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Original article

Lithodynamics of the Coastal Zone in the Inkit-Pitsunda Area (Abkhazia)

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Abstract
The paper studies lithodynamic processes in the Black Sea coastal zone from Cape Inkit to Cape Pitsunda in the Republic of Abkhazia. A review of past studies of the coastal lithodynamics in this area was carried out. The principles of allocation of lithodynamic areas were shown and the characteristics of the transverse and longitudinal structures of coastal systems were described. A scheme of lithodynamic zoning of the studied area has been developed. The paper describes sources of sediments intake and their movement in the studied coastal zone of the Inkit-Pitsunda area of Abkhazia and provides characteristics of the longshore sediment flow in the area. The coastline dynamics on a fragment of the Bzyb-Pitsunda coast was investigated. The paper estimates the volume of sediments carried out by the Bzyb River and compares it with the value of the total longshore flow of pebble sediments in the area. The coastline dynamics based on research materials of previous years was analysed, the aerial photographs taken into account. The paper also estimates sediment runoff into the tops of underwater erosion hollows (canyons) located on the underwater coastal slope from the Bzyb River to Cape Pitsunda. The paper shows that although the width of pebble beaches may reach fifty meters, in the upper part of the coastal zone, the ancient barrier beach and low terrace, which are composed of highly erodible sediments, are exposed to washouts. These washouts are caused by large waves during passing storms, and their run-up is not completely damped on the surface of even such wide beaches. The authors conclude that the existing beach is not wide enough to completely damp storm waves, as evidenced by the washouts of ancient barrier beaches. In addition, the erosion of the ancient barrier beach bases is due to the general retreat of the coastline within the sea terrace located between the mouth of the Bzyb River and Cape Pitsunda.

Keywords: abrasion, alluvial deposits, lithodynamics, lithodynamic zoning, beach, underwater canyons, sediment flow, coastal zone, accumulative terraces

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Литодинамика береговой зоны Инкит-Пицундского района Абхазии

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Аннотация

Исследованы литодинамические процессы в береговой зоне Черного моря на участке от м. Инкит до м. Пицунда в Республике Абхазия. Выполнен обзор исследований литодинамики данного участка берега прошлых лет. Показаны принципы выделения литодинамических районов. Описаны характеристики поперечной и продольной структур береговых систем. Разработана схема литодинамического районирования исследуемого участка. Описаны источники поступления наносов и их движение в береговой зоне исследуемого участка Инкит-Пицундского района Абхазии. Даны характеристики вдольберегового потока наносов на участке. Исследована динамика береговой линии на фрагменте берега Бзыбь – Пицунда. Выполнена оценка объема наносов, выносимых р. Бзыбью, и его сравнение с величиной общего вдольберегового потока галечных наносов на участке. Проанализирована динамика береговой линии по материалам исследований прошлых лет с учетом аэрофотосъемок. Оценен сток наносов в вершины подводных эрозионных ложбин (каньонов), расположенных на подводном береговом склоне от р. Бзыби до м. Пицунда. Показано, что, хотя ширина галечных пляжей может достигать 50 м, в верхней части береговой зоны наблюдаются подмывы древнего берегового вала и низкой террасы, сложенных легко размываемыми отложениями. Эти подмывы обусловлены воздействием больших волн во время шторма, накат которых не гасится полностью на надводной части даже таких широких пляжей. Сделан вывод о том, что ширина существующего пляжа недостаточна для полного гашения штормовых волн, о чем свидетельствуют подмывы древних береговых валов. Кроме того, такие подмывы обусловлены общим отступанием береговой линии в пределах морской террасы, расположенной между устьем р. Бзыби и м. Пицунда.

