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INTEGRAL ASSESSMENT OF THE GEODYNAMIC CONDITIONS FOR THE FORMATION OF THE BLACK SEA BASIN AND CONNECTION WITH THE CURRENT REGIME OF GROUNDWATER IN ITS NORTHWESTERN SHELF

The paper has a multidisciplinary character connecting bathymetric, geophysical and geological information to innovatively reconstruct the geodynamic conditions of the Black Sea basin formation, their influence on the modern relief and groundwater regime within its northwestern shelf as a reference region. The major goal is the rationale of modern geodynamic settings for the Black Sea Basin against the background of the processes of its closure under tangential compression conditions, as well as their relationship with the hydrogeological conditions of the shelf zone.

As primary evidence, the author determined the spatial positions of the Constanta-Sinop and Sub-Pontian Suture Zones, pinpointing absorption locations of the Earth's crust at subduction zones. The facts and arguments presented in this paper are well integrated into the scheme of the oncoming of the Pontides island arc to the Eurasian Plate and the gradual closure of the back-arc marginal Black Sea Basin with a crust of transitional-type crust.

The specific feature of the study is an innovative approach to comprehensive analysis of data that are a result of geological and geophysical works within the Black Sea water area. In doing so, major attention is paid to the spatial morphostructural analysis and interpretation of newly integrated digital data array, as a result of bathymetric surveys, namely the EMODnet 2019—2022. The subject of analysis is the basic structural surfaces, including the Modern and on its margin consolidated basement.

New justification is formulated on the confinement of gas seeps and mud volcanoes, within the Black Sea Basin, to the deep earth's crust structures. The graphical correlation of the mentioned ones is performed as well as their spatial position in the structural-geodynamic model of the region is theoretically substantiated.

A generalized geomorphological zoning of the northwestern shelf of the Black Sea with the identification of the Dobrogea, Odesa and Kalamit zone is proposed. Within the Odesa geomorphological region, an integrated geological and geomorphological analysis was carried out and, as a result, dividing the shelf into submarine groundwater discharge (SGD) zone of aquifer was substantiated.

The study, carried out by the author is of crucial importance to understanding the tectonic and geodynamic characteristics of the Black Sea Basin as well as for forecasting SGD zones and fresh ground-

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water resources. It is recommended to set targeted prospecting works to assess fresh groundwater resources in order to meet the water needs of coastal communities.

Keywords: *Black Sea Basin, bathymetry, the Eastern Black Sea Basin, gas-mud volcanic structures, the Western Black Sea Basin, suture zone, Constanta-Sinop Suture Zone, northwestern sea shelf, submarine groundwater discharging (SGD).*

Introduction

The purpose of this publication is a comprehensive analysis of the data which are a result of geological and geophysical works within the Black Sea water area. The reason that prompted the author to contribute to numerous hypotheses about the current and historical geodynamic settings of the region is the publication of an updated 2019—2022 digital integrated bathymetry data array, on the EMODnet portal [6]. This is an excellent addition to the previously analyzed data namely seismic, gravity, magnetic, and Earth Remote Sensing (ERS).

The subject of analysis is the basic structural surfaces, including the modern one (the bottom of the Black Sea) and the Kimmeridgian consolidated basement. The morphology of the latter in the context of new data makes it possible to identify additional structural elements and refine the already known ones. This is important for understanding the features of tectonic and geodynamic conditions of the Black Sea Basin and for formulating new search criteria in relation to hydrocarbons as well.

Additional information that contributes to the development and refinement of previously established factors makes it possible to obtain new ideas about the confinement of gas seeps and mud volcanoes to deep structures that play the role of discharge channels during mantle degassing. Such structures, first of all, are suture zones, as traces of the Earth's crust plunging into subduction zones, including the A-type, which is characteristic of the collision of terranes with continental crust. Terranes in the classical sense are formations containing fragments of the crust formed in one tectonic plate and attached to the crust of another plate during their collision.

Assumptions, although it sounds paradoxical, are confirmed in obedience to the results of seismic profiling [7] and on the profiles of the complex effective parameter (CEP), calculated for the Odessa Segment of the North-Western Shelf. According to the mentioned geophysical data, the plunging footprint of the Constanta-Sinop Suture Zone under the Crimean Mountains orogen and further under the Scythian Epiorogenic Zone is clearly recognized [11]. It is noteworthy, that in this case the spatial depth of the lower boundary of the subcontinental lithosphere, close to the coast of the Crimean Peninsula, reaches 200 km.

