УДК 550.8.012 DOI: https://doi.org/10.24028/gj.v45i1.275178

Contrasting lithospheric geophysical structure of the Black Sea subbasins: Relevance to testing geotectonic models for this mega depression

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Received 28 November 2022

We present an integrated analysis of the geophysical parameters of the lithosphere of Black Sea basin obtained as a result of the interpretation of magnetic, gravity, thermal, deep seismic sounding and seismic-tomographic data. It first demonstrates inherent significant differences in geophysical parameters of lithosphere in the Western and Eastern Black Sea subbasins existing from the prerift stage. The set of reviewed parameters responsible for formation of the present-day lithosphere includes types of crust, depths to acoustic basement, configuration of subbasins, depths to Moho, heat flow and relief of the thermal-asthenosphere boundary (LAB), trends of main deep faults of the crystalline crust, their kinematic types, occurring linear magnetic anomalies, velocity pattern of subcrustal mantle. The above-mentioned parameters of the lithosphere are indicators of the age, geodynamics and driving mechanisms for opening of a subbasins. Oblique trends of the subbasins and the topography of Moho discontinuity in the west and east domains, oblique striking of pre-rifting Istanbul zone and the Shatsky Ridge and different trends of deep faults in the crystalline crust suggest distinct lithospheric structure existing from pre-opening of the Black Sea subbasins and different geodynamical conditions of its formation. The Odesa-Sinop-Ordu deep fault zone as a direct continuation of the Golovanivskaya suture zone of the Ukrainian shield and its slope, probably is of the Precambrian age. So it could be the tectonic boundary between two segments of pre-rift continental crust and between future subbasins. The examples illustrate how indicated parameters of the lithosphere can geophysically confirm the basic ideas of available models for geodynamics of the Black Sea.

Key words: Black Sea, subbasins, lithosphere parameters, rifting, crustal types, crystalline crust faults, tectonic evolution.

Introduction. The Black Sea basin, consisting of the western and eastern subbasins, has a multiphase history of development. Despite almost a century of study of the Black Sea Basin (BSB) and numerous publications, the cardinal problems of geology, tectonics, and the deep structure of the lithosphere still remain debatable. Two of the key problems, according to [Stovba et al., 2020] are «… a) triggering and driving mechanisms of the formation of the main tectonic units and b) the timing, duration and geological consequences of tectonic events that have taken place in the Black Sea region since the Cretaceous».

In solving these problems, data on the thickness of the crust from the lithosphere as a whole provide valuable information. Currently, most researchers recognize the formation of BSB on the continental crust of the Eurasian Plate as a result of rifting [Zonenshain, Le Pichon, 1986; Finetti et al., 1988; Nikishin et al., 2015; Stephenson, Stovba, 2022, etc.], extension, thinning of the Earth's crust and lithosphere with the formation of a new. At the same time, three stages of crustal evolution are distinguished: rift, post-rift (thermal), and post-rift with periodic inversion deformations [Stovba et al., 2020]. The degree of crustal extension is determined by the ratio of the thickness of the original crust to the thickness of the stretched one. Under the conditions of deep-water basins, the only source of data for such an assessment is the Moho relief and the thickness of the crystalline crust. The type of crust or its basicity can be predicted from the results of 3D gravity modeling, taking into account velocity models [Makarenko et al., 2021]. As an oceanic type of crust, a consolidated crust is considered, consisting entirely of a conventionally identified basalt layer. The crust, consisting of basalt and diorite layers, can be classified as high stretching or suboceanic.

The age of formation of subbasins is also actively debated. In addition to direct determinations of the age of sedimentary deposits and seismostratigraphic data of their deep-water parts (see, for example [Stovba et al., 2020] and many others), their relative age can be characterized by general strikes of the main tectonic elements [Starostenko et al., 2004, 2010, 2015; Rusakov, Pashkevich, 2017] (oblique strike of the axes of the subbasins and structures of the Moho relief, the direction of the main deep faults).

The mechanism of subbasins formation is also discussed in numerous publications. The origin of the Black Sea basin is currently associated with the extension of the continental lithosphere and active rifting in a back-arc setting, deep faults in the consolidated crust should be taken into account as «driving» the movements of terranes.

The role of deep faults in this case is evaluated only with an integrated approach to their tracing, evaluation of depth, kinematics, and activation in various tectonic phases. This goal can be achieved if there is a scheme of faults of the consolidated crust and their classification within the entire Black Sea basin [Rusakov, Pashkevich, 2017].

Models of simultaneous, as well as two-stage, opening of subbasins leave the issue of their division debatable. As such, the Mid Black Sea High (MBSH) is traditionally accepted. It includes the Andrusov and Arkhangelsky ridges and the fault of the Mid-Black Sea ridge. As shown by [Chekunov, 1987; Kravchenko et al., 2003; Starostenko et al., 2015; Rusakov, Pashkevich, 2017], the Black Sea basin is divided into the Western and Eastern subbasins by the Trans-Black Sea Odesa-Sinop-Ordu (OSO) zone of deep long-lived strike-slip faults. Subbasins have different configurations, depths, oblique orientation of the axes, and radically differ in the structure of the lithosphere [Starostenko et al., 2010; Yegorova, Gobarenko, 2010]. We analyzed the lithosphere parameters and first revealed their inherent contrasting structure existing from the pre-rift stage.