Ключевые слова: абразия, аллювиальные отложения, литодинамика, литодинамическое районирование, пляж, подводные каньоны, поток наносов, прибрежная зона, аккумулятивные террасы

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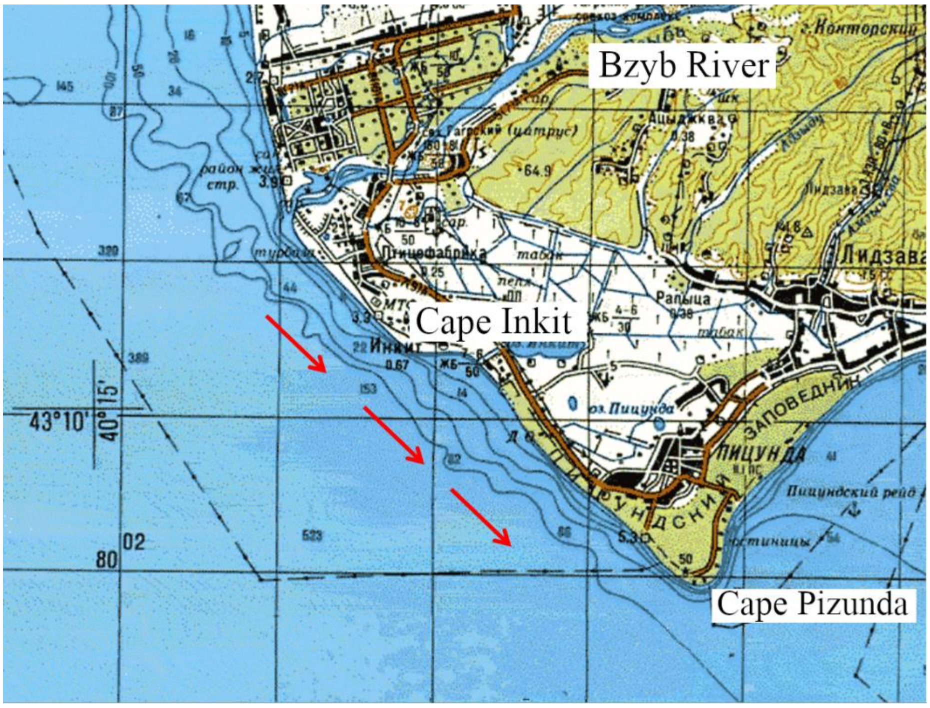
Introduction

The investigated section of the shore is located on the southwestern flank of the Pitsunda Peninsula between Capes Inkit and Pitsunda. The adjacent section of the bottom between the mouth of the Bzyb River and Cape Pitsunda is complicated by an extensive system of underwater canyons, the tops of which come close to the shore. The largest of them is the Akula Canyon [1], which opens to Cape Inkit (Fig. 1). Erosion hollows on the underwater slope complicate coastal processes.

A reliable estimate of the natural processes occurring in the coastal zone of the sea and their direction is of very important scientific and practical importance. Thus, the reliability and effectiveness of coast protecting structures against wave



F i g . 1 . The investigated shore. The arrows show the direction of the longshore sediment flow (adapted from https://satmaps.info/map.php?s=100k&map=k-37-033)

action depend largely on the knowledge and correct estimate of the lithodynamics and morphology of the section [2, 3]. Moreover, only long-term observations of the shore state can reveal the influence of various factors.

No comprehensive studies of coastal processes in order to estimate their direction have been carried out on the shore section between the mouth of the Bzyb River and Cape Pitsunda from the end of the last century to the present. The dynamics of the pebble beach was also not observed. After the Abkhazia conflict (1992–1993), only some researchers of the Academy of Sciences of Abkhazia with limited participation of the Russian scientists have carried out special coastal studies [4]. All this makes it difficult to estimate objectively the coastal processes currently occurring in the section under consideration and the direction of their development.

Based on the analysis of available data on the state of the coastal zone between the mouth of the Bzyb River and Cape Pitsunda and the processes occurring in this zone, as well as the influence of the anthropogenic factor on them, the degree of knowledge of these processes at the present stage can be characterized as insufficient.

The study aims at the estimate of the geomorphological conditions of the coastal zone between Capes Inkit and Pitsunda and identification of the direction of lithodynamic processes.

