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DETAILED ZONING OF THE COASTAL AND SHELF AREAS OF MARINE ECOREGIONS: A CASE STUDY OF THE BLACK SEA

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M. D. Spalding, G. Allen, H. Fox, and N. C. Davidson (Spalding et al., 2007) developed principles for zoning marine ecoregions of the World. The authors designated 12 realms, 62 provinces and 232 ecoregions (marine basins).

This zoning system reflects the major global features of life in the ocean. However, the assessment of biodiversity, productivity, and the use and conservation of biological resources requires the development of a more detailed system of ecoregion zoning units. This article discusses principles of detailed bionomic zoning of the coastal and shelf areas of marine ecoregions using the Black Sea as an example.

1. SYSTEM OF UNITS FOR BIONOMIC ZONING OF ECOREGIONS

Bionomic features of coastal and shelf areas of seas show the influence of geological and geomorphological setting and depth on the distribution of hydrobiont assemblages and the coastal zone position in the system of geographical zonality units (Petrov, 2008 and 2020, b).

Geological and geomorphological settings (morphostructures) of coastal and shelf areas.

An important factor in changing the bionomic conditions in the coastal and shelf areas is changes in the relief, the effect of abrasion and sedimentation. Morphostructural features of continental margins, recent and contemporary tectonic movements are of significant importance in these processes. In the Neogene-Quaternary, the morphostructures evolved from planetary to local, which specified the main topographic features of marine margins of platforms and orogens. The morphostructures control the relief of the coastal zone, the contour of the coastline, and the steepness of the nearshore slope. There are longitudinal coasts, where fold axes are located along the coastline, and transverse coasts, where the fold axes run along the normal to the coast. Growing longitudinal coasts are characterized by the formation of a coastal cliff, an abrasion submarine nearshore slope, a steep coast, and a narrow shelf. The axes of growing folds of the transverse-type coasts continue into the sea to form a system of capes, islands and bays; the shelf is wide. An abrasion-accumulative terrace with numerous reefs and banks in place of local folds is formed on the submarine nearshore slope. The abrasion-sculptural submarine nearshore slope is a special biotope of rocky ground dominated by attached biological forms (sessile biota).

A thick series of Quaternary deposits are accumulated in the place of tectonic troughs, and morphostructures of accumulative plains and coastal zones are formed. On the submarine slope, waves directed along the normal to the coast cause transverse movement of sediments and their grading. Fine sandy-silty material carried out from the coastal area is deposited at depths inaccessible to the action of waves. The propagation of waves at right and oblique angles to the coastline causes the alongshore sediment flow. Submarine-coastal bars and other forms of accumulative relief are typical forms of relief there. In the upper part of the submarine nearshore slope, within the active influence of the wave field, mainly mobile forms live on sandbanks; in the lower part, where the impact of waves is weakened, a biotope of sandy-silt deposits is formed, where hydrobionts (infauna) burrowing into the ground dominate.

The following size range of morphostructural zoning units is proposed: gigachores (counties), megachores (districts) and macrochores – underwater landscapes.

Vertical zonation. With increasing depth, there is a rapid change in bionomic conditions the nature of biotopes and bottom biocenoses, so the subdivision of the shelf into three belts is proposed. The upper belt includes the coastal zone (submarine nearshore slope). It occurs within the limits of wave action; it has a seasonal rhythm (first of all, warming up during the warm season) and illumination sufficient for the evolution of macrophyte communities. The intermediate belt is located below the thermocline, the wave activity is weakened, the seasonal rhythm is weakly expressed, and the illumination is low. Single multicellular and some unicellular algae are found here. Due to the weakened hydrodynamics in this belt, fine silty material rich in detritus is deposited, and diverse infauna is formed. The lower belt corresponds to the bottom profile bend towards the continental slope. Here, hydrodynamic activity increases, sculptural forms of relief are formed, and the diversity of sessile fauna groupings increases.

