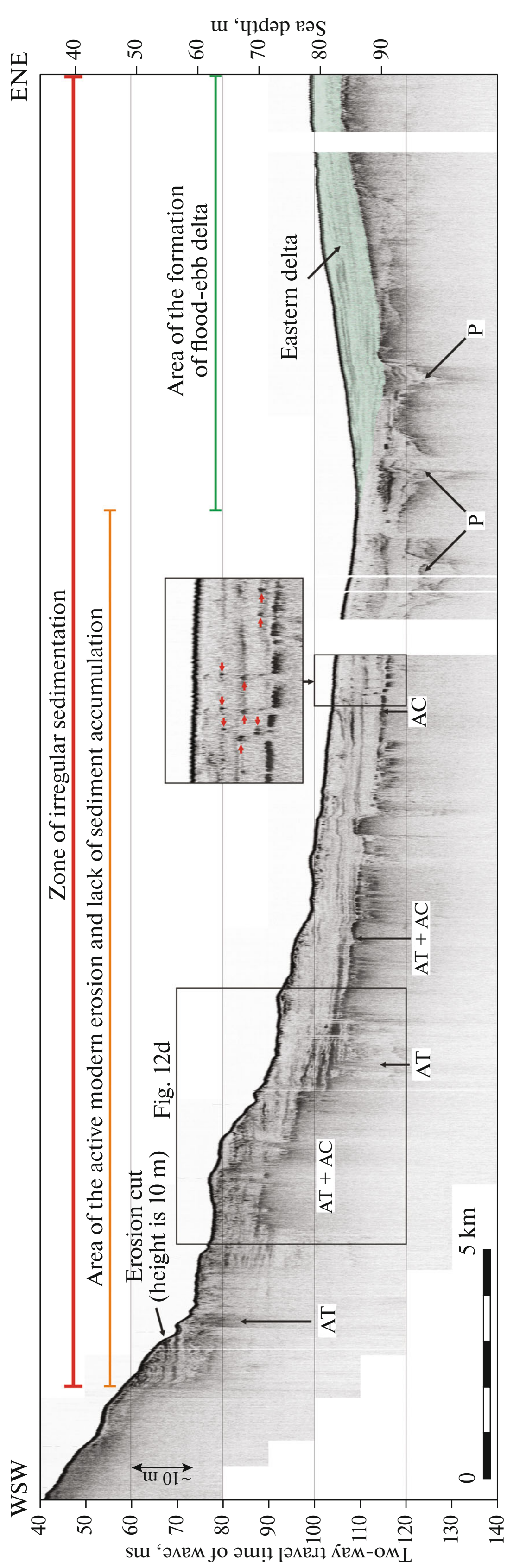


Fig. 8. The seismoacoustic profile illustrating the features of the structure of buried tributaries/arms of the Paleo-Tumannaya River on the outer shelf of Peter the Great Bay. The acoustic columns are shown in the inset with red horizontal lines in Figs. 11 and 12: AC, acoustic cover.

