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Original article

Material Accumulation in the Modern Accumulative Body of the Anapa Barrier Beach (Caucasian Coast of the Black Sea): Paleolithodynamic Prerequisites

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Abstract
The Anapa Barrier Beach is a large Holocene coastal accumulative form formed by sediments of terrigenous and marine origin in the north-western Caucasian coast of the Black Sea. In recent decades, the barrier beach shoreline has been retreating. The main reason for the retreat is the natural processes that caused the shortage and redistribution of sediments in the lithodynamic system of the barrier beach. With the sea level rising, the coast retreat may accelerate, and in the future, it may lead to degradation of the entire geosystem of the Anapa Barrier Beach. The paper aims to analyze and generalize information about the origin of the sediment material composing the accumulative body and the mechanisms of its redistribution in time and space, which is necessary for assessing the stability of the modern accumulative body. Based on a comprehensive analysis, which includes a number of paleogeographic, geomorphological, cartographic, granulometric, and mineralogical studies, several options for accumulating a large supply of sand were considered. It is shown that the development of the accumulative body of the Anapa Barrier Beach was determined by changes in the shore configuration, fluctuations in the sea level, as well as the direction and length of alongshore sediment flows. The Phanagorian regression interrupted the previous course of development of the accumulative geosystem of the Anapa Barrier Beach. The geosystem acquired its modern form during the Nymphean transgression. The accumulative body of the modern barrier beach was formed from the abrasion material of the indigenous shores of the Taman Peninsula and alluvium of the Kuban River. The alluvium came directly to the seashore during the Phanagorian regression.

Keywords: Black Sea, Caucasian coast, Anapa Barrier Beach, lithodynamic processes, sea-level fluctuations, accumulation, sediment flow, shoreline

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Палеолитодинамические предпосылки накопления материала современного аккумулятивного тела Анапской пересыпи (Кавказское побережье Черного моря)

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Аннотация

Анапская пересыпь – крупная голоценовая прибрежно-морская аккумулятивная форма, сформированная наносами терригенного и морского происхождения на северо-западе Кавказского побережья Черного моря. В последние десятилетия наблюдается отступание берега пересыпи. Основной причиной отступания являются природные процессы, обусловившие дефицит и перераспределение наносов в литодинамической системе пересыпи. На фоне повышения уровня моря отступание берега может ускориться, а в дальнейшем – привести к деградации всей геосистемы Анапской пересыпи. Целью работы является анализ и обобщение информации о происхождении слагающего аккумулятивное тело пересыпи материала и механизмах его перераспределения во времени и пространстве, что необходимо для оценок устойчивости современного аккумулятивного тела. На основе комплексного анализа, включающего ряд палеогеографических, геоморфологических, картографических, гранулометрических и минералогических исследований, проанализировано несколько вариантов накопления большого запаса песка. Показано, что развитие аккумулятивного тела Анапской пересыпи определялось изменениями конфигурации берега, колебаниями уровня моря, направлением и протяженностью вдольбереговых потоков наносов. Фанагорийская регрессия прервала предшествующий ход развития аккумулятивной геосистемы Анапской пересыпи, а современный вид геосистема приобрела в ходе нимфейской трансгрессии. Аккумулятивное тело современной пересыпи было сформировано из аллювия реки Кубани, поступавшего непосредственно на морской берег во время фанагорийской регрессии, и материала абразии коренных берегов Таманского полуострова.

Ключевые слова: Черное море, Кавказское побережье, Черноморское побережье Кавказа, Анапская пересыпь, литодинамические процессы, колебания уровня моря, аккумуляция, поток наносов, береговая линия