Geographic zonation. The primary factor of zonation is the temperature regime. In the early 20th century, Setchell (1917), while studying geographical patterns of the distribution of submerged vegetation, identified stenothermic groups of marine benthic algae, confined to waters, the temperature regime of which differs by 5-10°C. The biological explanation for the existence of stenothermal groups of algae was given by L.P. Perestenko (1982). She found that individual evolution and life cycles of macrophytes are associated with temperature gradients, which correspond to values of 0, 5, 10, 15, 20, 25°C. These thermal boundaries are proposed to be used to identify geographic belts zones and related to them zonal types of species groupings in the World Ocean. For example, in the Northern Hemisphere in the cold belt, there are the Arctic and subarctic zones with biologically active water temperatures in summer, respectively, 0-5°C and 5-10°C. In the temperate belt, there are boreal and nemoral zones with biologically active temperatures in winter, respectively, 0-5°C and 5-10°C. In the warm zone, there are subtropical and tropical zones with biologically active temperatures in winter above 20°C.

Boundaries of the surface and bottom zones merge in shallow marine waters; at great depths, natural zones of the same type that zones identified on the sea surface are not traced below the transition layer. An important additional characteristic of thermal zones is the salinity of seawater. A salinity value below 24.69 $^{0}/_{00}$ separates seas with normal salinity from brackish water basins. This boundary separates marine biota from brackish water biota, which is accompanied by a significant loss of biodiversity.

2. SUBMARINE LANDSCAPE CONCEPT

Studies of the coastal and shelf areas, based on the general theory of landscape science, started in Russia in the middle of the 20th century (Gur'yanova, 1959; Petrov, 1989, 2020 a). However, the development of submarine landscape science was hampered to a certain extent by the lack of a conceptual apparatus that would naturally become part of the theory of oceanology. First of all, it must be recognized that landscape is a general concept applicable to the study of objects both on land and on the seabed.

The variety of underwater landscapes of the coastal zone depends on a number of factors. Hydrological conditions are related to the climate and the meteorological regime of the atmosphere, which controls the seasonal rhythm of natural processes in the coastal zone.

The penetration of solar radiation supports the photosynthesis of phytoplankton and phytobenthos. Water mobility controls abrasion, lithodynamics, and sediment accumulation and also promotes good aeration, the influx of nutrients, and the spread of anlages. The discharge of liquid and solid land runoff causes a strong variability in the salinity of sea waters and results in enrichment in biogenic and organic substances. Large species diversity and richness of lifeforms are responsible for the dense occupation of various ecological niches.

The underwater landscapes of the coastal and shelf areas bear the imprint of the influence of the Pleistocene regression with which relict relief forms, the presence of subaerial deposits, and the disjunction of hydrobiont areals and the Holocene transgression, which determined the youth of underwater landscapes, are associated.

The main properties of underwater landscapes of the marine coastal zone are as follows:

- the seabed landscape is isolated in a crustal section, which generally has a similar geological setting; as a rule, it is related to the evolution of one regional morphostructure;

- each landscape is characterized by a certain set of lithological varieties of recent bottom sediments or bedrock outcrops that control the nature of sculptural micro- and mesoforms of the submarine relief;

- subaquatic illumination, temperature, and wave processes change with depth that specifies the vertical subdivision of the coastal zone;

- a variety of forms of relief, ground, hydrological settings control the diversity of biotopes and, accordingly, the diversity of bottom biocenoses.