It is not our task to critically analyze geophysical materials. They are perceived as an objective reality. Therefore, we will focus on the morphological features of the major structural surfaces of the Black Sea Basin. The existing tectonic range of the consolidated basement of the region is not also revised in this publication [10, 17]. To the best of our ability and the available new data, we consider only the nature of the articulation of individual structural elements and the geodynamic conditions of their formation. The modern topography of the Black Sea bottom according to EMODnet data [6] clearly reflects the structure of the basin, which was formed during the Alpine-Himalayan Epoch of tectogenesis. The modern structure of the Black Sea Basin has inherited only certain features of the Kimmeridgian Basement and is distinguished by a significant restructuring that is characteristic of the entire Alpine-Himalayan Fold Belt.

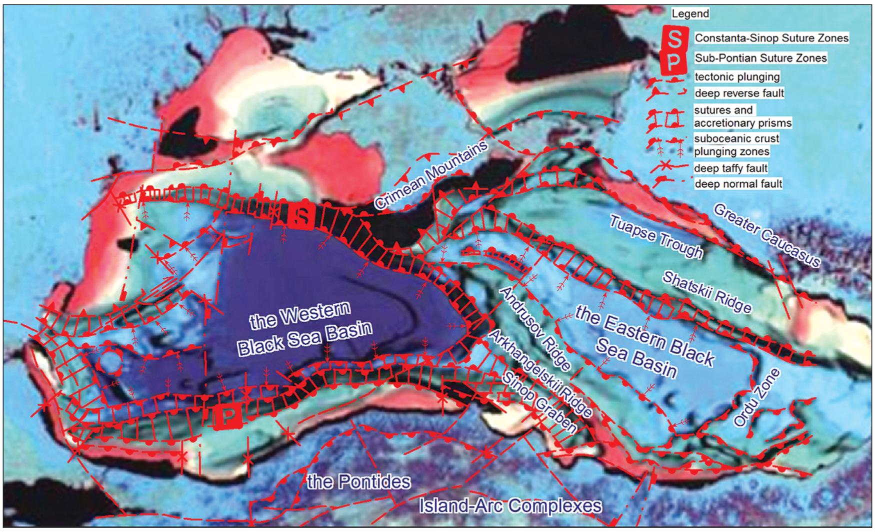

Fig. 1. Structural-tectonic scheme of the Black Sea Basin on the scale of 1 : 7,000,000, based on the Robinson model of 1996

Analysis of modern and consolidated Kimmeridgian structural surfaces of the Black Sea Basin. Let's look at the major morphological features of the structural floor surfaces of the Black Sea Basin, previously unknown, and unidentified. Only in extreme cases tracing their connection with the structural elements of onshore. Under the major surfaces of the structural floors, we mean, firstly, the contact of the basement and the sedimentary cover, and secondly, the modern topography of the Black Sea bottom.

The consolidated Kimmeridgian Basement of the Black Sea Basin is probably composed of metamorphosed formations. Its structure was formed at the end of the Kimmeridgian Epoch of tectogenesis. This is the conclusion reached by most researchers in the region. This is not related only to the northern shelf, where, within the Scythian epiorogenic zone, it is clearly Hercynian in age. The structure of the basement is shown in Fig. 1. The basis of the scheme shown in Fig. 1 is borrowed from [2, 10, 15—17] and supplemented by us with structural elements taking place at the boundaries of microplates (terranes).

In our opinion, sutures play a special role in the structure of the basement of the Black Sea Basin. The basis for their substantiation was the assumption that the correlation loss zones, in geophysical data, correspond to zones of tectonic mélange in the structural-tectonic sense. Their zones are often lenticular-layered, which is typical for accretionary prisms. It is the sutures fixing the locations of crustal plunging in subduction zones.

A special role in the deep construction of the Black Sea Basin is played by two suture zones shown in Fig. 1, closing the Western Black Sea Basin, with oceanic crust, on the north and south. The northern suture zone along the Constanta-Sinop line determines the structural heterogeneity of the entire Black Sea Basin. To the north and northeast of it, the basement rocks experienced tangential compression with the formation of ramparts and uplifts separated by depressions of graben genesis.