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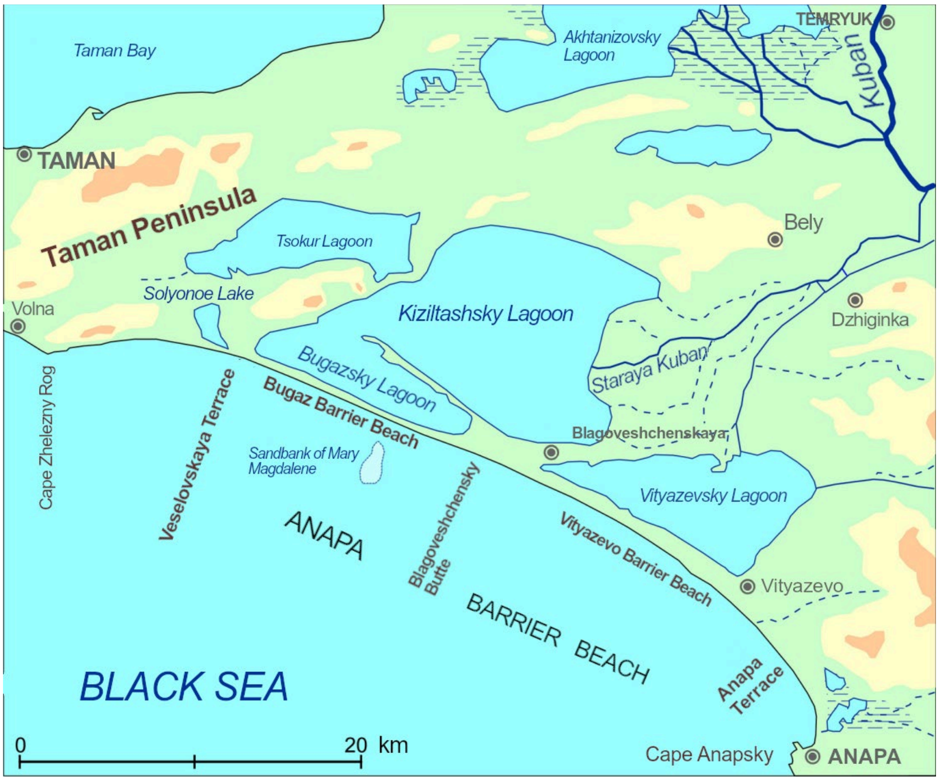
Introduction

The Anapa Barrier Beach is a large Holocene coastal accumulative form formed by sediments of terrigenous and marine origin. It is located on the sea edge of the lowland alluvial plain of the north-eastern Black Sea region, in the junction zone of tectonic elements of the north-western (Caucasian) and sublatitudinal (Kerch–Taman) extension. The accumulative body of the 47-kilometer Anapa Barrier Beach (Fig. 1) is composed of quartz sand with an admixture of shell detritus and pebbles. Its width is maximum in the south-eastern part (almost 1.5 km) and decreases gradually to 150–200 m to the northwest. Transverse and longitudinal sediment flows are observed within the lithodynamic system of the Anapa Barrier Beach. The alongshore sediment flow is characterized by a bimodal regime with a predominance of transport to the south-east [1–4].

In recent decades, there has been a retreat of the barrier beach shoreline. In some areas, the retreat made about 80 m in 50 years [5]. The main reason for the retreat is the natural processes that caused the shortage and redistribution of sediments in the lithodynamic system of the barrier beach. With the sea level rising, the coast retreat may accelerate, and in the future, it may lead to degradation of the entire geosystem of the Anapa Barrier Beach [1].



F i g. 1. Map of the Anapa Barrier Beach

To determine the limits of stability of the barrier beach accumulative body, it is necessary to obtain information about the origin of the material composing it and the reserves of such material. The paper aims to analyze and generalize information about the origin of the sediment material composing the accumulative body and the mechanisms of its redistribution in time and space, which is necessary for assessing the stability of the modern accumulative body. To analyze the origin of the accumulative forms of the Anapa Barrier Beach, it is necessary to consider the following important issues – what is the genesis of the material composing them, when and how it entered the lithodynamic system.