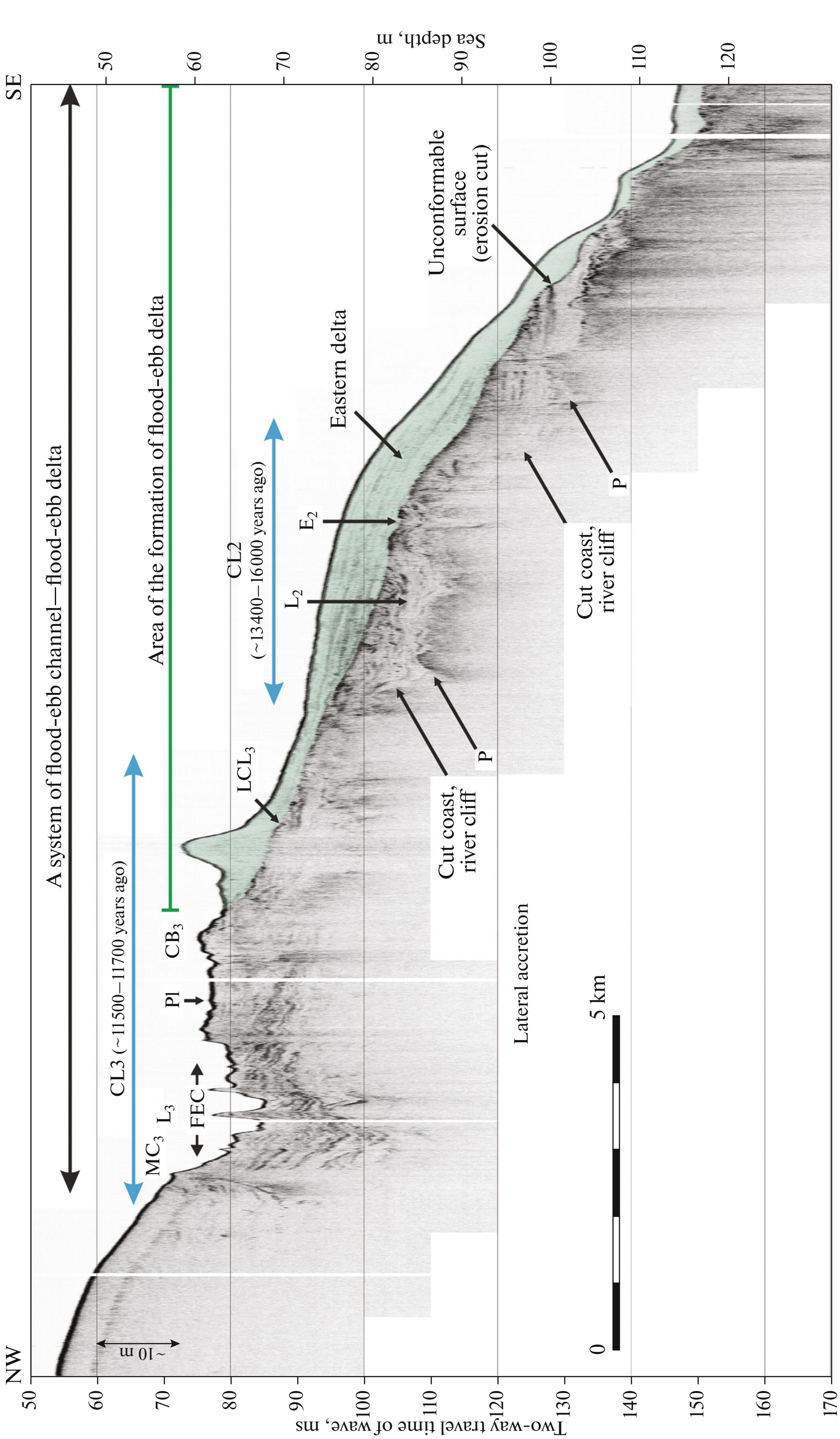


Fig. 9. The seismoacoustic profile illustrating the structure of the main elements of the modern system consisting of the flood-ebb tidal channel (FEC) and the associated sedimentary body of the eastern flood-ebb tidal delta. Water exchange occurs along the channel between the inner shelf (Expedition, Novgorodskaya, Raid Pallada, Kitovy and Posyet bays) and the outer shelf in the western part of Peter the Great Bay. The rest of the legend are in Fig. 5.