These processes were accompanied by the closure of the Eastern Black Sea Basin, the formation of a transitional-type crust (from suboceanic to subcontinental) within it, and subduction phenomena under the structures of the Crimean Mountains and the Greater Caucasus. By the end of the Kimmeridgian Epoch of tectogenesis, the structures of the east of the Black Sea Basin were probably soldered into a single tectonic plate with a transitional-type crust.

From the south, the Western Black Sea Depression is closed by the Sub-Pontian Suture Zone, which separates this depression and the Pontides Island-Arc Complexes. In fact, these structures should be considered as rearward islands-arc with respect to the Sub-Pontian Suture Zone, with the Pontides Island-Arc Complexes rolling over the Black Sea basin and the simultaneous subduction of the oceanic crust of the Western Black Sea Basin under the island arc. By this kind of dynamics is assumed the existence of an extension regime above the mantle plumes in the basin itself, in accordance with the ideas of V. Kobolev [10] and earlier ideas of A. Chekunov [5]. Both Sub-Pontian and Constanta-Sinop branches of the sutures close within the Sinop Graben, which is cut off from the south by the thrust structures of the Pontides. In the west outside, the Constanta-Sinop Suture is shifted along a transform fault. This is the sinistral strike-slip fault with a significant displacement amplitude (170 km). The transform fault fades in the Pontian Suture Zone and is not traced further in the Central Pontides. Its northwestern continuation is probably the Pechenyaga-Kamenna Deep Fault by I. Mokryak [13] which positions this fault as the limit of the Eastern European Platform. In the opinion of this paper's author, the Northern Dobrogea is a one-sided orogen delimiting the Western and Eastern European Platforms, and the Mechin and Tulcha zones are conjugate components of a tectonic flow overhanging the foreland of the Eastern European Platform in the A-subduction zone. In major, these structures, together with the mentioned transform fault and the Rava-Russian Zone, fit perfectly into the Trans-European Suture Zone (TESZ), also known as the Teisseire Tornquist Zone or the Danish-Polish Groove separating the platforms mentioned above [9].

Subduction processes are also fixed on the flank of the Eastern Black Sea Depression. In the southwestern direction, the suboceanic crust of the basin plunges under the Andrusov Ridge (without the formation of a suture), and in the northeast, through a pronounced suture, under the Shatsky ridge. The latter, through the Tuapse Trough, plunges under the orogen of the Greater Caucasus. Judging by the results of three-dimensional modeling [2], already in the Oligocene (Pont-Maikop), in the Tuapse Trough, a system of layered underthrusts of the Maikop Formation under the Greater Caucasus is observed. In the northeastern part of the Tuapse Trough, in the Oligocene, an accretionary prisms type structure was formed, which is traced westward along the entire Crimean Mountains and further, eventually merging with the Constanta-Sinop Suture Zone. Judging by the fact that in the frontal part of this suture a Holocene Seismic Focal Zone was observed, steeply plunging under the Crimean Mountains and the Greater Caucasus, subduction processes continue here up to the current moment. The East Black Sea Plate formed in Kimmeridgian Epoch of tectogenesis, which includes the Arkhangelskii Ridge, Andrusov Ridge, Shatskii, East Black Sea, and Tuapse Depressions/Troughs, plunges under the orogens of the Crimean Mountains and the Greater Caucasus, forming the A-subduction zone.

The modern surface of the Black Sea bottom is shown in Fig. 2. The bottom topography map was built using modern tools of geoinformation systems (GIS), which ensure the performance of a spatial analysis of bathymetric information with parameters that