Materials and methods of research

Materials from geological surveys, field studies, remote sensing, archival and literary sources were used in the research. In the 1970s, a longitudinal drilling profile consisting of two dozens of wells with a depth of up to 200 m was made along the entire length of the Anapa Barrier Beach. At the same time, a transverse profile was drilled through the Staraya Kuban River valley along the Dzhiginka–Bely line [6]. In the early 2000s, a complex of studies was carried out (mollusk fauna, carbon dating, mineral and granulometric composition) based on the data from a network of wells with the depth up to 10 m (44 wells along 10 profiles). In 1998, archaeological and paleogeographical research was carried out on the Taman Peninsula, the purpose of which was to study the variation of the Black Sea level in the last 3–4 thousand years [7]. In 2005, Ya. A. Izmailov reconstructed the formation history of the Anapa Barrier Beach in detail, based on the analysis of a complex of geological and geomorphological data [6]. Since 2010, employees of the Southern Branch of the Institute of Oceanology of RAS and of the Faculty of Geography of Moscow State University have studied the processes of formation of land and underwater relief, landscape and morphological structure, spatial features of sediment distribution and hydrological regime on the Anapa Barrier Beach [1, 8–12].

Results and discussion

<u>Stages and factors of formation of the Anapa Barrier Beach before the Phanagorian regression</u>

Possible scenarios concerning the origin of the Anapa Barrier Beach have been studied by many researchers [6, 7, 13–16]. The formation of the accumulative body of the future Anapa Barrier Beach began with the end of the last ice age from the alluvium of the proto-Kuban, accumulated during the period of its direct flow into the Black Sea. As the sea level rose, part of the material moved along with the shoreline movement in the form of a bar, which is typical during the development of such accumulative forms [17]. It is possible that the material available at that time was sufficient to form accumulative forms that completely or partially blocked the baymouths.

After the Black Sea reached a level close to the modern one (5–5.5 kya) [18], the entire delta region of the Kuban River was flooded. The alluvium sedimentation began after the formation of bays deeply cut into the land [1)]. In that period, the configuration of the indigenous shore was determined by the presence of several capes or islands, among which spits, barrier beaches or tombolos were formed. The rate and vectors of growth of accumulative forms were different. In different periods of time, their development could occur independently or concertedly.

From that moment, the formation of the Anapa Barrier Beach took place due to the material formed in the process of the indigenous shore abrasion and shells coming from the underwater slope. As studies of the sediment thickness of various profiles of the Anapa Barrier Beach show, the proportion of shells (shell detritus) is up to 5% in the total volume of sediments, and this value is almost independent of their age [1]. It is more difficult to determine the proportion of sediments resulting from abrasion. Since the abrasion shores to the north-west of the Anapa Barrier Beach have retreated over the past 5 thousand years to a distance of about 2 km, and some of their profiles have been completely washed away, the composition of their rocks is unknown. In the modern cliff, the content of beach-forming material is no more than 10%, the predominant part of which is represented by well-graded fine and medium sands of alluvial origin of the Pliocene age [2)]. After wave processing, these sands cannot be distinguished from the Kuban alluvium, so it is not possible to determine the share of abrasion material in the total volume of the Anapa Barrier Beach. The presence of abrasion material is indicated by the insignificant number of pebbles from ferruginized limestones, the source of which is considered to be rocky crags located on the underwater slope or at the base of Cape Zhelezny Rog. These pebbles are found in small quantities along the entire length of the barrier beach, including its rear part. The number and size of the pebbles decreases in the direction from the north-west to the south-east. In general, the lithodynamics of the modern Anapa Barrier Beach is determined by sands, while the influence of shells, and especially pebbles, is of a subordinate nature.

Rapid growth of the southern part of the future Anapa Barrier Beach occurred due to the predominance of sediment movement from the north-west to the south-east. The Anapa Cape, composed of rocks, retained incoming sediment, and the resulting accumulative forms remained stable and moved towards the sea. The rear part of the barrier beach is exactly the area where the most ancient surface accumulative sediments were discovered [6].