The most of papers concerning tectonics of the Black Sea describe models briefly, without details of how they are supported by modern sets of deep geophysical observations. This give not a complete picture of the state of geotectonic modeling of Black Sea Basin. We analyzed some sample of papers with a view to the degree of their geophysical support.

The aim of this work is to analyze the data on the parameters of the modern BSB lithosphere obtained by us [Starostenko et al., 2015] and other researchers [Nikishin et al., 2015; Tsvetkova et al., 2017; Makarenko et al., 2021] in terms of their use as indicators of age and driving mechanisms of subbasin opening.

Given the ambiguity of the interpretation of geophysical and even geological data, the authors of the article do not claim to create a non-alternative model for the opening of the Black Sea subbasins. However, using the examples of some geodynamic models, we would like to emphasize the basic parameters of the lithosphere, which must be taken into account in any model representations.

Results. ***Analysis of geodynamic models of the Black Sea and the degree of their correspondence to the geophysical parameters of the lithosphere.*** Analyzed articles related to geodynamic models were ranked on order of frequency citations using Parish 7 Software analyzed information from the most comprehensive and the most accessible Google Scholar database. Ten years after publishing a papers is the most productive for citations. That is why to be sure that relevant information is now available we reviewed only those papers that appeared by 2010. Table 1 presents rank of papers described the geodynamic models for the Black Sea according to their total and average annual citations in the literature.

Table 1. Geotectonic models for Black Sea, created on 2010. Estimation of citations on July 1, 2022

Authors	Citations/ Year	Citations
Golonka, 2004	49.06	883
Zonenshain, Le Pichon, 1986	14.86	520
Nikishin et al., 2003	15.9	286
Okay et al., 1994	14.0	544
Meijers et al., 2010b	9.27	102
Shillington et al., 2008	9.25	111
Finetti et al., 1988	7.81	250
Stephenson, Schellart, 2010	7.45	82
Cloetingh et al., 2003	6.5	117
Yegorova, Gobarenko, 2010	6.27	69
Spadini et al., 1996	6.2	135
Robinson et al., 1995	5.15	139
Meredith, Egan, 2002	2.45	71
Banks, Robinson, 1997	0.89	31
Chekunov, 1987	0.59	18
Okay, Görür, 2000	0.58	10
Saribudak, 1989	0.3	7
Kobolev, 2003	0.11	2

As can be seen from the table, the geodynamic models proposed by the authors back in the 80s—90s of the last century are still popular today.

Let us consider what parameters of the lithosphere were not taken into account when substantiating the models described in these works.

Golonka J. [2004] considering the opening of the Western subbasin as a result of rifting, and the Eastern subbasin as a result of the northern movement of the Shatsky terrane, the author does not indicate which faults are involved in this process. Any transform faults in the West Black Sea restorations were not depicted.

The opening model of the Western Black Sea basin (WBSB) by *Okay A.I. et al. [1994]* employs the hypothetical West Crimea (WCrF) and West Black Sea (WBSF) faults along which the Istanbul terrane moved to the Pontides. If these tectonic disturbances would really have existed as supposed by [Okay et al., 1994], their oblique striking does not allow classify them as strike-slip faults for moving terranes [Molnar, 2015]. Moreover, according to seismic data, these faults are recorded only in the sedimentary cover and the uppermost part of the consolidated crust. For the opening of the Eastern Black Sea basin (EBSB), the authors propose a counterclockwise rotation mechanism for the eastern segment of the continental crust.

Zonenshain L.P. and Le Pichon X. [1986] based on seismic observations and subsidence history concluded that the deep parts of the Black and Caspian basins have an oceanic crust. However, deep penetration regional seismic data from the international project Geology without limits revealed the areas of highly rifted continental crust within these domains in the deep Black Sea basins. According to 3D gravity modeling data [Makarenko et al., 2021], this type of crust can be developed only in separate blocks in the Western subbasin and is much more widespread in the Eastern one. Here it covers almost the entire subbasin.

Nikishin A.M. et al. [2003] argue that both Western and Eastern Black Sea basins opened almost simultaneously during Cenomanian to Coniacian times. The authors assumed specially for the model of BSB opening the interregional dextral slip-strike West Black Sea deep fault to enable large scale movement along it. As shown by [Starostenko et al., 2015], this fault, if it exists, cannot be accepted as a «driving» when moving to the southeast of the continental terrane.

Finetti I. et al. [1988] were the first to utilize a large amount of seismic information obtained by the geophysicists of Italy, of former Soviet Union and Bulgaria for developing comprehensive geotectonic model for the Black Sea region. The model supposes the opening of the Black Sea as the back-arc basin behind the Western and Eastern Pontides. However, the model accepted that the hypothetical regional WCrF transcurrent fault played important role in moving terranes, which, as mentioned above, is wrong.

Meijers M.J. [2010b] reported Jurassic–Cretaceous low paleolatitudes of circum-Black Sea region (Crimea and Pontides) due to True Polar Wander. Çinku et al. [2013] considered this inference is a result of using remagnetized rocks.