All of these things serve as a basis for identifying a system of morphological units of intralandscape differentiation. Characterization of the underwater landscapes morphology includes a description of the units of horizontal and vertical subdivisions. The main units of the horizontal subdivision of underwater landscapes are facies and landforms. The submarine facies is the smallest elementary bottom natural assemblage. It is a specific biotope associated with one form of microrelief or one element of mesorelief (top, slope, foot of the bank) and is located in a certain depth interval. The facies is composed of one lithological variety of recent sediments or is confined to a rock outcrop of homogeneous petrologic composition and occupied by one biocenosis. The facies association forms an underwater landform. The underwater landform is a natural complex associated with a certain mesoform of relief, with pronounced boundaries. The differentiated evolution of local structures results in the formation of two types of landforms. On the structures, which underwent uplifting, the bottom is eroded, and abrasion-sculptural landforms are formed: the alongshore cliff belt, submarine banks and reefs far from the coast. A complicated morphological structure of the landscape, a wide variety of biotopes and associated biocenoses appear (Fig. 3). On the structures, which experienced subsidence, sedimentary bottom levelling occurs, and accumulative-type landforms appear. In areas of active lithodynamics, underwater landforms are represented by coastal bars, submarine spits, etc. In a quiet hydrodynamic environment, landforms of monotonous sandy-silty plains are formed in stable sedimentation areas. Ground properties are an important environmental factor of these landforms. There are communities of attached biological forms associated with rocky grounds and communities of organisms burrowing into the loose bottom, which habitus has adaptive traits caused by the fact that they lived in different types of ground.

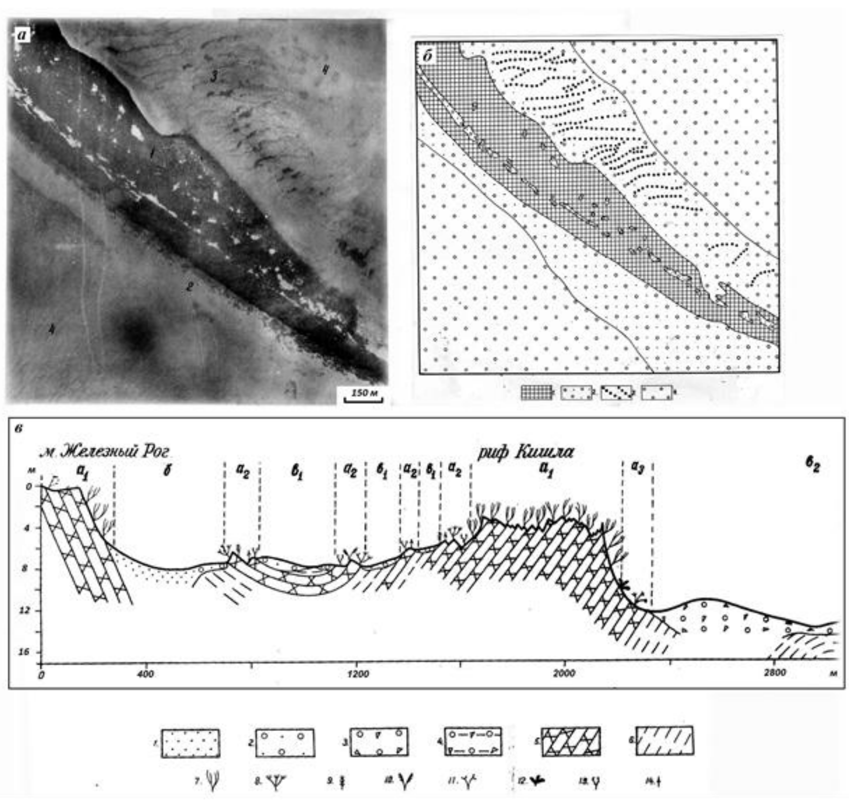

Fig. 1. Morphological structure of a section of the submarine slope of the Taman Upland, complicated by a large reef: a) aerial photograph: 1 - submarine reef formed by thick layers of brown iron ore overgrown with

brown algae *Treptacantha (Cystoseira) barbata* and others, 2 - landforms of sandy plains, 3 - sandy accumulative forms, 4 - shell fields; b) landscape map: 1 - landform of rocks and stones, Treptacantha (Cystoseira) barbata biocenosis, 2 - landform of sandy plains, 3 - landforms of sandy accumulative forms, 4 - landform of shell fields; b) landscape profile: 1–6 - grounds: 1 sand, 2 detritus sand with an admixture of shells, 3 - shells (thanatocenosis of mussels, oysters, scallops, etc.), 4 - silted shells, 5 - stones and rocks, 6 - clay in bedrock; 7–14 - dominants of plant communities: 7 Treptacantha (Cystoseira) barbata, 8 - Nereia filiformis, 9 - Chondria capillaris, 10 - Dasya baillouviana, 11 - Ceramium virgatum, 12 - Phyllophora crispa, 13 *Dictyota* (*Dilophus*) *fasciola*, *14 – Laurencia obtusa*;; a – c - underwater landforms: a - rocks and stones, b - sandy plains, c - shell fields.