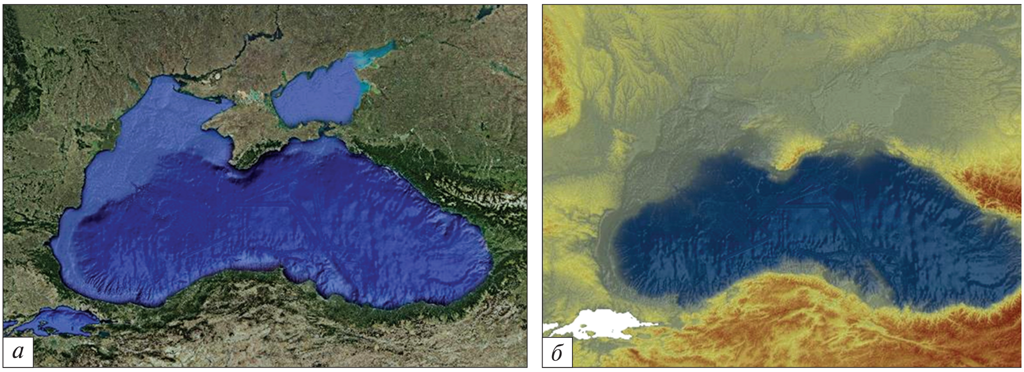

Fig. 2. Modern topography of the Black Sea bottom and adjacent onshore (out of scale), spatial model by S. Klochkov, joint with Landsat ETM$^+$ (*a*) and SRTM4 (*b*) data

are optimal for visual perception. As input, digital integrated data of bathymetric surveys, published on the EMODnet portal 2019—2022, were involved [6].

The result of the spatial analysis of the integrated data of bathymetric surveys of the Black Sea made it possible, with a high degree of probability, to identify the features of the latter-day geodynamics within the same name basin and to find explanations, by interpreting the bathymetric data, for the features of the underwater relief. Its morphology is a consequence of a series of tectonic processes that took place during the Alpine-Himalayan Epoch of tectogenesis.

Tectonic activity in the region remains at a high level at the present time, as evidenced by a fairly high seismic activity. But, in our opinion, there is a tendency for its attenuation. This is evidenced by a comparative analysis of the structural plan of the cretaceous basement relief and the modern underwater relief. The latter is characterized by a significant simplification in comparison with the former, but at the same time by the manifestation of new morphological features that were not previously present, shedding light on the tectonic processes of the past and present. We are talking about the processes that left a footprint, firstly, in the sedimentary cover, overlying the cretaceous basement of the Black Sea bottom.

Following major yarn, the structural interpretation of the morphological features of the modern bottom topography appears very reasonable. Note that the obvious heterogeneities of the bottom surface are explained quite satisfactorily by its location within the Alpine-Himalayan Fold Belt.

First of all, steals attention cross-section of the sea bottom, which has a pronounced asymmetry. If in the north, in the west, and in the east observed a wide shelf zone (up to 200 km), with the exception of the southern coastal zone of the Crimea and the western coastal zone of the Caucasus, then in the Black Sea south the nature of the onshore-offshore transition is completely different. Here, the shelf is practically absent, and the coastal zone directly passes into the continental slope, indented by deep gullies and having a clearly defined foot at the transition to the abyssal.

The maximum depths of the Black Sea bottom are observed along the northern continental slope. Fig. 3 shows the axial line of the abyssal zone, oriented along the northern continental slope. The deep-water trench is fragmentarily reduced to varying degrees, but the seabed has a clear tendency to immersion precisely to this line along its entire strike. Along the axial line, there is a clear convergence of northern and southern canyon-like incisions, most often oriented submeridionally, and probably formed by turbidity flows. This is a clear visualization of the subsidence of the marine bed basement complexes under the Crimean-Caucasian active continental margin as a result of subduction processes.

Some authors [10] have an opinion that the Western Black Sea Basin tends to further expand. At the same time, the presented facts allow us to confidently state that, as a short-term episode, it (the tendency to expand) took place in the Kimmeridgian Epoch of tectogenesis, but at the Alpine-Himalayan stage, this regime is clearly replaced by the contraction of the Western Black Sea Basin, its closure.

The bottom morphology of the Western Black Sea Basin, the deepest part of the Black Sea water area, is also of undoubted interest. Here, according to bathymetry data, the contours of circular structures up to 240 km in diameter are clearly identified. In our opinion, they correspond to collapse paleo-calderas. It is possible that structures of this kind arose over cooling mantle diapirs or plumes. In this case, the idea of individual authors about the formation of the Western Black Sea Basin in the zone of secondary extension above the mantle plumes seems quite viable. To some extent, this explains the striking difference between Western Black Sea Basin and the Eastern Black Sea Basin. If in the basement of the Western Black Sea Basin, according to seismic data, an oceanic crust was identified, then the Eastern Black Sea Basin was formed by transitional-type crust.