Materials and methods of study

The study used materials from field work carried out by the authors in the summer of 2023 (bathymetric and topographic surveys, investigation of the coastal zone), as well as data obtained from an analysis of ongoing coastal processes, taking into account the supply of beach-forming material from rivers and the coastline configuration [5].

Results and discussion

A lithodynamic system is a set of characteristic natural and anthropogenic factors that determine the interconnected coastal processes occurring on the coastal section under consideration independently of neighbouring sections and state the stability of the system itself.

The coastal lithodynamic system is characterized by transverse and longitudinal structures. The transverse structure includes data on the formation of the transverse profile of a pebble beach under the influence of waves and its longshore changes. As for the pebble beaches, the coastal lithodynamic system on the sea side is limited by the place where pebble material is pulled back during a storm, which corresponds to the depth of the last wave breaking [5]. The top of the wave run-up is the upper limit on the shore. Consequently, the width of the coastal lithodynamic system is equal to the run-up length of the maximum possible (calculated) storm in terms of the cross section. Transverse drifting of pebble material with its differentiation and formation of a beach profile occur within this designated zone. Surface waves (wind and swell ones) and various currents excited by them, which play a crucial role in the sediment drifting and transformation of the coastal zone topography, are the main factor determining the pebble beach profile formation and the underwater slope topography. Sea depth is one of the main characteristics that determines wave propagation direction and velocity and, as a consequence, shore and bottom deformation. The influence of the bottom topography on wave heights and angles of their approach to the shore begins to manifest itself from the depths equal to half the wavelength.

The longitudinal longshore structure of the lithodynamic system is primarily characterized by the volumes of drifted material and their changes in different sections of the shore, as well as changes in the transverse structure caused by the configuration of the coastline, supply of beach-forming material from watercourses and abrasion processes, changes in depths, etc.

The main lithodynamic characteristics, information about which is obtained during the study, are the direction of movement and volumes of sediment drifting under the influence of hydrogenic factors, as well as subsequent transformations of the topography of the beach and adjacent underwater slope. Therefore, the most complete estimate of the processes occurring in the coastal zone can be obtained by studying the longshore and transverse structures of the sediment flow as an integral factor determining its state. The boundaries of the lithodynamic system along the shore determine the beginning and end of the sediment flow, and the transverse structure of the sediment flow determines the depth of the sea to which it is necessary to analyze the lithodynamic processes occurring in the coastal zone. Thus, the lithodynamic system is primarily identified by the longshore sediment flow determined by the influence of waves on the beach-forming material entering the coastal zone. The longshore sediment flow is resulting material drifting influenced by the entire spectrum of waves over a long period (usually a year) or, more precisely, of the longshore projection of the wave energy resultant, which is distributed very unevenly along the shore and the magnitude of which depends on the exposure of a particular section of the shore. Beach material can move along the coast in opposite directions under the influence of waves of different directions.

A fragment of the shore between the mouth of the Bzyb River and Cape Pitsunda adjoin the younger near shore part (the age of which does not exceed 2.0–2.5 thousand years) of the accumulative plain of the Pitsunda Peninsula, which is part of the all1uvial-marine terrace formed over the last 11–12 thousand years. The coastal plain is composed of highly erodible sediments 90–100 m thick. The sediments are represented by separate layers of silty clays and sands, reaching a thickness of 6–18 m, which are covered by peat bogs up to 4–5 m thick. In the north, the Pitsunda Lowland adjoins the southern slopes of the Myusser Upland. The western border of the lowland runs along the left bank of the Bzyb River lower course [6], and the southern border is limited by the sea coastline. Low elevations of the lowland surface contributed to the formation of relict lakes, the largest of which is Lake Inkit.

The investigated shore section located between Capes Inkit and Pitsunda includes three morphologically different shore fragments. Inkit Bay is located on the northern flank, smoothly turning into a relatively straight central shore fragment, giving way to a bay-shaped shore stretching to Cape Pitsunda on the eastern flank. The straightness of the middle section of the shore composed of highly erodible sediments with their azimuth of 140° is explained by its turn parallel to the front of the resultant of the waves.