Robinson A.G. et al. [1995] declare that the West Black Sea was opened by breaking the West and Central Pontides in the Middle Barremian and by terranes moving along assumed major meridional strike-slip faults. Such a meridional strike-slip in the present-day crystalline crust has not been found in the complex of geophysical data [Starostenko et al., 2015]. In addition, as a continuation of the fault in the Western and Central Pontides, it should cross the Western subbasin in the central part. Our comprehensive studies on the fault tectonics of the crystalline crust [Rusakov, Pashkevich, 2017] showed that such a meridional strike-slip does not manifest itself either in potential fields or in the 3D density model of the crystalline crust [Makarenko et al., 2021].

Spadini G. et al. [1996] put forward an innovative idea that pre-rift contrast lithospheric structure controls Black Sea formation. At the same time, there is more strong lithosphere in BSB. This notion is the only one which is in line with the relief pattern of Moho discontinuity [Starostenko et al., 2004]. The axes of the Moho uplifts of the Western and Eastern subbasins are at an angle of 115° (are strong oblique). The strike of the axis of the Moho uplift of the Western subbasin is consistent with the strike of the Istanbul terrane according to the pre-rift reconstruction [Nikishin et al., 2015]. It follows that contrasting structure of the lithosphere in Black Sea is inherited from the pre-rift stage. Unfortunately, this model is based on pre-rift reconstruction of [Banks, Robinson, 1997] which involves serious space problem, associated with the supposed movement of the Istanbul terrane along non-parallel faults.

A thermo-mechanical modeling *Cloetingh S. et al., [2003]* shows that deformation of strong crust coupled with strong upper mantle in the WBSB and strong upper crust decoupled from a weak hot mantle in the EBSB explains differences in the thermo-tectonic age of the lithosphere of the subbasins. The rheological model uses parameters that are subject to discussion, in particular: density on the surface of the crust equal 2.8 g/cm^3, on the surface of the mantle 3.4 g/cm^3, β-factor of the crust and subcrustal mantle 6.0 and 2.3 for the Western and Eastern subbasins, respectively.

Shillington D.J. et al. [2008] tested depth-depended stretching models for Cenozoic evolution of the eastern EBSB and revealed the controversial effects of paleowater depth and elastic thickness of a plate on the results, particularly for deep-water basins and margins. The paper presents a map of the β-factor, indicating a differentiated character of the basin extension, varying from β=3 to more than 5 in the area between the Shatsky and Arkhangelsky ridges, and 2—2.5 in the structures surrounding the subbasin. Deep faults, including strike-slips, do not participate in the constructions. The differentiated nature of β-factors distribution in the EBSB correlates with the heterogeneous density at the Moho section and the basaltic type of the crust in the center of the subbasin [Makarenko et al., 2021].

Stephenson R. and Schellart W.P. [2010] were the first to apply a new mechanism for formation of the Black Sea behind a subduction zone. It supposed that an asymmetrical counter-clockwise roll-back of continental terranes is responsible for its origin as a single entity. Therefore, the development of Western and Eastern subbasins is simultaneous although the extension began to develop earlier in the western domain with the youngest activity being in the east and north-east. This mechanism for opening the Black Sea necessarily requires the existence of a transform-like plate boundary near its western margin. As the most probable fault of this type, we consider a deep dextral strike-slip tracing from the Balkanides to the Pontides in a northwestern direction.

Meredith D.J. and Egan S.S. [2002] assumed that extension in the EBSB started in the Paleogene and continued throughout the Cenozoic.

Yegorova T. and Gobarenko V. [2010] argue that the WBSB originated on the Moesian Platform while the EBSB formed within the Transcaucasus domain with a time lag between rifting phases. The process of the Black Sea opening is not described in the work. Besides, they utilized the probable dextral transform faults along the western margin of the Black Sea Basin proposed by [Okay et al., 1994], what was discussed above.

Banks C.L. and Robinson A.G. [1997] utilized two hypothetical transform faults for moving of the Istanbul terrane to south-east: the western fault of MBSH and WBSF. However the boundary of the Mid-Black Sea High is not parallel to the direction of the West Black Sea fault.

Chekunov A.V. [1987] presented his view of the mantle diapir in the form of a mushroom without indicating values of rheological parameters.

Okay A.I. and Görür N. [2000] used hypothetical transform faults proposed by [Okay et al., 1994]. Saribudak M. [1989] used paleomagnetic results from semi-Blacked al Sea regions and did not favour rifted back arc origin of the Black Sea. However, he measured remagnetized rocks [Çinku et al., 2013].

Kobolev V.P. [2003] associates the formation of the Western and Eastern basins with the uplift of two epicontinental arches caused by the uplift of the western and eastern diapirs. The two-stage development of the Black Sea depression is considered: progressive with the formation of two arches and regressive — with a sharp subsidence of paleo-arches and the development of magmatism along the Circum-Black Sea Fault.

This brief review of the principles for constructing geodynamic models for the origin and opening of the Black Sea Basin (BSB) showed that most of the models are based mainly on seismic data, and none of them use the full range of lithospheric parameters from the pre-rift phase to the present. They also do not dispose of data on faults in the crystalline crust of the entire basin, among which, instead of hypothetical transform faults, deep faults would be identified that provide the leading mechanism for the movement of continental terranes during the opening of basins, if such a mechanism was assumed.

For the thermomechanical model and calculation of the basin subsidence, ambiguous, rather predictive, data were used, such as, for example: the pre-rift thickness of the lithosphere, the initial thickness of the crust, the density on the surface of the crust and mantle, which are included in the process of estimating the β-factor [Cloetingh et al., 2003]. The latter is the most important indicator of the formation of the oceanic crust.