The mentioned structural and morphological features of the major lateral surfaces and considerations of the features of geodynamic processes are very indicative. They are most typical for the Okhotsk Sea type of the back-arc basins with a transitional-type crust.

Geomorphological zoning of the northwestern sea shelf. Taking into account the fact that the northwestern part of the Black Sea, in the classical sense, is considered to be the shallow shelf part of the Black Sea, bounded by capes Tarkhankut in the east and Kaliakra in the southwest [23], it is the conditional line that unites these two capes that is taken as

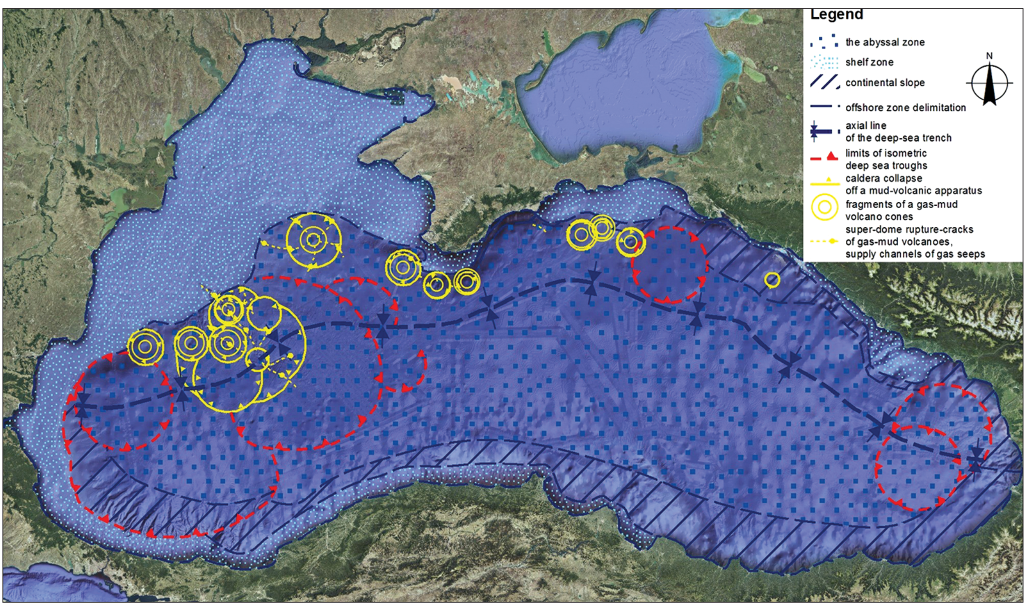

Fig. 3. Structural-geomorphological scheme of the Black Sea Basin to scale 1 : 7 000 000, base — EMODnet data, integrated with Landsat ETM$^+$ (spatial model by S. Klochkov)