As studies [1), 2)] [1] showed, due to the peculiarities of the hydrodynamic regime of the sea within the shore section from Cape Kodosh, a natural barrier to sediment drifting located north-west of the city of Tuapse, and to Cape Pitsunda for 160 km earlier (before the construction of various hydraulic structures, such as enclosing breakwaters of the ports of Tuapse, Sochi, Imereti) a single longshore sediment flow was expressed. This fact makes it possible to distinguish this shore fragment into a single Kodosh-Pitsunda lithodynamic system.

[1)] Zenkovich, V.P., 1958. [*Coasts of the Black and Azov Seas*]. Moscow: Gosudarstvennoe izdatelstvo geograficheskoy literatury, 374 p. (in Russian).

[2)] Zenkovich, V.P., 1958. [*Morphology and Dynamics of the Soviet Coasts of the Black Sea*]. Moscow: Izdatelstvo AN SSSR. Vol. 1, 187 p. (in Russian).

The beach strip on the coast of the Krasnodar Krai and Abkhazia from Cape Kodosh to Cape Pitsunda is composed of sand and pebbles. The main source of nutrition for the pebble beaches of the region under consideration is predominantly coarse material supplied by rivers [3)] [7]. A small part of the fragmentary material, which is not of decisive importance, comes from abrasion of the beach scarp and physical weathering of its constituent rocks and also as a result of bedrock abrasion.

In the structure of the longshore sediment flow, three components are distinguished, each of which is characterized by the dominance of certain development processes [4)]. The first part is the zone of sediment flow origin, within which abrasion and erosion predominate. The second part is the transit area of the longshore sediment flow, where abrasion and erosion alternate with the deposition of beach material. The third part is the discharge area, where the accumulation of material drifted under the influence of waves occurs.

Under natural conditions, in the longshore sediment flow from Cape Kodosh to Cape Pitsunda, no classical division into zones of its origin, transit and discharge (accumulation) took place. The processes of sediment accumulation and drifting in the coastal zone of the considered shore fragment were associated with solid river runoff, its redistribution under the influence of wave and surf flows and currents generated by these flows. Surge phenomena and wind (drift) currents play a subordinate role in the distribution of beach pebble material.

No single source of beach material entering the coastal zone was observed in the identified natural Kodosh-Pitsunda lithodynamic system. Throughout the entire system, there was a constant replenishment of beach material from a single longshore sediment flow due to the solid runoff of large and small rivers, as well as streams and temporary watercourses. Under complex orographic conditions in the presence of numerous temporary watercourses, small streams and relatively large rivers (Ashe, Psezuapse, Shakhe, Sochi, Mzymta, Bzyb), the zones of origin, replenishment and transit of the longshore sediment flow merged into a single zone, i.e. the zone of sediment flow saturation [5].

Without taking into account anthropogenic intervention, the discharge zones of longshore sediment flow (accumulation of beach material) are adjacent to the northwestern flanks of the cuspate forelands of the Ashe, Psezuapse, Sochi, Mzymta and Bzyb Rivers. Areas of accumulation of beach material can also be observed near such capes as, e.g., Uch-Dere, Vidny, Pitsunda.

The magnitude of the longshore flow of pebble sediments can vary within the identified lithodynamic system depending on the supply of beach material to the coastal zone and changes in the drifting ability of waves determined by the relationship between their direction and coastline contour. No classical division of the lithodynamic system into zones of origin of longshore sediment flow and its transit is observed on the coastal section (Cape Kodosh – Cape Pitsunda).

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3) Makarov, K.N., Tlyavlina, G.V. and Tlyavlin, R.M., 2019. [*Scientific and Methodological Rationale for the Master Layout of Coastal Protection of the Sochi Agglomeration Morskoy Fasad*]. Sochi: Sochinsky Gosudarstvenny Universitet, 213 p. (in Russian).