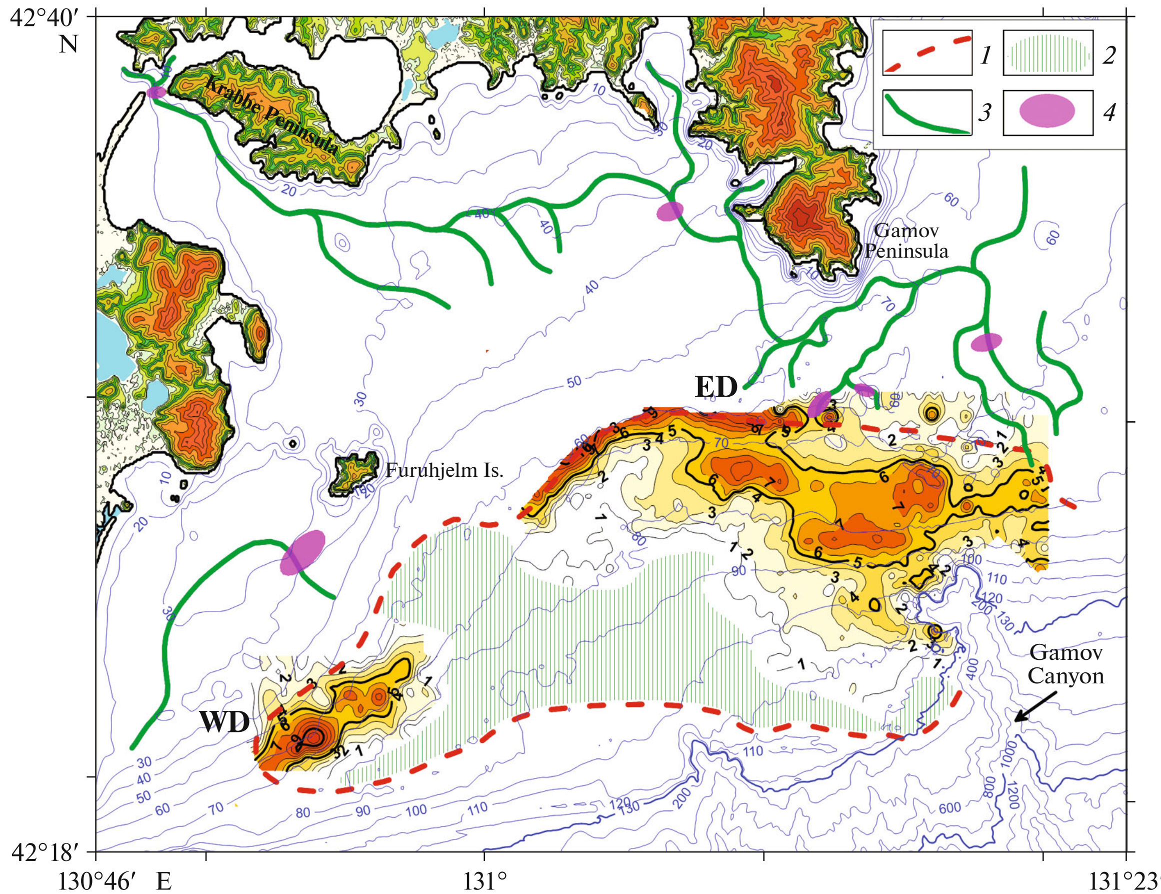


Fig. 10. A map of sediment thickness of the western (WD) and eastern (ED) flood-ebb tidal deltas and the location of the major modern flood-ebb tidal channels. Isopachous lines are drawn at 1-m intervals. (*1*) Outer boundary of the zone of irregular sedimentation; (*2*) boundaries of the area of active erosion, (*3*) suspected location of flood-ebb channels and water exchange paths between the inner and outer shelves; (*4*) location of the main inlets of flood tidal streams.

form of small hills up to 2-m high. The width of the hills is 100–300 m, sometimes reaching 1000 m. Sometimes, downward concave reflections are observed along the edges of the "pipes" (Figs. 6, 12).

In addition, during bathymetric survey by the Sea-Beam 3050 multibeam echosounder, numerous gas plumes were detected in the water column. They were revealed at the edge of the outer shelf west of Gamov Canyon. The water depth in this area is 110–150 m. The height of the plumes reaches 100 meters.

We mapped different types of gas accumulations in the western part of Peter the Great Bay and complied a map of their distribution (Fig. 13). The area of the gas occurrences is heterogeneous. We established 35 localized isolated zones and areas of the gas accumulation. Three main groups of anomalies are distinguished. The common feature of the first group of anomalies is their location within the lagoons and bars of the fourth and fifth coastlines within the shallow areas of the inner shelf. The second group of anomalies is observed within the outer shelf, where the sea depth is 50–95 m. The third group of anomalies occupies part of the outer shelf and the upper continental slope, where the sea depth is 110–300 m.

DISCUSSION

Peter the Great Bay is located at the junction of two significant mountain systems in East Asia: the East Manchurian Mountains and the Sikhote-Alin Range. On the shores of the bay, there are the Paleogene–Neogene rift-related coal-bearing depressions up to 1300-m deep [19]. The Tumannaya and Razdolnaya rivers flow into the bay. There is no geological information on the age and structure of the Tumannaya River delta. However, it is known that one of the two largest sedimentary depocenters in the northwestern part of the Sea of Japan, located within the continental foot, is directly adjacent to the mouth of the Tumannaya River [8–11]. The depocenter is well recognized both on the bathymetric map and on the sediment thickness map. The thickness of sediments in this depocenter reaches 2.0–2.4 s, which corresponds to about