The analyzed works, however, as well as further models, do not include 3D gravity modeling data on the density heterogeneity of the modern consolidated crust. Meanwhile, this parameter is a direct indication of the possible presence of oceanic crust in the Black Sea basin.

As the experience of later studies has shown, the initial parameters of the pre-rift, post-rift, and modern lithosphere (the composition of the crystalline crust, the presence of oceanic crust, etc.) and the mechanism of basin opening itself are still debatable (see, for example, [Stovba et al., 2020; Stephenson, Stovba, 2022]). With that, almost every publication on the tectonic structure of the Black Sea basin notes that it consists of two subbasins developing individually.

According to one of the versions about the types of crust [Nikishin et al., 2015], three types of crust are distinguished in the Black Sea: continental, highly stretched continental and oceanic (Fig. 1).

The Black Sea was formed on the amalgation of the continental terranes of different ages [Golonka, 2004]. In particular, the WBSB originated on the crust of the Moesian Platform while the EBSB — within that of the Trans Caucasus domain [Yegorova, Gobarenko, 2010, etc.].

Below we will consider a set of fundamental parameters of the lithosphere, paying special attention to the characteristics of the relief of the crust base, thickness of the crystalline crust, its structure and the deep faults of the crystalline crust.

We also mark out the information about the contrast in the structure of the subbasin lithosphere from the pre-rift stage to the present.

Moho image, thickness and predicted composition of the crystalline crust of the Black Sea from gravity modeling. Since rifting is accompanied by a reduction of the crust thickness and an uplift of the Moho section,

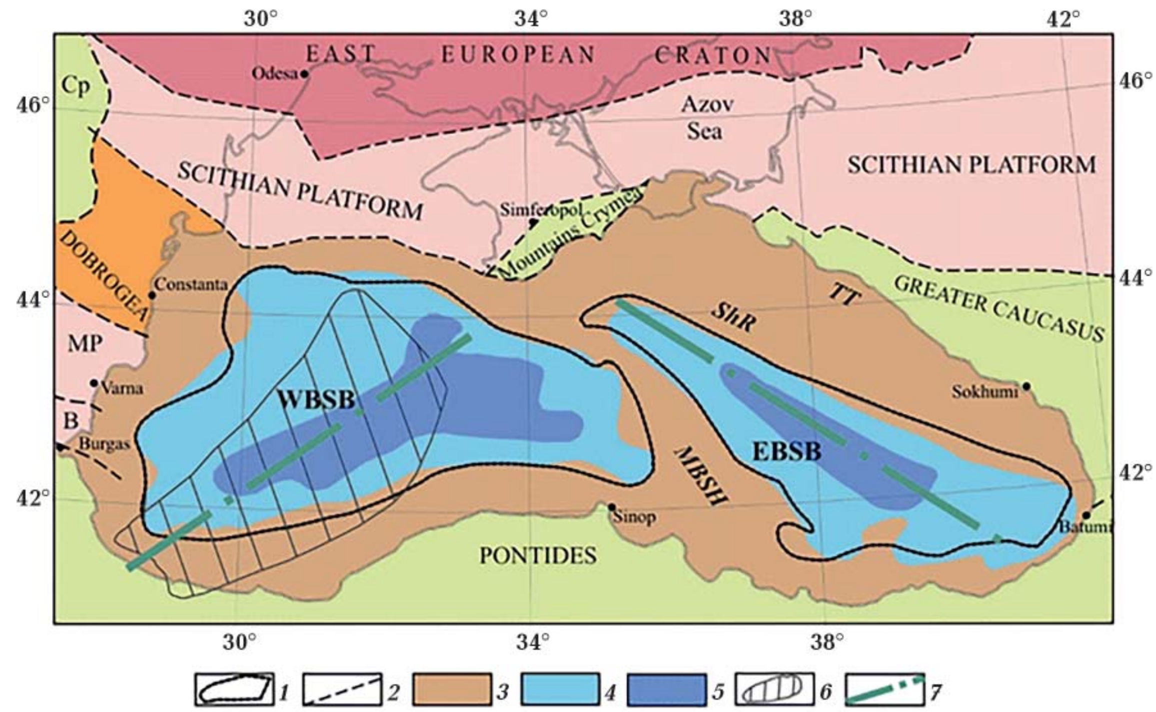

Fig. 1. Crustal types in the Black Sea [Nikishin et al., 2015] and adjacent regions: *1* — boundaries of WBSB and EBSB; *2* — boundaries of adjacent tectonic elements; *3*—*5* — types of the crust from [Nikishin et al., 2015] (*3* — continental crust, *4* — highly stretched continental crust, *5* — oceanic crust); *6* — Istanbul terrane from pre-rift reconstruction of [Nikishin et al., 2015]; *7* — axis of subbasins. WBSB — West Black Sea basin, EBSB — East Black Sea basin, MP — Moesian platform, B — Balkanides, MBSH — Middle Black Sea High, ShR — Shatsky ridge, TT — Tuapse Trough.

the strike of large positive structures in its relief can be considered as a consequence of stretching stresses. The depth to the Moho and the thickness of the crystalline crust are the main, if not fundamental, factor to estimate the degree of crustal stretching — stretching-factor (β).