In the central part of the barrier beach, south of the Blagoveshchensky butte, several generations of beach and dune ridges are observed. The oldest and most distant from the sea ridges are located at an angle to the modern shoreline [10, 11, 19]. Probably, these ridges appeared when the configuration of the sea edge of the Blagoveshchensky butte was different, and the orientation of the spit that formed to the south-east of it differed from the orientation of the modern shoreline of the barrier beach.

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1) Zenkovich, V.P., 1958. [*Morphology and Dynamics of the Black Sea Coasts Within the USSR Boundaries. Vol. 3, Part 3. Regional. Section 2. The Central Part (Southern Crimea, Kerch and Taman Peninsulas)*]. Moscow: Izd-vo Akademii Nauk, 187 p. (in Russian).

2) Azhgirey, G.D., ed., 1976. [*Geology of the Greater Caucasus*]. Moscow: Nedra, 262 p. (in Russian).

In the northern part of the Anapa Barrier Beach (within the Bugaz Barrier Beach), ancient generations of accumulative forms were not preserved, which was a consequence of the rapid destruction of the indigenous shores composed of unconsolidated rocks by the sea, and constant retreat of accumulative forms deep into the lagoon. Nevertheless, the existence of such accumulative forms is indicated indirectly by the fact that, according to [20–22], 3.5 kya, it was the Bugaz Barrier Beach, along which one of the most important land transport routes between the Taman Peninsula and the Anapa Region passed.

It is difficult to state when the complete destruction of the capes in the central part of the future Anapa Barrier Beach occurred, but this event led to significant changes in the lithodynamic regime. According to the work [6], the connection of the northern and southern parts (Bugaz and Vityazevo Barrier Beaches) with the formation of a uniform lithodynamic system took place no earlier than 2.5 kya. This connection is close in timing to the beginning of the Phanagorian regression (perhaps caused by it). Subsequently, the northern part of the formed abrasion-accumulative shore arc, more than 50 km long, shifted over time as accumulative forms retreated deeper into the bays [23], and the southern part moved out to the sea due to the growth of new generations of beach ridges.

In addition to spatial changes caused by accumulative or abrasion processes, the development of the accumulative body was complicated by fluctuations in the sea level. From the point of view of assessing the stability of the accumulative body of the modern Anapa Barrier Beach, the final stage of its formation is interesting, the beginning of which was stipulated by the Phanagorian regression and the subsequent Nymphean transgression.

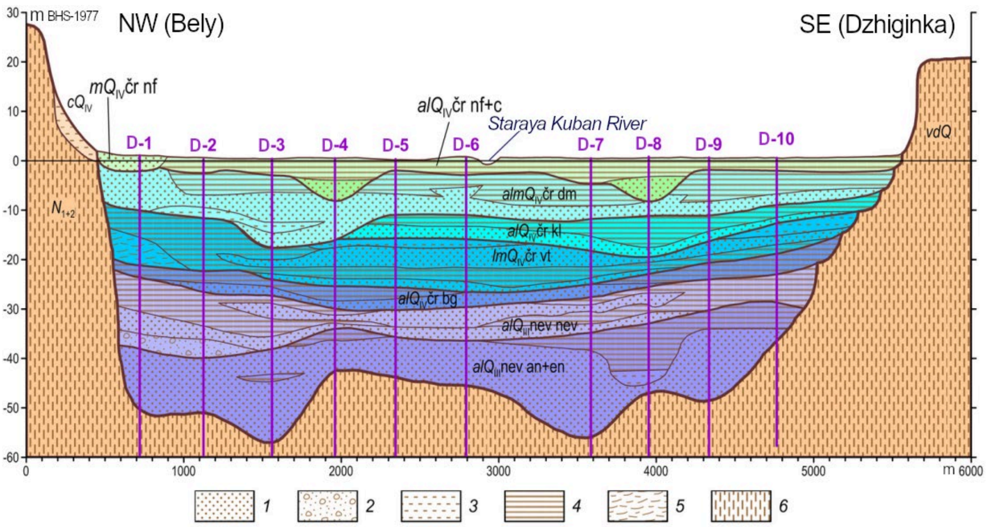
Development of the Anapa Barrier Beach during the Phanagorian regression

The Dzhemetinsky stage (5.2–2.5 kya) [6] ended with a regression known in the Black Sea region as Phanagorian. Most modern researchers [24–27] estimate the decrease in sea level during the Phanagorian regression at 5.0–5.5 m relative to the previous and modern level.