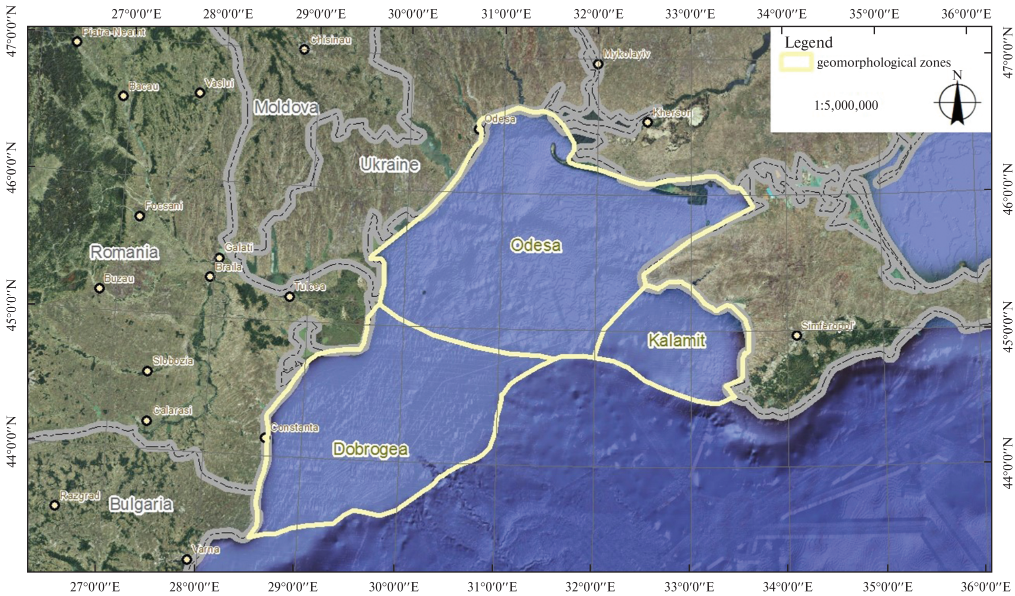

Fig. 4. Geomorphological zoning of the northwestern shelf based on bathymetry data (spatial model by S. Klochkov)

the basis for the areal boundaries. At the same time, a spatial morphostructural analysis and interpretation of new integrated digital data from bathymetric surveys was carried out. EMODnet 2019—2022 data [6] made it possible to perform geomorphological zoning of the sea shelf, which is the basis for substantiating the differentiation of SGD zones in the future (Fig. 4). Within the limits of the sea shelf, three zones are generally proposed, which separate three contrasting background hypsometric levels of the bottom surface: Dobrogea/West (–70 m), Odesa/Nord (–30 m) and Kalamit/East (–110 м).

The rationale for the proposed geomorphological zoning is an integrated assessment of the spatial geometry of the modern sea shelf relief, including the altitudinal position of subhorizontal surfaces, gradients and extrema of the slope parts. The main characteristics of the spatial geometry of the proposed areas are shown in Tab.

As follows from Tab. 1, the key characteristic basing the proposed zoning is the hypsometric level of the sea shelf. For the Dobrogea zone, its average value is –70 m, for Odesa –30 m, for Kalamit –110 m. It should also be noted the spatial connection of geomorphological regions with known tectonic structures on the onshore. The Dobrogea zone has tended to continue the Predobrogea trough and Upper-Prut ledge, the Odesa region is actually located in the continuation of the South-Ukrainian monocline up to the sea shelf area, the Kalamit region is controlled by the continuation of the

Key characteristics of the spatial geometry for geomorphological zones

Name	Limit length, km	Area, sq. km	Shoreline length, km	Hypsometric levels, m
Dobrogea	850	25,100	240	–70
Odesa	385	34,800	570	–30
Kalamit	720	8,350	185	–110