4) Safyanov, G.A., 1996. *Coastal Geomorphology*. Moscow: MGU, 400 p. (in Russian).

As the flow moved in the southeast direction, its magnitude changed constantly as a result of the replenishment of the flow with beach-forming pebble material due to solid river runoff.

The entry of beach-forming pebble material into the coastal zone caused by solid river runoff and determining the change in the magnitude of the longshore flow of pebble sediments can be taken as the basis for the division of a single lithodynamic system into subsystems. Based on this, the boundaries of lithodynamic subsystems can be the mouths of rivers that are most significant in terms of solid runoff. The factors listed above provide the basis for identifying lithodynamic subsystems in a single lithodynamic system [5]. From Cape Kodosh to Cape Pitsunda, taking into account the main sources of material supply (large rivers of the region under consideration, such as the Ashe, the Psezuapse, the Shakhe, the Sochi, the Mzymta, the Bzyb), several lithodynamic subsystems can be distinguished, which are integral parts of the single Kodosh-Pitsunda lithodynamic system. They are Ashe-Tuapse, Ashe-Psezuapse, Shakhe-Psezuapse, Shakhe-Sochi, Sochi-Mzymta, Psou-Mzymta, Psou-Bzyb and Bzyb-Pitsunda ones. The common feature of these lithodynamic subsystems was a longshore sediment flow directed from northwest to southeast (from Tuapse towards Cape Pitsunda). The sediment flow does not bypass Cape Kodosh, but passes through the mouths of the above rivers and bypasses such capes as Uch-Dere, Vidny and some others. Final discharge of the longshore flow of pebble sediments, which, being deposited on the beach and underwater slope, contributed to the general extension of the cape towards the sea, took place at Cape Pitsunda [8]. Therefore, the lithodynamic subsystems under consideration were previously open (before the construction of the enclosing breakwaters of the ports of Sochi and Imereti). The erected breakwaters of the ports of Sochi (1936) and Imereti (2008) interrupted the single longshore flow of pebble sediments, as a result of which the Sochi-Mzymta and Psou-Mzymta lithodynamic subsystems became separate.

Based on the proposed principle of identifying lithodynamic subsystems which is based on the longshore sediment flow replenished from a significant source of beach-forming material (large rivers of the region under study), the shore section under consideration is included in the Bzyb-Pitsunda lithodynamic subsystem. Similar to this is the idea of identifying six independent shore dynamic systems, including the Bzyb one, in the coastal zone in the area between the mouths of the Psou and Inguri rivers according to the criterion of the presence of separate longshore sediment flows formed by river sediments [9].

Such identified large structural cells as the lithodynamic system and its subsystems include extended shore sections determining general direction of the coastal processes occurring there. When choosing engineering solutions for coast protecting structures, it is necessary to identify smaller lithodynamic structures within which detailed lithodynamic studies should be carried out for a detailed accounting of coastal processes occurring on the shore section under consideration.

Based on the influence of the coastline configuration (Cape Inkit extending into the sea) on the longshore sediment flow, the Bzyb-Inkit and Inkit-Pitsunda lithodynamic areas can be distinguished in the identified Bzyb-Pitsunda lithodynamic subsystem. Taking into account the configuration of the coastline, three lithodynamic sections can be distinguished within the Inkit-Pitsunda lithodynamic area (Fig. 2):