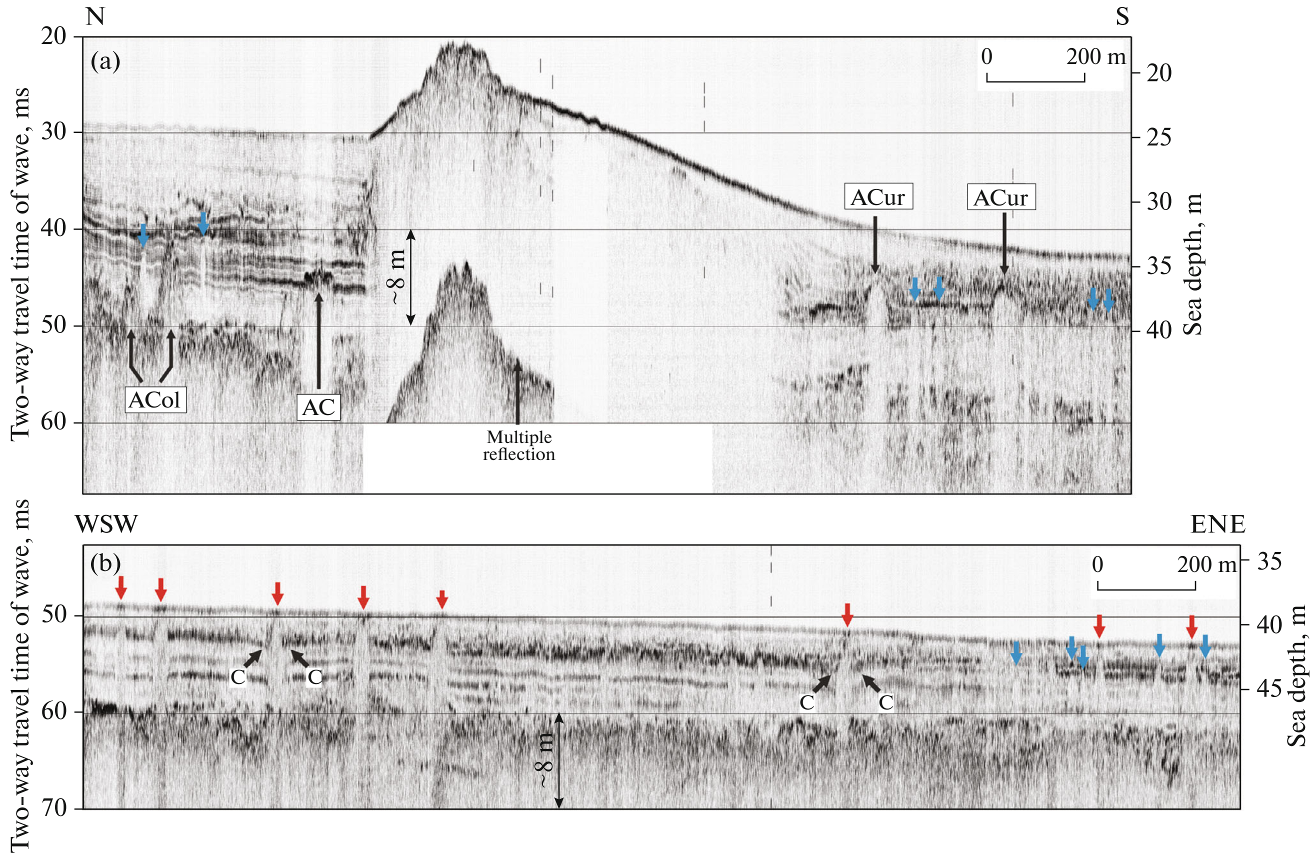


Fig. 11. Seismoacoustic profiles illustrating the structure of suspected zones of high pore pressure and vertical gas migration. ACur, acoustic curtain; ACol, acoustic column; AC, acoustic cover. Vertical blue arrows indicate the position of columnar acoustic voids. Red arrows show the position of columnar acoustic voids reaching the sea surface from the seafloor. Here and in Fig. 12: C, concave downward reflections.

2500 m [9, 10]. This depocenter may have been formed as a result of sediment transport by the Tumannaya River and, possibly, by the Razdolnaya River. Geological dredging of the continental slope revealed that it is covered by marine sediments with ages ranging from the Late Oligocene to Holocene [2, 4]. The sedimentary cover on the shelf and the upper part of the slope has two unconformable surfaces, the upper of which reflects a nondepositional hiatus of 10.0–8.5 Ma [10]. These unconformities divide the sedimentary cover into three complexes. The middle Sh2 complex was accumulated in the Late Oligocene–Early Late Miocene, and the upper Sh3 complex was formed between the Late Miocene and Holocene. The age of the lower Sh1 complex is assumed to be the Paleogene.

The study of Late Oligocene mudstones, which have been dredged on the slope of the bay in the depth range of 900–1900 m (Fig. 1c) and compose the base of the Sh2 complex, show that the shallow marine conditions and low sedimentation rates prevail on the slope at this time [4]. Palynological data show that in the Late Oligocene, the landforms of the adjacent part of the sea were highly dissected and included both mountains and marshy plains. River systems could have formed on the slopes of these mountains, which are now probably represented by the Tumannaya River. As a result of abrasive impact of flows of these rivers, a system of depressions on the shelf and canyons on the continental slope was formed (Figs. 1c, 4). The largest of the canyons is Gamov Canyon. Gamov Canyon was already formed in the middle Miocene, as evidenced by the presence of sedimentary bodies of similar ages on its slopes (Fig. 3b). It can be assumed that sediments of the Sh2 and Sh3 complexes compose the delta of the Tumannaya River on the shelf of the bay. The delta is represented on land by a thin cover of the Eocene, Oligocene, Early Miocene, and Quaternary sediments with a thickness of no more than the first hundred meters [20]. It is noteworthy that the total thickness of Sh2 and Sh3 sediments on the shelf reaches 0.85 s, which is 2.5 times less than the thickness of sediments accumulated within the continental foot adjacent to the Tumannaya River [9]. It can be concluded that since the Late Oligocene, the western part of the bay has predominantly been a transit zone for sedimentary material that has been transported