Since the 1970s, a number of Moho depth maps have been built using DSS data with an uneven and sparse network of profiles. In this regard, in addition to significant discrepancies in the depths of the Moho, its relief did not reflect large structures, such as the Shatsky Ridge and the Tuapse Depression.

Fig. 2 presents the Moho image of the Black Sea from gravity modeling. Uncertainty of modeled Moho depths is similar to that inferred directly from seismic refraction data [Starostenko et al., 2004]. A mean difference (neglecting sign) from 33 calculations is ±1.4 km (20 %). Its advantage over seismically derived depths is that it covers the whole Black Sea Basin over a uniform network and adequately characterizes main tectonic features. The minimum Moho depth is 19 km in the western domain and 22 km in the eastern one. The axes of Moho uplift within western and eastern BSB are distinctly oblique to each other and have the same strikes as the axes of subbasins. The angle between them is about 115°. As it is seen in Figs. 1 and 2 the strike of the Istanbul Terrane on the pre-rift Black Sea restoration [Nikishin et al., 2015] and the strike of the Moho topography in the WBSB are similar. It follows that Moho pattern inherits the pre-rift stage. Accordingly, the Moho images of the WBSB and EBSB are tectonically contrasting domains.

If the Moho topography was formed during rifting and crustal extension, then the disconformity in the strikes of the axes of the Moho uplift can unambiguously indicate different extensional stress fields in the subbasins. They could not exist simultaneously in the entire Black Sea basin, which indicates a different age of opening of the subbasins.

The reduced thickness of the crystalline crust of the central parts of the subbasins, estimated from seismic data and the depth of the base of syn-rift formations [Stovba et al., 2020], as well as from the results of gravity modeling [Makarenko et al., 2021] is 3—4 km in WBSB and 9—10 km at EBSB. In the WBSB, it increases in the northwestern part to 10—18 km, while in the EBSB it is almost constant throughout the entire subbasin. It is indicative that both subbasins are characterized by the absence of the upper (ρ<2.75 g/cm^3) and middle (ρ=2.75÷2.90 g/cm^3) crust in most of them. In [Makarenko et al., 2021], the crust of the Black Sea basin is typified, according to which the crystalline crust of the subbasins is attributed to the basaltoid type. Actually, «oceanic» can be considered the crust, completely consisting of the so-called «basalt» layer (ρ>2.90 g/cm^3). Such a crust, according to these data, is only partially developed in the WBSB, but almost completely covers the EBSB. This result is in accordance with the data on the estimate of the value of the β-factor. In BSBS, according to [Stovba et al., 2020; Stephenson, Stovba, 2022], it does not exceed 2.0, while in EBSB, according to [Shillington et al., 2008], β values range from 3 to more than 5 in the center of the subbasin. The latter value is a sign of crustal rupture (lithosphere?) during rifting and the possibility of oceanic crust formation in EBSB.

Differences in the composition of the crystalline crust of the subbasins also manifest themselves in the distribution of density on the Moho. In WBSB it decreases from 3.07 g/cm^3 in the north to 3.0 g/cm^3 in the south. In the entire eastern subbasin, the density varies from 3.05 to 3.10 g/cm^3 with a local maximum of 3.15 g/cm^3 in the southeastern part. Also, such a values of density are usually interpreted as the presence of a crust-mantle mixture (ρ>3.05 g/cm^3) and ultramafic rocks.

Thus, the predicted crustal composition obtained from gravity modeling, in combination with the stretching factor, provides additional information about the presence of oceanic crust and the stretching regime.

Fault tectonics of the crystalline crust. It can be considered generally accepted that the