In the work [22, p. 75], the authors wonder why no ancient authors "tell us about the presence of the vast Kiziltashsky (Paleo-Kuban) Lagoon." According to the work [6], on the profile in the northern part of the Bugaz Barrier Beach (near the Bugaz spout) between the late Dzhemetinsky (dated 2660–2520 years ago) and Nymphean sediments (dated 1110 years ago), a layer of fine sands of the alluvial type with a base elevation of minus 6.6 m was observed, i.e. the level of the river bottom was significantly lower than the modern sea level. According to the profile in the central part of the Bugaz Barrier Beach between the Upper Dzhemetinsky (dated 2750 years ago) and Nymphean (dated 1940 years ago) sediments, a layer of the eolian sands with an absolute mark of the base minus 1.55 m was traced (at the same time, extrapolation shows high probability of tracing the marks of the base of the eolian sands to minus 2.5 m [6]). Taking into account the fact that the modern eolian sediments are located 1.5 m above the sea level, the sea level near the Bugaz Barrier Beach during that period was lower than the modern one by at least 3.5 m. At this sea level, the level of the lagoons connected to it hydraulically should have decreased by the same amount.

Taking into account the hydrological characteristics (the depths in most of the area of modern lagoons not exceeding 1 m) [28], the estimated value of the level drop and geological data, it can be argued that during the Phanagorian regression period (i.e., in ancient times), no extensive bays or lagoons existed in the place of the modern Kiziltashsky Lagoon.

The flow of the Kuban River into the sea was carried out through the water area of the lagoons, which dried out as the sea level decreased, along erosive channels carved out in previous sediments. The geological profile (Fig. 2) [29] shows two pronounced erosional channels filled with alluvial sands. The composition of the sediments indicates that current velocities were high enough to transport large volumes of driven sediments, in this case the sand. The bottom of the channels is located at minus 5 m. With no lagoons, the basis of erosion for the Kuban River during this period was the Black Sea level. Therefore, the Kuban River solid runoff flowed directly into the Black Sea during the period under consideration. In the above-mentioned paper [22, p. 75], the authors provide a figurative description of Hipponactus from Ephesus, ancient Greek poet (second half of the 6th century BC), presumably referring specifically to the Kuban mouth.



F i g. 2. Dzhiginsky geological profile across the Staraya Kuban River (adapted from [29, p. 82]). Lithological composition: 1 – sand; 2 – sand with pebbles; 3 – siltstone; 4 – clays; 5 – silts; 6 – loess. Genesis: a – river; l – lagoon; m – marine; v – eolian; d – slope; c – landslide. Age: N1+2 – Neogene; Q – Quaternary; an+en – Antsky-Yenikalsky; nev – Novoevksinsky horizon; nev nev – Novoevksinsky layer; QIVčr – Black Seahorizon; bg – Bugazsky; vt – Vityazevsky; kl – Kalamitsky; dm – Dzhemetinsky; nf – Nymphean, modern; D-5 – well numbers

Downcutting of a river channel into underlying sediments as a result of sea level decrease was observed during the Caspian Sea level drop in 1931–1945. At the mouth of the Kura River, the sea level drop did not affect the entire length of the longitudinal profile immediately, but spread from the mouth upstream gradually. In general, the decrease in the Caspian Sea level accompanied by the active downcutting of rivers on its western coast, contributed to a significant increase in the areas of mouth formations [3)]. This process was actively influenced by alongshore sediment flows and shell bars covering mouth parts.

As indicated in the work [30], with alongshore sediment flows, active downcutting of channels into the underlying sediments is not necessarily accompanied by a significant movement of the mouth parts towards the sea. Entering river sediments are actively involved in alongshore transport contributing to the development of accumulative form within the entire lithodynamic system. Probably, the Anapa Barrier Beach developed in a similar way during the Phanagorian regression.