Vertical differentiation of shallow marine waters reflects the height of the surf impact, the rhythm of tidal phenomena, the weakening of waves, and the decrease in subaquatic illumination with depth. These factors influence processes of relief formation, sedimentation, and the entire set of environmental conditions that control the distribution of bottom biocenoses. The bathymetric profile is the basis of a conjugated series of benthic natural assemblages. Facies, landforms, and entire landscapes are subject to a regular change with depth. Vertical zones are the main units of subdivision of underwater landscapes with depth. In the upper belt of the shelf, there are three vertical zones: supralittoral, littoral (pseudolittoral), and sublittoral. Deeper, there is the elitoral zone, which belongs to the intermediate belt of the shelf. The next unit, into which the zones are subdivided vertically, is proposed to be called a floor. In the supralittoral, they reflect the height of the surf impact; in the littoral, tidal rhythms; in the sublittoral, the weakening of the effect of waves on the bottom and the decrease in subaquatic illumination. Sometimes the floors can be subdivided into steps, differing in the composition of bottom biocenoses. The size of intervals of vertical subdivisions varies with depth from centimetres to tens of meters; generally, the system of units of the vertical subdivision of landscapes of the coastal zone resembles a spring, compressed at the beginning and stretched at depth.

The concept of morphological units occupies a special place in studying underwater landscapes. The morphological units are the main target of marine and underwater investigations and mapping. Regular spatial combinations of morphological units are like a genome, which controls the stability of the landscape as a whole.

3. BLACK AND CASPIAN SEA AS ECOREGIONS OF THE PONTO-CASPIAN PROVINCE

There are nine realms in the Northern Hemisphere, including the Temperate North Atlantic Realm. It hosts six provinces, including the Mediterranean and the Black Sea provinces (Fig. 1).

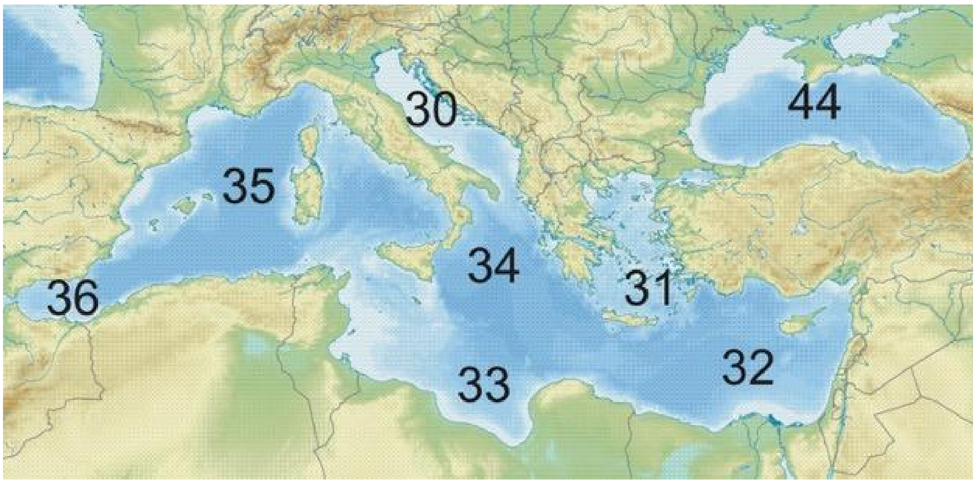

Fig.2 Ecoregions of Mediterranean and Black Sea provinces of Temperate North-Atlantic Realm (fragment of the map by Spalding et al. (2007)): 4 – Mediterranean Province ecoregions; 30. The Adriatic Sea, 31. The Aegean Sea, 32. The Levantine Sea, 33. Tunisian Plateau/Gulf of Sidra, 34. The Ionian Sea, 35. Western Mediterranean, 36. Alboran Sea; 7 – Black Sea province, ecorigeon; 44. Black Sea