1) western section, located within Inkit Bay,

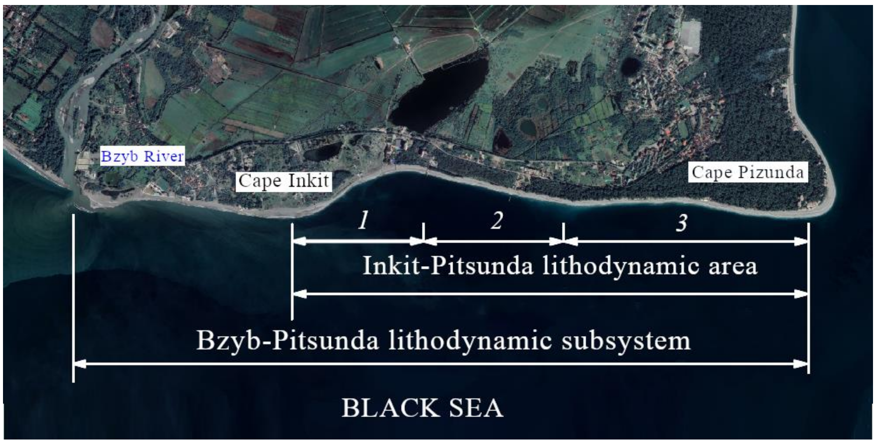
2) central section, representing a flat fragment of the shore,

3) eastern section, bay-shaped, ending with Cape Pitsunda.

The division of a single lithodynamic system into parts is stipulated by the need for more detailed lithodynamic studies, e. g., to justify coast protecting measures.

In this regard, it is necessary to consider, on the one hand, the possible influence of anthropogenic intervention on them and, on the other hand, their influence on the constructed coast protecting structures for a reliable estimate of modern processes occurring in the coastal zone. In addition, it is necessary to forecast possible state of the beaches and longshore sediment flow of the Bzyb-Inkit lithodynamic area located upstream of the flow, i.e., starting from the mouth of the Bzyb River.

The shore section under consideration is located within the Inkit-Pitsunda lithodynamic area, which is part of the Bzyb-Pitsunda lithodynamic subsystem. The dynamics of the beaches of this lithodynamic subsystem is primarily determined by the longshore sediment flow directed towards Cape Pitsunda. The main volume of sediment entering the coastal zone and, under the influence of waves, forming the longshore flow, which determines the condition of the beaches on the shore section under consideration, comes from the Bzyb River. Of this volume, the share of



F i g . 2 . Scheme of lithodynamic zoning of the studied area. Google Earth image (available at https://www.google.com/intl/ru/earth/)

suspended sediments accounts for [5] 715 thousand tons, and the runoff of bed load amounts to 205 thousand tons. According to expeditions of Tbilisi University carried out from 1972 to 1978, in the runoff of bed load of the Bzyb River, the proportion of particles with a diameter of more than 50 mm is 26% of the total weight, with a diameter from 50 to 100 mm – 31%. During spring floods, almost half of bed load carried by the river accounted for particles with a diameter of 20 to 100 mm. The alluvial deposits contained small amounts of sediment with a diameter of more than 200 mm. In a long-term context, the volume of sediment carried out by the Bzyb River exceeds the volume of the longshore flow of pebble sediments, and therefore its mouth is mainly formed under the predominant influence of the river factor [9]. The state of beaches on the shore from the mouth of the Bzyb River to Cape Pitsunda is significantly influenced by the considerable depth of the underwater slope complicated by a system of underwater erosion hollows – canyons. They cause high waves to approach the shore, which change little compared to the open sea waves. Under the influence of disturbances in the western directions, sediments carried out by the Bzyb River are lost in the tops of underwater canyons during their drifting. The most active and closest to the shore is the Akula Canyon located in the area of the Inkit cuspate foreland [1]. The sediment runoff into the top of this canyon can reach 50 thousand m^3 per year, which is more than a half of the longshore sediment flow in the considered shore section [6], according to estimates equal to 80 thousand m^3 per year [1]. Losses of beach sediments in the Akula Canyon are the main reason for the incision of Inkit Bay [1], where coastal retreat is estimated on average at 0.3–0.5 m/year [6]. The area under study near the shore reveals no erosion hollows at the bottom that affect the longshore drifting of beach-forming material and wave conditions.