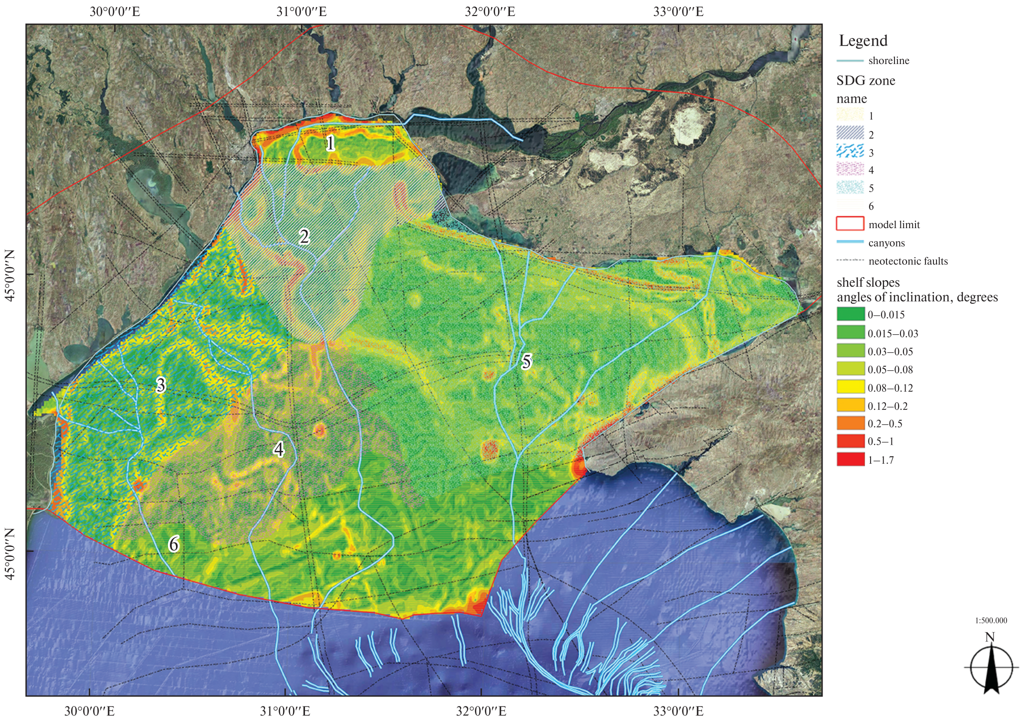

Fig. 5. Zoning by type of submarine unloading (spatial model by S. Klochkov)

Scythian Plate (epiogenetic zone) up to the sea shelf area. If perform correlate the proposed scheme of geomorphological zoning and structural-tectonic, we can trace a stable connection between the boundaries of geomorphological regions and key fault zones, including deep reverse faults and sutures, majorly the Constanta-Sinop suture zone mentioned above. This proves the heredity of the neotectonic conditions for the region, which form the modern topography of the bottom surface.

Features of the SGD. The close relationship between the geodynamic conditions for the formation of the Black Sea basin in general and its sea shelf zone in particular with the neotectonic regime has a decisive influence on the formation of SGD zones.

Modeling results for most of the world's sea shelf groundwater systems suggest that most of nowadays submarine resources were deposited through topographically driven flow during historical low sea levels over the past millennia. Volumetric estimates of shelf groundwater resources can be significantly revised if the factors of aquifer SGD are taken into account. That is why an important component of the forecast is the zoning of the coastal part in accordance with the type and conditions of SGD.

For this purpose, it is proposed to zoning by types of SGD based on key factors influencing the formation of this process, namely:

i. gradient zones of the modern bottom surface,

ii. composition of bottom sediments,

iii. zones of neotectonic faults,

iv. submarine canyons.

An integral assessment of the listed factors allows to perform the appropriate zoning. To substantiate the zones, an integrated multifactorial model proposed (Fig. 5). The sources are historical geological information [8], bathymetric data [6] and Remote Sensing Data [14].

Thus, within the northwestern shelf of the Black Sea, as a reference object, it is proposed to identify 6 regions, each of which has unique conditions for SGD of groundwater horizons, the main characteristics of which are given below:

1) Sandy bottom, intensive water exchange of fresh water betwixt the Dnieper and aquifers.

2) Silt, an area of intense SGD, due to the fresh water of the Dnieper, a slight mineralization is expected.

3) Coquina, separate zones of SGD are associated with bottom gradients and areas of sandy deposits.

4) Coquina, stable areas with fragmentary SGD along canyons, submeridional faults and in places of increased bottom surface gradients.

5) The alternation of areas of coquina and muddy bottom, in equal proportions, with areas of sandy bottom, it is assumed that intensive SGD of a chaotic nature within 50% of the area.

6) Silt, an area of intense SGD near the edge of the shelf with significant salinization (mineralization) of groundwater. This is demonstrated by the example of the Black Sea basin as a whole and its northwestern shelf.

Conclusions and recommendations

The facts and assumptions presented in this paper clearly demonstrate the capabilities of modern tools for the spatial interpretation of digital depth data presented in the form of a continuous matrix of elevations of the bottom for water areas. This information is available through modern services for providing knowledge using web portals. Digitally integrated bathymetric data is a relevant tool for analyzing the modern geodynamic conditions of marine and oceanic areas, in addition to seismic data and directly geological information. This narrative is demonstrated by the example of the Black Sea Basin in general and its northwestern shelf.

Author's structural analysis made it possible to show that nowadays geodynamic processes are reflected some extent in the morphology of the lateral surfaces. Therefore, the use of structural-morphological analysis in tectonic reconstructions is promising.

Geomorphological zoning of the northwestern sea shelf is proposed as the basis for forecasting zones of SGD. A spatial connection of geomorphological regions with known tectonic land structures has been established. The correlation of the proposed geomorphological zoning and the structural-tectonic scheme is carried out, demonstrating a stable relationship between the boundaries of geomorphological regions and key fault zones, including deep reverse faults and sutures, primarily the Constanta-Sinop suture zone. The hereditary nature of the neotectonic conditions of the region, which form the modern relief of the bottom surface, is proven.