Development of the Anapa Barrier Beach during the Nymphean transgression

During the Nymphean transgression, a vast water area with actively occurring hydro- and lithodynamic processes was formed again within the dried lagoons, as indicated by the presence of beach accumulative ridges and small lagoons at the foot of the indigenous slope. Dating of shell material from relict accumulative forms [15] makes it possible to attribute their formation to the middle of the 2nd millennium AD [20]. Similar, though more ancient, accumulative forms in the line between the village of Dzhiginka and the khutor of Bely can be traced in the form of two shell sand spits (approximate age 2.8–3.5 kya) directed towards each other from the western and eastern sides of the valley at level 2.5–4.5 m below modern sea level [20].

In the work [21, p. 339], it is suggested that during transgressive periods, "erosion and flooding of the Bugaz Barrier Beach took place with the transformation of the lagoon into a marine shallow open bay, the shores of which were exposed to the influence of the open sea waves." This assumption is confirmed by the formation of abrasion ledges on the indigenous sides of valleys and accumulative forms on the western shore of the Kiziltashsky Lagoon. In the work [20, p. 488], it is stated that "In the second half of the first millennium AD, a rise in sea level by 2–3 m caused the flooding of the ancient barrier beach that separated the paleo-Bugaz lagoon, and the short-term transformation of the lower reaches of the ancient Kuban (modern Kiziltashsky) Lagoon into an open sea bay." The authors of the work [20] argue that recovery of the barrier beach and formation of a lagoon with limited connection to the sea, which was subsequently filled with lagoonal-alluvial sediments, occurred only as the transgression slowed down.

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3) Leontev, O.K., 1963. [*Brief Course of Marine Geology. A Textbook*]. Moscow: MGU, 461 p. (in Russian).

It should be noted that the authors of the works [20, 21] do not take into account the rates and mechanisms of formation of surface sandy capping forms under transgression conditions. The Nymphaean transgression was not catastrophic (as indicated by the lack of literary information). The Nymphean rise in sea level did not lead to the destruction of the Anapa Barrier Beach or its parts, but its accumulative body shifted towards the land. Under conditions of a gradual rise in level, sandy barrier beaches on shallow coasts exhibit the ability to shift along with the horizontal elevation of the shoreline towards the land [31, 32], maintaining their integrity and even morphological structure.

Thus, we believe that the Nymphean rise in sea level resulted not in the destruction of the Bugaz Barrier Beach, but rather in the displacement of its body towards the lagoon. At the same time, the lagoon basin was filled with water, and the size and configuration of the resulting water area determined the activation of abrasion-accumulation processes on its shores inevitably. Bilateral water exchange through the Bugaz spout determined the presence of shells of marine conch mollusks in the accumulative sediments on the lagoon shores (nowadays, shells are still found there). Lagoon level fluctuations influenced by floods or storm surges, contributed to the active abrasion of the lagoon shores. In some areas, abrasion is observed even now, after the river flow cutoff and in the actual absence of free water exchange with the sea.

Composition, age and mechanism of redistribution of the Anapa Barrier Beach modern sediments

In the southern and central parts of the Anapa Barrier Beach, the relief and sediment composition are distinguished by an ancient generation of coastal-marine sediments in the lagoonal part and a modern generation stretching along the seashore in a continuous bar up to 200 m wide. The structure and dynamics of this bar display features of both a full-profile beach and a dune ridge. The lower layers of sediments are represented predominantly by quartz sand with a significant (up to 30%) admixture of shells. In contrast to the sediments of more ancient parts of the barrier beach, the material of the new generation contains relatively few pebbles of ferruginized limestones. In the upper part of the sediments of the shoreline bar, well-graded quartz sands with a low (up to 3%) shell content occur and migrate actively.