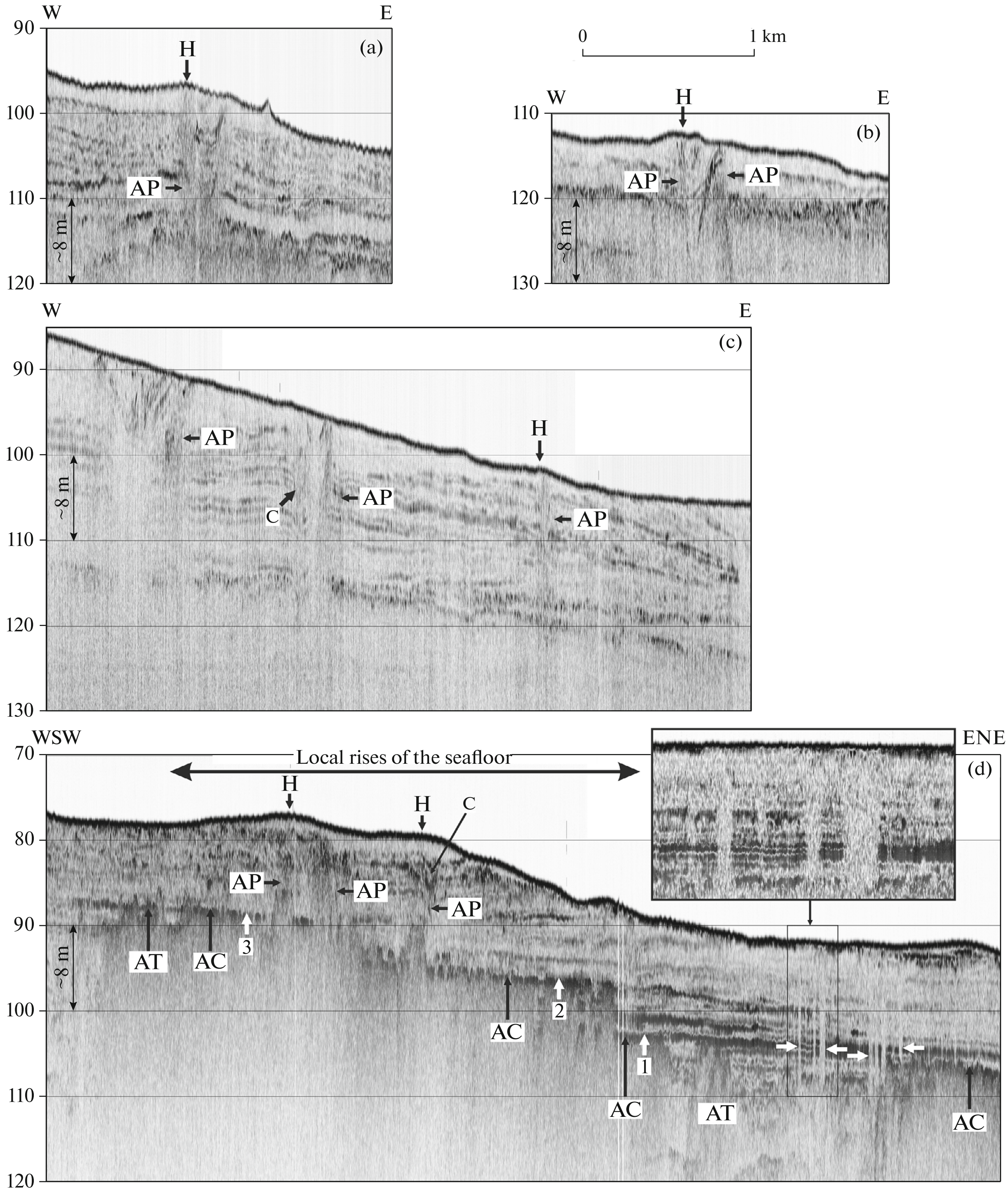


Fig.12. Examples of seismoacoustic profiles showing the vertical gas migration and formation of localized seafloor rises on the outer shelf of Peter the Great Bay. Vertical white arrows with numbers indicate different levels of the acoustic "cover" roof, demonstrating the successive upward displacement of the gas front and the formation of local seafloor highs above it. Horizontal white arrows indicate position of columnar acoustic voids. H is a hill. The scale on the left is the two-way travel time of the wave, ms. The rest of the symbols in Figs. 5, 6, 8, 11.

from the land to and accumulated on the northern edge of the Japan Basin developing its foot.