Within the limits of the reference object — the northwestern shelf of the Black Sea, the principle of the integral assessment of the SGD is demonstrated. As a result, it is proposed to allocate 6 regions, each of which has unique conditions for the SGD within the reference object.

The facts and arguments presented in this paper are well integrated into the scheme of convergence of the Pontides Island Arcs and the Eurasian Plate with the gradual closure of the back-arc marginal Black Sea Basin with a transitional-type crust. The accompanying subduction of the oceanic and suboceanic crust of the Black Sea Basin under the Scythian Epiorogenic Zone led to the emergence, on its margin, the orogens namely the Crimean Mountains and the Greater Caucasus, during the Kimmeridgian and Alpine-Himalayan Epochs of tectogenesis.

The geological and geomorphological analysis presented in the article confirms the high prospects of multivariate modelling in assessing groundwater resources in the sea shelf zone and, as a result, overcoming the shortage of fresh water for coastal communities.

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ІНТЕГРАЛЬНА ОЦІНКА ГЕОДИНАМІЧНИХ УМОВ ФОРМУВАННЯ БАСЕЙНУ ЧОРНОГО МОРЯ ТА ЗВ'ЯЗОК ІЗ СУЧАСНИМ РЕЖИМОМ ПІДЗЕМНИХ ВОД ПІВНІЧНО-ЗАХІДНОГО ШЕЛЬФУ

Стаття має міждисциплінарний характер, поєднує батиметричну, геофізичну та геологічну інформацію для реконструкції геодинамічних умов формування басейну Чорного моря, їх впливу на сучасний рельєф та режим підземних вод у межах його північно-західного шельфу як еталонного регіону. Основна мета — обґрунтування сучасних геодинамічних обстановок Чорноморського басейну на тлі процесів закриття його в умовах тангенціального стиснення, а також їх зв’язок із гідрогеологічними умовами шельфової зони.

Як ключовий доказ розглядаються просторові позиції Констанца-Синопської та Припонтійської сутурних зон, що фіксують локації поглинання земної кори у зонах субдукції. Викладені у цій статті факти та аргументи добре інтегруються у схему зближення Понтійської острівної дуги з Євразійською плитою та поступовим закриттям задугового крайового Чорноморського басейну з корою змішаного типу.

Специфічною особливістю дослідження є інноваційний підхід до комплексного аналізу даних геолого-геофізичних робіт у межах акваторії Чорного моря. При цьому головну увагу приділено просторово-морфоструктурному аналізу та інтерпретації нових цифрових інтегрованих даних батиметричних зйомок EMODnet 2019 2022 рр. Предметом аналізу є базові структурні поверхні: сучасна та кіммерійського консолідованого фундаменту.

Сформульовано нові обґрунтування приуроченості газових сипів та грязьових вулканів Чорноморського басейну до глибинних структур земної кори. Виконано графічну кореляцію останніх, а також теоретично обґрунтовано їх просторову позицію у структурно-геодинамічній моделі регіону.

Запропоновано генералізоване геоморфологічне районування північно-західного шельфу Чорного моря з локалізацією Добруджинського, Одеського та Каламітського районів. В межах Одеського геоморфологічного району виконано комплексний геолого-геоморфологічний аналіз і, як наслідок, обґрунтовано диференціацію шельфової зони на райони з різним типом субмаринного розвантаження горизонтів підземних вод.

Проведене дослідження має важливе значення для осмислення особливостей тектоніки та геодинаміки Чорноморського басейну, а також для прогнозу зон субмаринного розвантаження та ресурсів прісних підземних вод.

Рекомендовано постановку цільових пошукових робіт для оцінки ресурсів прісних підземних вод з метою забезпечення потреб у воді прибережних громад.

Ключові слова: *басейн Чорного моря, батиметрія, Східно-Чорноморський басейн, газово-грязеві вулканічні споруди, Західно-Чорноморський басейн, острівні комплекси Понтид, Констанца-Синопська сутурна зона, північно-західний шельф, субмаринне розвантаження.*