In his work [1)], V. P. Zenkovich asks: “What is the origin of the pure (quartz) sands that form the outer bar of the southern and central part of the barrier beach? ... The formation of a clean sand bar more than 200 m wide in the eastern part of the barrier beach shows that there was a period when these masses of sand came from the bottom to the shore, but now such process is not observed.” By now, based on the materials of numerous studies, it is possible to propose several opinions concerning the origin of the material that became the basis for the modern generation of sediments in the central and southern parts of the Anapa Barrier Beach.

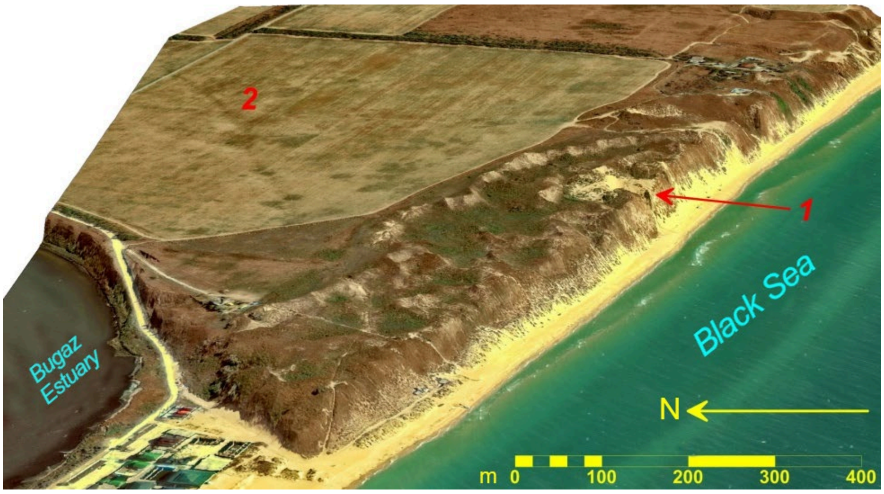
Opinion 1. The Phanagorian regression (a drop in sea level by 5 m in the period 2.5–1.7 kya) led to the resumption of alluvium entry from the Kuban River directly into the Black Sea coastal area. The alongshore transport of this material to the south-east contributed to the extension of the coast and increase in the width of the beaches. The mineral and mechanical composition of the sediments (well-graded alluvial sands) favoured the growth of eolian formations that overlaid earlier sediments with a noticeable admixture of pebbles and shells.

Opinion 2. During the period of Phanagorian regression, sediments arriving from the north (sands mixed with pebbles and shells) were traversed and accumulated between a sandbank or island at the site of the modern Sandbank of Mary Magdalene (depth of 1–5 m). After the level rose, the alongshore transport of accumulated sediments to the southeast was resumed. Opinion 2 is easily combined with opinion 1 and even enhances it, but it does not inherently explain the simultaneous appearance of a large amount of well-graded sand in the southern part of the barrier beach.

Opinion 3. During the period of Phanagorian regression, sediment accumulation occurred in the form of a beach ridge near the shoreline, which was located more seaward and lower at that time. During the Nymphean transgression, that ridge was displaced towards the land and joined the previous generations of beach ridges. Opinion 3 is easily combined with opinion 1, but it does not inherently explain the origin of the sand.

Analysis of paleontological and archaeological finds makes it possible to clarify the time frame for the beginning of the arrival of large masses of sand. The Blagoveshchensky butte composed of Neogene clay loams is located in the central part of the Anapa Barrier Beach. The accumulative body of the barrier beach is attached to an ancient abrasion ledge and grows into a marine accumulative terrace. The Blagoveshchensky butte is characterized by a vast (about 20 ha) area in its north-western part, where the dunes are located on the surface of the indigenous shore, that is, they are raised relative to the level of the accumulative terrace to a height of 15–20 m [1]. The appearance of dunes on the surface of the Blagoveshchensky butte makes it possible to clarify the dating of the beginning of the movement of large masses of sand.