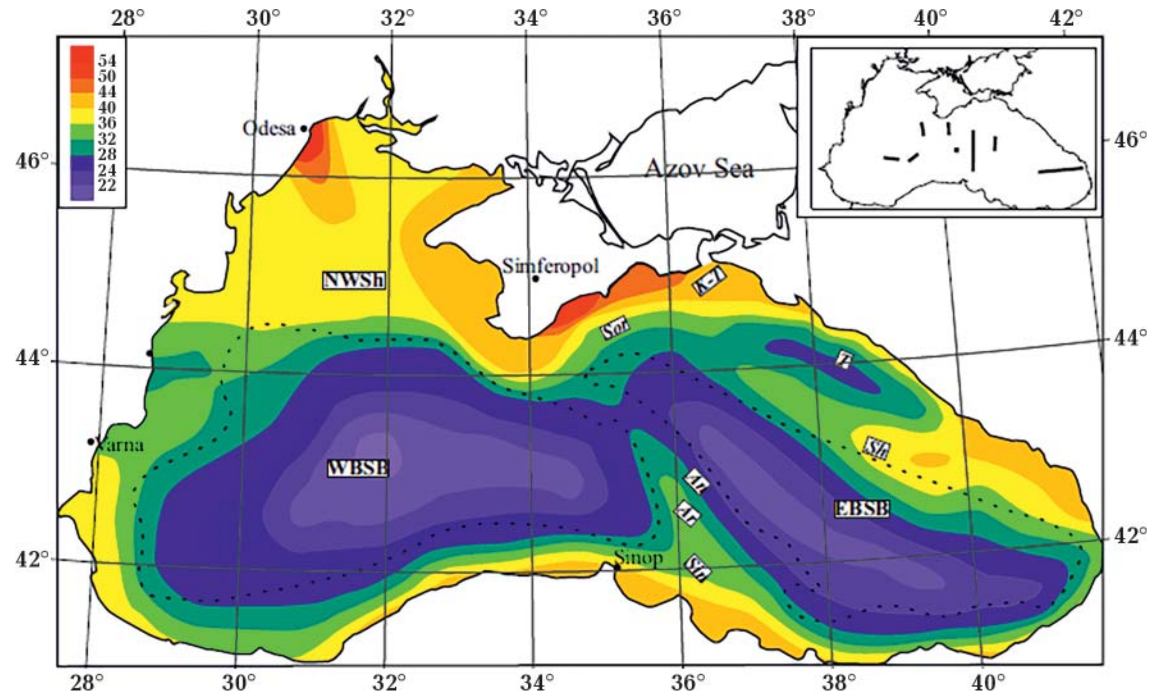

Fig. 2. Moho depths inferred from gravity modeling [Starostenko et al., 2004]. Units are in km. Lines of inset indicate depths directly controlled by refraction interfaces at 33 points.

Black Sea basin was formed on the continental crust, opened up during the Cretaceous (Alb-Cenoman) rifting (see, for example, generalizations in [Stovba et al., 2020; Stephenson, Stovba, 2022, etc.] and went through a multi-phase history of development. There is also a difference in the thickness of the prerifting lithosphere and in the paleorheology of the subbasins. In the WBSB, the pre-rift lithosphere is thicker and stronger than in the EBSB [Spadini et al., 1996; Robinson et al., 1995 and other latest publications]. Cloetingh et al. [2003] believe that the WBSB had a strong crust and a cold mantle, while the EBSB had a strong crust and a weak hot mantle.

The data presented are sufficient to state that such subbasins, which are different in their initial composition, should already be separated by a large long-lived suture zone of mantle faults already at the pre-rift stage. On the other hand, during subbasin rifting, the kinematics of faults should be related to strike-slip. For the first time, as such a zone the Odesa-Sinop fault zone was considered by A.V. Chekunov [1987].

In order to substantiate the existence of such a trans-Black Sea suture zone and a network of main faults of the modern crystalline crust, a geological interpretation of magnetic and gravitational fields of the crystalline crust was carried out. Map of horizontal gradients of these fields allows us to develop a scheme of faults of the crystalline crust of the Black Sea [Starostenko et al., 2015]. The results were confirmed by the geological interpretation of 20 deep penetration regional seismic lines which revealed numerous faults of the same type all over the Black Sea [Nikishin et al., 2015]. The common position of faults from both studies coincide in 135 out of 150 cases that comprises 15 % [Rusakov, Pashkevich, 2017]. A large number of faults are in line with commonly acknowledged basis numerical model of McKenzie [1978] for basins formation and evolution, which envisage fault-controlled subsidence. It is worth emphasizing again extremely good coincidence of results obtained by of independent teams from different geophysical methods. This information confirms indisputable validity of contrasting pattern of the tectonic style in subbasins.

There are major diagonal (NE and NW striking) and orthogonal (NS and WE striking) fault systems in the Black Sea. In the deep water area of the Black Sea, a dense network of faults of the modern crystalline crust of different ranks and depths has been established. The reliability of faults in the crystalline crust is confirmed by comparing them with faults in the sedimentary sequence. For example, the well-studied Golitsyn, Sulina-Tarkhankut, and Euxinian faults on the NW shelf [Stovba et al., 2020] retain the strike of crystalline crust faults [Starostenko et al., 2011]. Their complex configuration in the sedimentary cover with linearity in the crystalline crust can be explained by the plasticity of sedimentary rocks and the brittleness of crystalline ones.

Faults in the crystalline crust form diagonal and orthogonal systems, which can be associated with different stages of the development of the basin. To evaluate the role of faults in the formation of subbasins, data on their manifestation in the mantle component of the gravitational field were used. On this basis, the OSO, BP and WBS fault zones are classified as deep ones, while the AB fault zone is classified as a crustal structure.

The main faults of the diagonal system are shown in Fig. 3.

The Trans-Black Sea OSO fault zone (320—325°) and its southeastern branches play the role of a long-lived suture zone from the time of its origin to the present. Its deep origin is confirmed by 3D gravity modeling [Makarenko et al., 2021, using seismic profiles 18 and DOBRE-5].

On the map of Chekunov [1987] the Odesa-Sinop (OS) fault zone crosses the Black Sea from the Ukrainian cost to the Sinop on Turkish onshore. Starostenko et al. [2015] geophysically refined the position and structure of this fault prolonging it to the Ordu offshore (Turkey). The eastern border fault of the OSO zone on the Crimean offshore is the WCrP transform fault. Its north segment partially corresponds to earlier known WCrF, which was defined only in the sedimentary cover [Finetti et al., 1988]. We delineated the

WCrP transform fault in the crystalline crust across the WBSB to the Pontides (see Fig. 3).