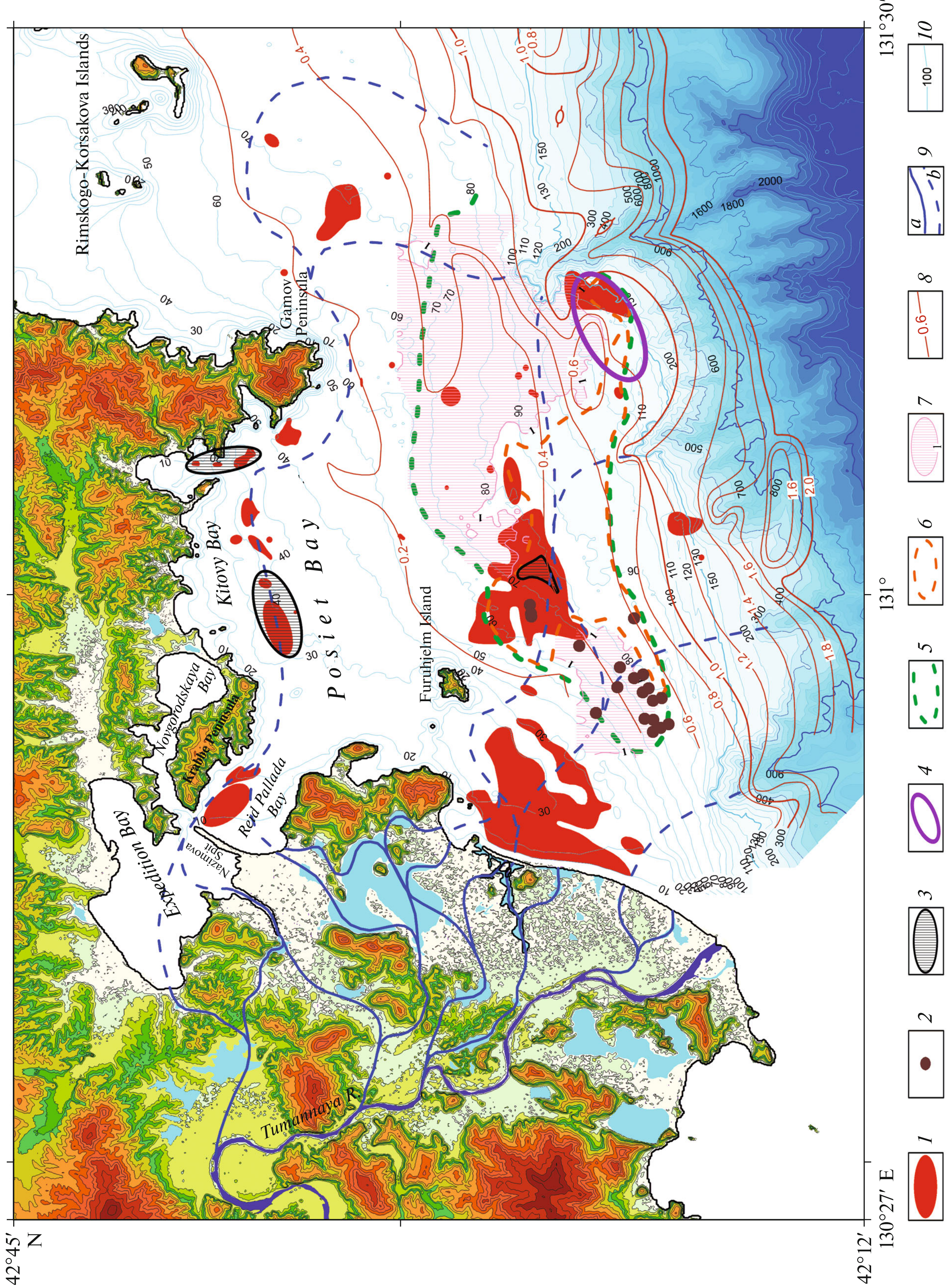
Despite the fact that mudstones of the Sh2 complex are mainly of terrigenous origin, single samples of cristobalite have been encountered in the Early Miocene sediments [4]. Cristobalite is formed as a result of the diagenetic transformation of amorphous opal in sedimentary sequences. According to the results of ODP drilling, the modern boundary of the opal A/opal CT in the sediments of the Sea of Japan is located at a depth of 300–450 m [34]. It was concluded [4] that the Early Miocene rocks of the Sh2 complex containing cristobalite were previously located at a depth of at least 400 m and only later were exposed on the seafloor surface. This can be explained by the active erosion and destruction of Sh2 and Sh3 sediments in the areas around the canyons and their transport into the deep-water basin (Fig. 3). This process particularly intensified in the Late Miocene, as evidenced by the presence of numerous deposits of mass transport and landslides in sediments of the continental foot [9]. Sediment transport remains very active, as indicated by the presence of numerous landslides and associated structures up to 90 km from the base of the slope [14]. These facts indicate the active destruction of the frontal part of the Tumannaya River delta, which may have started in the Late Miocene simultaneously with the formation of the upper unconformity and continues until the present time.