In the work [33], the ancient settlement of Blagoveshchensky-4, which existed from the 6th century BC to the 2nd–3rd century AD, is noted to the north of the dune massif. The settlement is oriented along an ancient road to the Bugaz Barrier Beach (Fig. 3). The abundance of pottery and no remains of capital structures make it possible to suggest that the settlement of Blagoveshchensky-4 was a logistics center where transshipment from sea vessels to land or river transport could be carried out. In accordance with the works [20, 21], one of the most important land transport routes passed there. In the work [33], unfortunately, no dune massif is mentioned. Meanwhile, a large number of fragments of ancient pottery were discovered on the surface of the indigenous clay loams under the dunes blown by wind [1]. Estimated datings made by A.M. Novichikhin and N.I. Sudarev, show that the earliest finds date back to the 6th century BC, and the latest ones – to the 2nd–3rd centuries AD. The given datings coincide with the datings of finds from the settlement of Blagoveshchensky-4 [33] and indicate that the eolian accumulative formations did not exist on the surface of the Blagoveshchensky butte at least until the beginning of the 3rd century AD.



F i g. 3. Dune field on the NW tip of the Blagoveshchensky butte: *1* – dune; *2* – localization of the main finds of the ancient settlement of Blagoveshchensky-4 along an ancient road

After the comparison of paleogeographic reconstructions of the Black Sea level variation [6, 34] and archaeological data, it becomes possible to conclude that the formation of dunes on the butte surface occurred no earlier than the beginning of the Early Nymphean transgression around 1.7 kya. Perhaps, it was the consequences of this transgression that contributed to the cessation of economic activity in the indicated area of the Blagoveshchensky butte. The water level decrease in the lagoons cut off the Blagoveshchensky butte from a number of land transport routes [20], and the arriving sand prevented the use of this area.

Conclusion

The development of the accumulative body of the Anapa Barrier Beach was determined by changes in the shore configuration, fluctuations in the sea level, as well as the direction and length of alongshore sediment flows. More ancient generations formed during the Dzhemetinsky period, distant from the sea, and modern generations stretching along the coastal area, are clearly distinguished in the barrier beach structure. The coastal areas of the Anapa Terrace, the Vityazevo Barrier Beach, and the southern part of the Blagoveshchenskaya Terrace are of Nymphean age. The Nymphean generation of beach ridges, the formation period of which covers the last 1.5 thousand years, adjoins the ancient generation of beach ridges on the seaward side. Under the modern generation, a layer of sediments that chronologically occupies an intermediate position between the Nymphean and Dzhemetinsky generations, was revealed in the process of drilling. These sediments are represented by the silts of the lagoon type with the chronological range of accumulation 2.7–1.6 kya confirmed by a series of shell material carbon dating, which characterizes the period of sea level position 3.5–5.5 m below the modern one.

Thus, we have the sufficient grounds to assert that the Phanagorian regression interrupted the previous course of development of the accumulative geosystem of the Anapa Barrier Beach. The geosystem acquired its modern form during the Nymphean transgression. The accumulative body of the modern barrier beach was formed from the abrasion material of the indigenous shores of the Taman Peninsula and alluvium of the Kuban River. The alluvium came directly to the seashore during the Phanagorian regression. In general, it is possible to assume the following course of events:

– during the Phanagorian regression, the shoreline moves towards the sea and becomes stable;

– the Kuban River solid runoff (well-graded quartz sand) flows into the coastal zone of the sea again, being involved in alongshore transport;

– during the period of regression, the alluvium, which enters the coastal area and becomes redistributed along it, forms a beach ridge;

– a shallow lagoon is formed between the growing new and old beach ridges (it prevents the development of the eolian forms towards the shore);

– vegetation, including trees, appears along the shores of the lagoon;

– the Nymphean transgression mobilizes the formed beach ridge, which moves towards the shore, thus blocking the lagoon gradually;

– as the lagoon disappears, material from the new beach ridge is drawn into the eolian transport, accumulating along the rows of woody vegetation and forming ridges of stable dunes;

– when the sea level becomes stable, the intensity of sediment (primarily eolian) migration decreases gradually until the anthropogenic impact brings the system out of balance again.

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