The proposed zoning map of the World Ocean does not show the Caspian Sea. The Black and Caspian Seas have a common geological history with the Mediterranean Sea; they are all remnants of the closed Tethys Ocean. The genetic roots of the biota of these seas are common; more than 90% of the Black Sea biota consists of invaders from the Mediterranean Sea. During the Late Pleistocene-Holocene, the Black and Caspian Seas became increasingly isolated from the Mediterranean Sea; this process was accompanied by desalination of the water mass, depletion of the Mediterranean biota, and the formation of the endemic Ponto-Caspian biota (Zenkevich, 1963; Yanko and Kislov, 2017). Taking into account the common history of the formation of the Black and Caspian Seas and features of their biota, it is proposed that these seas be considered as ecoregions of a special Ponto-Caspian province (Fig. 2).

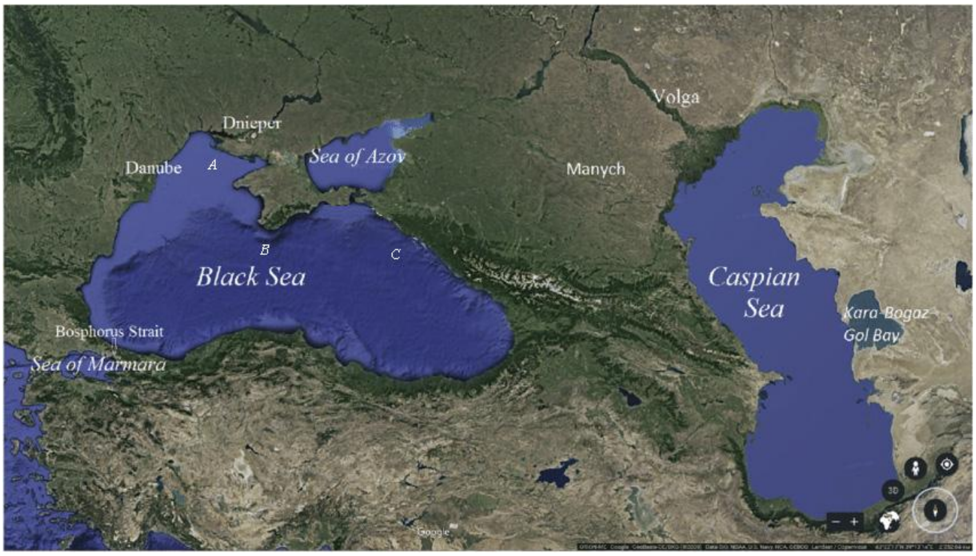

Fig. 3. Ecoregions of the Black and Caspian seas. Morphostructural counties of the north Black Sea: A - sea margins of the Northwestern platform, B - sea margins of the mountains in the southern coast of Crimea, C - Northeastern Black Sea morphostructural county.

4. BIONOMIC ZONING OF THE ECOREGION (CASE STUDY OF THE BLACK SEA)

In the northern part of the Black Sea, the following morphostructural counties were identified: A - sea margins of the Northwestern platform, B - sea margins of the mountains in the southern coast of Crimea, C - Northeastern Black Sea morphostructural county (see Fig. 2). There are two districts in the latter (Fig. 4): the first district from the Kerch Strait to the city of Anapa covers the transverse coasts of the southern margin of the Scythian Plate, the second one, from Anapa to the city of Novorossiysk, covers the longitudinal coasts of the Black Sea margin of the Caucasian Megaanticlinorium.