The northwestern part of OSO fault (the former OS fault) is a direct submarine continuation of the well-mapped mantle Talnivskyi fault as sinistral slight-slip in the Proterozoic origin on the Ukrainian Shield and its southern slope [Gintov, 2015], repeatedly activated. In turn, the last one is a constituent part of the Golovanivskaya suture zone dividing two continental Precambrian terranes with different deep structure and evolution [Chekunov, 1992]. The OSO fault zone was also active since its origin. Its activation in post-rifting stage as dextral fault led to shifting the EEC boundary (see Fig. 3). The displacement of the Early and Late Cretaceous magmatic fronts [Okay, Nikishin, 2015] within the Pontides along the southeastern extension of the OS part of OSO also testifies to a dextral strike slip into the post-rift stage. One of the crucial evidences for OSO activation is the fact that the striking of NW portion of the OSO fault zone coincides with that of major tectonic features in the Western and Central Europe at least since the Early Triassic time [Ziegler, Dèzes, 2006].

Southeastern continuation of OS part of the OSO zone is reflecting at sea and on land, where normal, reverse and thrust faults are known [Meijers et al., 2010a] The zone separates areas with different deformation types: normal faults occur to the east and reverse and thrust ones to the west from it. Such a relationship between tectonic units with different ages and the OSO deep fault of the

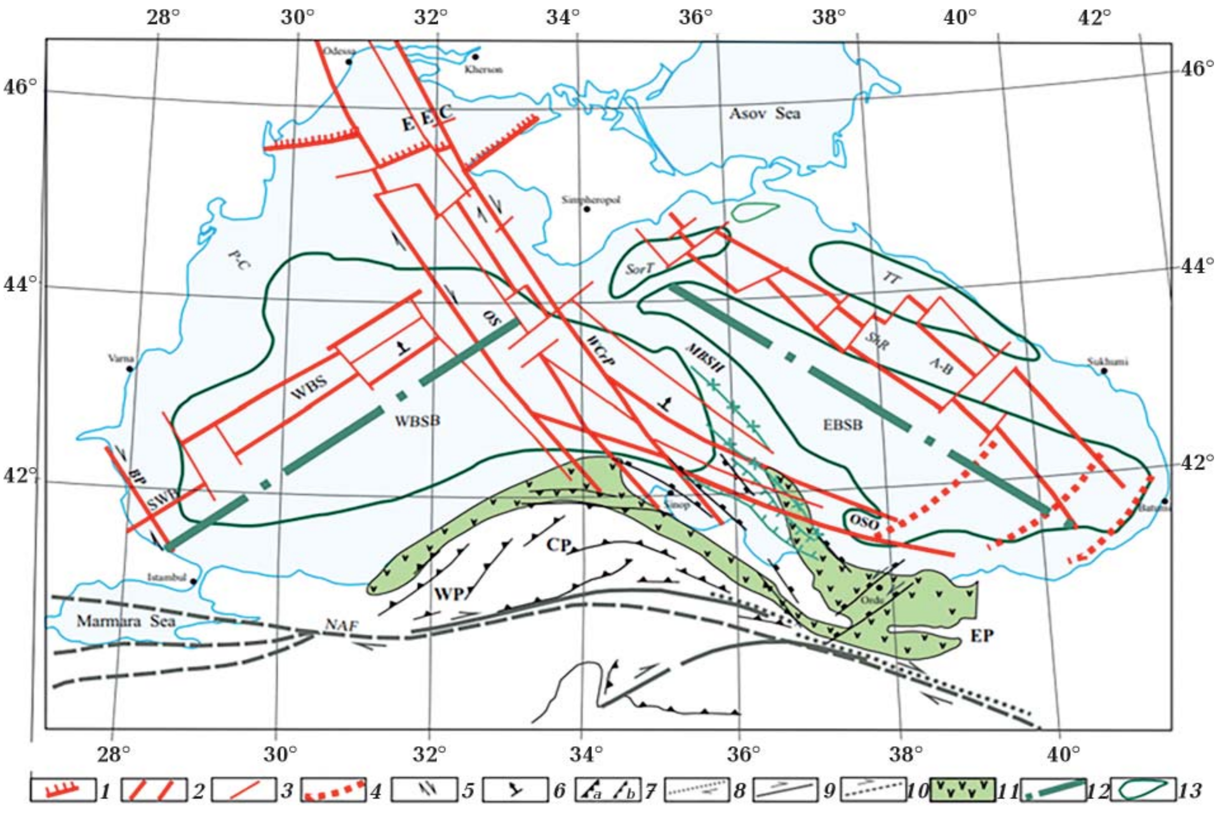

Fig. 3. Main fault zones of diagonal system of the crystalline crust: *1* — the EEC boundary; *2* — fault zones; *3* — their branch faults [Starostenko et al., 2015]; *4* — transform faults [Shillington et al., 2009]; *5* — directions of moving along strike-slip faults after rifting; *6* — direction of fault dip; *7* — reverse and thrust faults (*a*), normal faults (*b*) are from [Meijers et al., 2010a]; *8*—*10* — location of the North Anatolian fault (NAF) (*8* — [Gürbüz, 2010], *9* — [Meijers et al., 2010a], 10 — [Eyuboglu et al., 2012]); *11* — zones of the Late Cretaceous volcanism [Nikishin et al., 2015]; *12* — subbasins axis; *13* — subbasins boundaries. WP — Western Pontides, CP — Central Pontides, EP — Eastern Pontides. EEC — East European Craton fault zones: OSO — Odesa-Sinop-Ordu, BP — Balkanides-Pontides, SWB — South-Western Balkanides, WBS — Western Black Sea, WCrP — Western Crimea-Pontides, AB — Alushta-Batumi. For other abbreviations see Fig. 1.