Dynamics of the coastline in the section from the mouth of the Bzyb River to Cape Pitsunda is subject to cyclic fluctuations causing alternating stages of erosion and accumulation of beaches. The condition of the beaches on the western coast of the Pitsunda Peninsula is influenced by both long-term changes in the wave activity of the sea and changes in the amount of solid runoff of the Bzyb River. Periods of high wave activity usually coincide with a general decrease in solid runoff from rivers. As a result, the western coast of the peninsula begins to erode. Comparison of data on the amount of solid runoff from the Bzyb River shows that an acute sediment deficit or excess is periodically created in its pre-estuary area. When periods of decreased solid flow of the river coincide with a phase of increased wave activity, erosion of the beaches of the Pitsunda western coast is observed, as, e.g., in the early 1960s [10]. The variability of the Bzyb River solid runoff and the wave regime of the sea also affects the flow of sediment into underwater canyons.

Dynamic changes in the contour of the coastline stipulated by different cycles of wave activity and changes over time in the runoff of beach-forming sediments from the Bzyb River are developing against the background of a general retreat of the coastline of the Pitsunda Peninsula southwestern coast. In the long-term plan,

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[5] Khmaladze, G.N., 1978. [*Sediment Load Discharged by Rivers on the Black Sea Caucasian Coast*]. Leningrad: Gidrometeoizdat, 167 p. (in Russian).

this section of the Cape Pitsunda coast belongs to the area in which abrasion processes in the coastal zone are intensively developing [11]. A comparison of aerial photographs and satellite images indicates that over the past 80 years the shore in the area of Cape Inkit has retreated by 65–70 m [4]. The predicted rate of coastline retreat over the past hundred years was 60–110 m south of Inkit Bay [12].

Although the width of pebble beaches may reach 50 m, in its upper part, the ancient barrier beach and low terrace, which are composed of highly erodible sediments, are exposed to washouts. These washouts are caused by large waves during passing storms, and their run-up is not completely damped on the surface of even such wide beaches.

The washout scarp of the ancient barrier beach composed of sand mixed with gravel and small pebbles is shifting towards the shore. Waves wash the barrier beach and low terrace out which leads to the fall of pine trees (Fig. 3).

The rate of coastline retreat is significantly influenced by the frequency of strong storms, as well as the shore configuration which determines the heterogeneous distribution of wave energy. According to estimates, the rate of retreat of the coastline as a whole between Capes Inkit and Pitsunda has been 0.3–0.4 m/year over the past 20 years.

The topography of the underwater slope is not uniform. To a depth of 10–11 m, on the bottom composed of loose sediments, several erosion hollows can be traced, the tops of which reach depths of 5–5.5 m. The incision depth of these hollows relative to the surrounding surface of the bottom does not exceed 0.6 m. In the area of 5–5.5 m, the relatively flat bottom topography turns into a steeper one, the formation of which is caused by the displacement of large beach-forming material to the zone of final breaking of storm waves.

The underwater part of the beach (up to a depth of 5 m) is complicated by a number of shallow transverse hollows. Apparently, these hollows are formed during storms as channels for sediment flow to depth. Coarse sediments are not drifted seaward of the wave breaking zone, and small sediments are carried to lower horizons along the above-mentioned erosion hollows.

Fig. 3. The washout and fall of pine trees from the north side of the investigated shore section

Conclusion

Based on the performed lithodynamic studies and data analysis, the following results were obtained:

– the main source of beach material entering the shore section under consideration is the Bzyb River runoff;

– under the influence of waves, the beach pebble material drifting in the longshore sediment flow is directed to the southeast towards Cape Pitsunda;

– the shore and bottom of the underwater slope in the shore section under consideration are composed of easily eroded alluvial deposits;

– currently, the coastal zone is represented by a beach 50–55 m wide;

– in its upper part, the beach is composed of sand which changes to pebble and gravel sediment as it moves towards the sea;

– the width of the beach is maintained by the longshore flow drifting from the mouth of the Bzyb River;

– the depth of the existing beach is not sufficient to damp completely storm waves, as evidenced by the erosion of ancient barrier beaches;

– erosion of the bases of ancient barrier beaches is caused by the general retreat of the coastline within the marine terrace located between the mouth of the Bzyb River and Cape Pitsunda.

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Roman M. Tlyavlin – development of the research concept, processing and description of the research results

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