In the first district, there are two coastal zone landscapes (see Fig. 5, I). The first landscape (I-1) is formed on the continuation of transverse folds of the Taman Upland. In their place, a wide abrasion-accumulative terrace is formed on the submarine slope with rock and stone landforms (cystoseira biocenosis), with outcrops of bedrock clays (dactyl grouping), with shell fields (lancelet station) and sandy plains. The second landscape (I-2) corresponds to a low plain in place of a piedmont trough with Limans bordered by a sandbar. The submarine slope is accumulative with sandy plain landforms with a polychaetes grouping (Arenicola marina) and bivalve molluscs (Venus gallina, Spisula subtroncata, Divaricella divaricata) in the intermediate sublittoral; in the lower sublittoral, there are a bivalve grouping (Venus gallina, Meretrix rudis) and polychaetes (Nereis longissimi, Nephthys hombergi).

Fig. 4 - Bionomic zoning of the northeastern morphostructural county of the Black Sea. Districts: I - district of transverse coasts in the southern margin of the Scythian Plate, II - district of longitudinal coasts of the Black Sea margin in the Caucasian Megaanticlinorium. Landscapes: I-1 - the submarine slope of the Taman Upland, I-2 – the submarine slope of the sandbar. II-1 - longitudinal coasts with an active cliff, bordered by a belt of rocks.

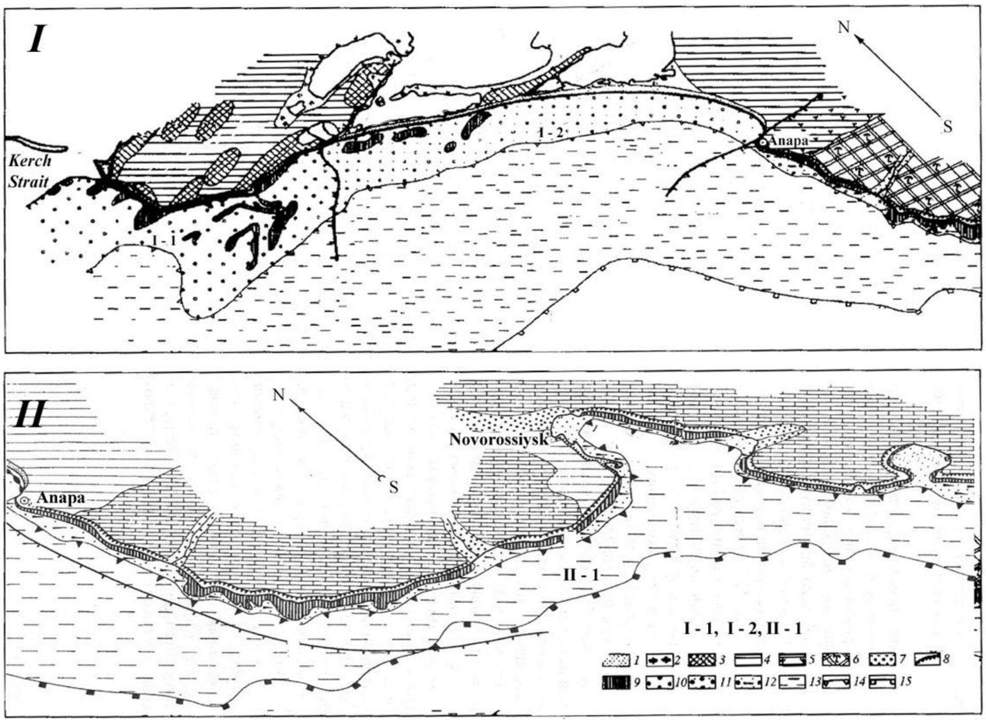

Fig. 5. Zoning of the Northeastern Black Sea morphostructural county: *I* - district of transverse coasts of the

southern margin of the Scythian Plate, I-1 - landscape of the submarine slope of the Taman Upland, I-2 - landscape of the submarine slope of the sandbar. *II* – district of longitudinal coasts in the Black Sea margin of the Caucasian Megaanticlinorium, II-1 - the landscape of longitudinal coasts with an active cliff bordered by a rocky belt.