The study of soil samples has shown that the bay sediments contain high gas concentrations (up to 3700 nM/cm^3), mainly methane [3]. The northern part of the Kraskinskaya Depression occurs under the waters of Expedition Bay and contains commercial coal deposits of the Eocene–Oligocene age [19]. The southern edge of the depression is hidden under the waters of Posieta Bay. Our data show that sediments of similar age exist in the western part of Peter the Great Bay (Fig. 3). Therefore, we believe that gas (methane) migration from coal-bearing sources can be proposed as the most likely cause of the formation of near-surface gas accumulations similar to those in the Amur Bay [31]. In addition, some anomalies are located in the lagoon sediments of the 2–5 coastlines (Figs. 5, 6, 11), which may be related to the decomposition of organic-rich sediments.

The buried elements of the Paleo-Tumannaya River in the form of tributaries and cliffs are well distinguished in the sediment structure on the seismoacoustic profiles (Figs. 5, 7–9). We attempted to approximately reconstruct the former location of the river channels on the shelf in the Late Oligocene–Holocene during the periods of low sea level and to reproduce the sequence of their migration to the present-day position (Figs. 4, 13). We suggest that in the Late Oligocene–Middle Miocene, the main channel of the Paleo-Tumannaya River could have been located within the bays of Expedition, Novgorodskaya, Reid Pallada, and Kitovy Bay, and then flowed into the Sea of Japan near Gamov Canyon. The regional rise, which began at 11–10 Ma (28), is probably the main reason for the gradual retreat of the river channel westward to its present position. One of the tributaries of the river may have kept its position and flowed into Gamov Canyon until the end of the Pliocene. This is indicated by the presence of a pattern of lateral extension in the upper part of the Sh3 complex near the top of the canyon (Fig. 3b, 7).

Five submerged coastlines are well recognized on the shelf in the southwestern part of Peter the Great Bay. To determine the age of the formation of these lines, we used the data given in [20, 31]. It was established that the first coastline was formed 17000–21900 years ago, the second 13400–16000 years ago, the third 11500–17000 years ago, the fourth 8800–11400 years ago, and the fifth 2200–8500 years ago. We used this information to determine the age of active erosion processes on the shelf. The sea level position during the formation of the first coastline is clearly visible on the seismic profiles (Figs. 5, 7) in the form of a step at a depth of 108–110 m and by the presence of a distinctly manifested buried platform with a flat top formed as a result of subaquatic wave-surge abrasion. About 16000 years ago, marine transgression began and the second and the third coastlines were formed. Our seismic profiles clearly indicate that sediments from the first and third coastlines in the shelf areas deeper than 45–60 m have been eroded (Figs. 5–9). We assume that the abrasion and formation of the irregular sedimentation zone on the shelf were activated approximately 11500–11700 years ago. At that time, the sea level was at about minus 60 m (20). This value is in good agreement with the position of the top part of the barrier of the third coastline cut off by wave abrasion (Fig. 9). The erosion could be activated by the change in the hydrological regime in the Sea of Japan, which occurred as a result of the climatic environment transformation from the late Pleistocene cooling period to the Holocene warming. This should have been accompanied by an increase in the amount of liquid precipitation, an increase in the river runoff from the adjacent land, and, first of all, the

Fig. 13. The location of acoustic anomalies associated with the presence of gas in the Late Pleistocene–Holocene sediments in the western part of Peter the Great Bay. (*1*), location of acoustic anomalies; (*2*), acoustic "pipe"; (*3*), zones of high pore pressure; (*4*), area of gas plumes in the water column; (*5*), outer contours of the irregular sedimentation zone; (*6*), area of the active modern erosion and lack of sediment deposition; (*7*), contours of the western and eastern deltas (limited by 1 m isoline); (*8*), contour lines of the acoustic basement depth, c; (*9*), supposed position of the tributaries of the Tuman River in the Late Oligocene), Quaternary on the land (a) and on the shelf (b) during periods of low sea level; (*10*), bathymetry, m.


Rimskogo-Korsakova Islands
Gamov Peninsula
Kitovy Bay
Posiet Bay
Furuhjelm Island
Novgorodskaya Bay
Krabbe Peninsula
Reid Pallada Bay
Expedition Bay
Nazimova Spit
Tumannaya R.
42°45′ N
42°12′
130°27′ E
131°
131°30′

runoff of the Tumannaya River with its increased erosion activity. This was the reason for the local expansion of the outer shelf between Furuhjelm Island and Gamov Canyon. Two flood–ebb tidal deltas (western and eastern) began to accumulate at the end of the formation of third coastline about 11 500 years ago. These deltas are located immediately adjacent to the main inlet flood-tidal streams and flood–ebb tidal channels through which seawater migrates between the inner and outer shelf. These deltas and channels form a system of flood–ebb tidal channels and flood–ebb tidal deltas in the western part of the bay (Fig. 9). Transgression began at the beginning of the Holocene and sea level reached minus 45–48 m 9100 years ago. Wave surf activity, as well as erosion by the Tumannaya River flows, are probably responsible for the extension of the outer boundaries of the irregular sedimentation zone to a depth of 45 m in the area south of Furuhjelm Island. By 8800 years ago, the sea level had risen to minus 26–33 m and the western and eastern deltas had begun to expand towards the mainland. As a result of the accumulation of these bodies, much of the irregular sedimentation zone has been covered by their sediments, while an area of extensive erosion still remains between them.

Analysis of the map of the distribution of gas-related acoustic anomalies shows that almost the entire area of gas-saturated sediments is located within lagoons and, especially, the area of active modern erosion (Fig. 13). In the areas where flood-ebb tidal deltas are common, anomalies are either few or localized in acoustic "pipes." The first group of acoustic anomalies is located mainly within the lagoons and barriers of the fourth and fifth coastlines in the water depth range of 10–45 m (Fig. 13). Typically, these anomalies are located either directly adjacent to the narrow passages to the Expedition and Trinity bays, or beneath lagoons and flood-ebb channels. The water masses in these bays are circulated through small narrow straits (e.g., the strait between Nazimova Spit and Krabbe Peninsula). In summer, the interaction of cold seafloor oceanic waters with warm surface waters can contribute to the formation of internal waves, which are also intensified due to the changing relief at the entrance to the bays. The largest anomalies are observed in the lagoon sediments of the fourth coastline. The seafloor water currents with velocities up to 0.56 m/s are observed in the channels (High atmospheric pressure (up to 1039 GPa), accompanied by strong northerly/westerly winds can cause a 1 m drop in the sea level in the bay, which contributes to a dramatic decrease in hydrostatic pressure over the sediments. In lagoons of the fourth coastline with water depths of about 40 m, the pressure decrease can be 2.5%, which dramatically affects the stability of the over-pressured gas accumulations and accelerates upward gas migration. At the same time, rhythmic storm waves 5–9-m in height [16, 18] and internal waves [17] act as a "hydraulic pump" on the gas accumulations and additionally cause their upward migration to the seafloor.

The second group of anomalies is observed within the irregular sedimentation zone. The highest concentration of the gas accumulations is observed in the area of extensive erosion. We explain this peculiarity by the fact that during the period of active abrasion of 9100–11 700 years ago, a minimum of 8–10 m of sediments was cut off. The decrease in the lithostatic pressure caused by these erosional processes, also created favorable conditions for gas movement upward to the seafloor. Where the erosion surface is covered by delta deposits, the number of anomalies and their sizes are significantly reduced. This can be explained by the load of the sedimentary cover and a local increase in the lithostatic pressure, which contributed to the formation of the gas accumulations under overpressure.

A common feature of the third group of anomalies is their location immediately adjacent to the tops of submarine canyons. The most likely cause of the gas inflow into the sediments and then into the water column may be the impact of internal waves that form here on the shelf edge [16].

Suspected zones of high pore pressure, similar to those described in [26, 30], have been identified in the sediments of the bay. When gas-saturated pore water with high pressure comes into contact with seawater on the seafloor, the pressure decreases and gas plumes are formed, as we observe in the vicinity of Gamov Canyon. Another indicator of the excessive pore pressure in sediments may be the presence of local rises of the seafloor above acoustic "pipes" up to 2-m high (Fig. 12). Zones of high pore pressure were detected in the depth range from 20 to 130 meters.

CONCLUSIONS

Five submerged ancient coastlines that formed as a result of sea level changes in the Late Pleistocene–Holocene, have been identified on the shelf in the southwestern part of Peter the Great Bay. It was found that a significant part of the shelf is occupied by a zone of irregular sedimentation underlain by the erosional surface. This surface is buried under the sediments of flood-ebb tidal deltas in the areas of active sedimentation and is exposed on the seafloor within the area of active modern erosion. The abrasion and formation of the irregular sedimentation zone on the shelf were activated about 11 500–11 700 years ago.

Numerous near-surface gas accumulations and gas plumes in the water column were identified in the Late Pleistocene–Holocene sediments in the southwestern part of Peter the Great Bay and their distribution was mapped. Seismoacoustic data also indicate the presence of high pore pressure zones in the bay sediments. It is concluded that the trigger mechanism that provides gas migration into sediments and the water column is mainly postglacial change in the sea level, abrasion processes, and the hydrodynamic regime in the bay.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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