Symbols: *1-8* – natural landforms of land: *1* – accumulative sand beaches with eolian forms of relief with psamophitos (Anapa sandbar): *2* – accumulative solonchak plains on liman coasts; *3* – hilly forms with steppe vegetation; *4* – agricultural lands on high Quaternary sea-shore terraces; *5* – high Quaternary marine terraces with groupings of xeromorphic shrubs and stunted trees (shibliak) partly with orchards and vineyards; 6 – mountain slopes (The Black Sea chain) with Mediterranean type of vegetation (shibliak, frigana, open juniper woodland); *7* – mountain river valleys with agricultural lands and settlements; *8* – active cliff; *9–12* – sublittoral underwater landforms: *9* – rocks and stones with cystoseira biocenosis; *10* – shell fields with lancelet station; *11* – sandy plains with bivalve molluscs biocenosis; *12* – sandy plains bordering the rock belt of the submarine slope of the Black Sea chain; *13* – elittoral lands, muddy and muddy-shell plains with biocenoses of mussel and phaseolin mud; *14* – the lower boundary of the sublittoral; *15* – the edge of the continental shelf.

The second district (Fig. 5, II), from Anapa to Novorossiysk, is represented by longitudinal coasts of the Caucasian Megaanticlinorium. The coasts with an active cliff are bordered by a belt of rocks descending to a depth of 25–30 m (sublittoral zone). The decrease in subaquatic illumination and the wave impact reduction allows subdividing the sublittoral into three floors (K.M. Petrov, 1967).

The upper floor from zero to a depth of 3 to 5 m is characterized by a depleted phytocenosis of the perennial *Cystoseira flaccida* kelp.

The intermediate floor at a depth of 3–5 to 10–15 m is occupied by lush seaweed cover of the perennial *Treptacantha (Cystoseira) barbata* brown alga, which specifies characteristic features of the Cystoseira biocenosis typical of the Black Sea. This biocoenosis consists of Mediterranean invaders, the first of which is the Cystoseira.

The upper step of the intermediate floor of the sublittoral at a depth of up to 6–7 m is occupied by the Treptacantha (Cystoseira) barbata–Cladostephus spongiosus f. verticillatus–Ellisolandia elongata (Corallina Mediterranea) with well-evolved epiphyte synusia. The lower step of the intermediate sublittoral at a depth of 6–7 to 10–11 m is occupied by the Treptacantha (Cystoseira) barbata–Phyllophora crispa–Gelidium spinosum community with depleted epiphyte synusia.

The Cystoseira biocenosis contains all typical lifeforms of the zoobenthos of rock and stone landform. A special grouping is associated with the Cystoseira crown: these are microperiphyton (diatomic unicellular algae, small crustaceans, small polychaetes, larvae of large crustaceans, molluscs and polychaetes), as well as epiphytic macrophytes and invertebrates (gastropods, polychaetes, bivalves, isopods, amphipods and decapods). The microperiphyton serves as the foundation on which the food chain of all animal species of the cystosyra community is based; its main part is highly productive diatoms. The formation of sessile zoobenthos occurs in the course of the competitive fighting for free rocky surfaces. At depths accessible to dense seaweed covers, zoobenthos is poorly developed; it occupies mainly on lower surfaces of overhanging boulders. As the depth increases, the density of seaweed covers decreases and sisile zoobenthos begin to play a dominant role on the surface of the stones. The lower level of the sublittoral at a depth of up to 25 - 30 m is occupied by a sparse community of the perennial Phyllophora crispa red algae. There, phytobenthos plays a subordinate role, and attached biological forms occupy the dominant position.

Let us determine the place of the identified landscapes in the global system of zoning the coastal and shelf areas of the World Ocean: Temperate North Atlantic realm - Ponto-Caspian province - Black Sea ecoregion - Northeastern morphostructural county - upper belt of the shelf - district of transverse coasts of the southern Scythian Plate margin: landscapes of the submarine slope of the Taman Upland and the submarine slope of the sandbar, lying in the nemoral zone; district of the longitudinal coasts of the Black Sea margin of the Caucasian Megaanticlinorium - the upper belt of the shelf - a landscape of longitudinal coasts with an active cliff, bordered by a belt of rocks, lying in the subtropical zone. Further study and zoning of the Black Sea Ecoregion is a task for the future.

The zoning of the coastal and shelf areas of the World Ocean implies the identification of higher taxa – realms, provinces, ecoregions (Spalding et al., 2007). Detailed regionalization ends with the identification of the main initial unit of zoning of underwater landscapes. It is proposed to establish the International Programme for Detailed Regionalization of Marine Ecoregions. The research materials can form the basis of a Database. Such a Database will make it possible to identify analogue landscapes – landscapes located in different ecoregions but having common properties.

5. ANALOGUE LANDSCAPES

Analogue landscapes in coastal and shelf areas of different marine ecoregions are formed on the same type of morphostructures, within the same vertical belt, in geographical zones with the same type of biologically active temperatures and salinity. These landscapes have a characteristic combination of underwater landforms and associated groupings of hydrobionte lifeforms. Underwater landforms of analogue landscapes are stations that can be used for the introduction of beneficial species or be biotopes favourable for the invasion of harmful species.

An example of introduction is the invasion in the mid-20th century of the polychaete Nereis diverse colour and the Abra ovata bivalve mollusc in sandy-silty landforms of the Caspian Sea from a similar area of the Sea of Azov. The introduction of these species led to the enrichment of the food resources for fish in the Caspian Sea.

An example of catastrophic invasions is the appearance of unwanted invaders in the Caspian, Black and Azov Seas. In the 1920s, the mollusc Mytilaster lineatus was accidentally introduced into the Caspian Sea. It was quickly propagated in the coastal zone of the Middle Caspian on rocky landforms, completely displacing two endemic native Dreissena elata and D. caspica species from this biotope. In the 80s of the 20th century, the Mnemiopsis leidyi comb jelly appeared in the epipelagic zone of the Black and Azov Seas; in the early 21st century, it ended up in the waters of the Northern Caspian. The food resources of the comb jelly are zooplankton, eggs and larvae of fish and benthic invertebrates. Actively propagating Mnemiopsis undermined the food resources for fish and limited the possibility of reproduction of many benthic invertebrates. As a result, fisheries decreased sharply. In the early 1990s, the Beroe ovata comb jelly, feeding on Mnemiopsis leidyi, also spontaneously appeared in the Black Sea. This invasion was positive, as the introduction of the Beroe ovata comb jelly led to a rapid decline in the population of Mnemiopsis.

Thus, the applied significance of the concept of analogue landscapes lies in the possibility of predicting the introduction of useful species and foreseeing the danger of invasion of harmful species.

CONCLUSIONS

1. Detailed regionalization of marine ecosystems is proposed to be carried out by identifying territorial units, which reflect

- Features of the geological and geomorphological structure: morphostructural counties, districts, landscapes;

- Changes in bionomic setting on the shelf with depth: belts - upper, intermediate and lower;

- The peculiarity of geographic zonality conditions on the ocean surface.

2. The underwater landscape is the main initial unit of zoning. Of particular interest is the identification of landscapes of the coastal zone (the upper belt of the shelf). They occur within a certain geographical zone, in the upper belt of the shelf, in one district and county.

3. Each landscape has features of morphological structure, which is revealed in the system of units of intralandscape vertical and horizontal differentiation.

4. Materials of the detailed regionalization of the coastal and shelf areas of marine ecoregions can be used to create a database that will allow identifying analogue landscapes. The applied significance of their identification consists in the possibility of predicting the introduction of beneficial species and foreseeing the danger of invasion of harmful species.

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