Precambrian origin suggests the long activity and crucial role of this zone in forming the subbasins.

In the Black Sea the OSO fault zone occurs on the rifted (hyper-stretched) continental crust [Graham et al., 2013; Scheleder et al., 2015, etc.] indicating its preservation during the Mesozoic rifting processes. The last large rejuvenation of this zone may occur during the Neoalpine stage because its general trend is concordant with that of the northern fragment of the tectonic front of the same age [Finetti et al., 1988]. The numerous cold seeps over the northern segment of the OSO zone indicate that it is still active at present time [Rusakov, Kutas, 2018].

The BP deep dextral strike-slip zone also has a NW trend. It is important to emphasize the parallelism of the OSO and BP fault zones. In the papers [Starostenko et al., 2015; Rusakov, Pashkevich, 2017] OSO and BP zones are considered as driving for rift opening.

The WBS fault zone is perpendicular to the OSO and BP strike and is accompanied by a series of magnetic anomalies. At the same time, it is parallel to the WBSB and to Moho uplift axes. The zone is broken by transform faults of the same strike as OSO and BP. We assigned it to the rift structure.

In the Eastern subbasin, the largest fault zone is the northwest-trending AB zone of crust origin, which accompanies the Shatsky Ridge. It is broken by transform faults, sequentially from NW to SE, shifting its fragments to the east.

Parameters of the lithosphere. The generalization of the parameters of the modern lithosphere of the Western and Eastern subbasins (Table 2) was performed according to our data [Starostenko et al., 2015; Rusakov, Pashkevich, 2017; Kutas, 2020] using data on the depth of the acoustic basement [Nikishin et al., 2015] and velocity characteristics of the subcrustal mantle [Tsvetkova et al., 2017].

The indicated parameters of the lithosphere are fundamental in determining the age and geodynamics of the subbasins formation. Different parameters support the contrasting lithospheric structure of subbasins.

Thus, the configuration of the basins and the oblique strike of their axes, as well as the orientation of the axes of the main Moho structures and the main deep faults, and the zones of magnetic anomalies undeniably testify to the different age of subbasins formation. At the same time, the strike of magnetic anomalies zones associated with zones of crustal extension indicate different geodynamic regimes in the subbasins during their opening. The absence of mantle faults of the diagonal system in the EBSB and the presence of such faults in the WBSB may be due to different mechanisms of their opening.

The depth to Moho, the thickness of the

Table 2. Geophysical lithospheric parameters of the WBSB and EBSB

Geophysical parameters	Western Basin	Eastern Basin
Configuration of basin	Weakly elongated of NE trend (235°, near oval shape	Elongated of NW trend (300°), triangular shape
Depth to acoustic basement	Up to about 18 km	Up to about 12 km
Orientation of major faults	NE (235°), NW (320—325°) mantle origin)	NW (295—310°) (crustal origin)
M-discontinuity relief	Maximum depth of 19 km,	Maximum depth of 22 km, NW trend (300°)
Crustal types	Zone of oceanic crust in the center part of NE trend (235—240°), rifted and highly rifted continental crust	Zone of oceanic crust in the center part of NW trend (300—305°)
Magnetic anomalies	Linear zone of NE anomalies (235°)	Set of NW anomalies (295—310°)
ΔV_P undercrust mantle	Negative	Increasing from S to N
Heat flow	Homogeneous	Differentiated
Relief of the thermal LAB	Flat, a depth of about 90 km	Dome-like, minimum depth of 80 km

crystalline crust and the depth of the LAB are necessary indicators of the degree of the Earth's crust stretching and its possible rupture during rifting.

The differentiated up-to-date heat flow and seismic velocities of the subcrustal EBSB mantle, as well as the LAB topography, are signs of differentiation of the original lithosphere and geodynamic processes of subbasin formation and greater activation of the EBSB lithosphere.

The dextral strike-slip of OSO zone and pull-apart structures. Stephenson and Schelart [2010] argued that the models involving two co-existing subduction zones with oblique orientation of their axes have significant complication due to the occurrence of cusp between southern parts of the subbasins, where local maximum depths to acoustic basement revealed from seismic-derived basement topography [Nikishin at al., 2015]. Here is an attempt to avoid this difficulty.

There are a set of dextral strike-slip faults of the OS and SO fragments of the OSO fault zone in the southeastern part of the WBSB which completely coincide with boundary of these local depressions (Fig. 4). A displacement along these faults produced the trapezium-like shape of depressions. Such tectonic situation resembles the geometry of widespread pull-apart basins [Liu, Konietzky, 2018]. The kinematics of the OSO fault zone agrees with known continental fault feature of Turkey. A single kinematic picture is presented by the joint of fragment of the OSO faults with eastern part of the North Anatolian dextral strike-slip fault. The set of dextral shifts is strictly parallel to it. All these arguments and occurring the Late Cretaceous volcanism indicate dextral activation of the OSO fault zone and validity of pull-apart mechanism for formation of local depressions in the southern part of the west domain of the Black Sea.

Possible modification of the model of Okay et al. [1994]. Almost every publication on the tectonic structure of the Black

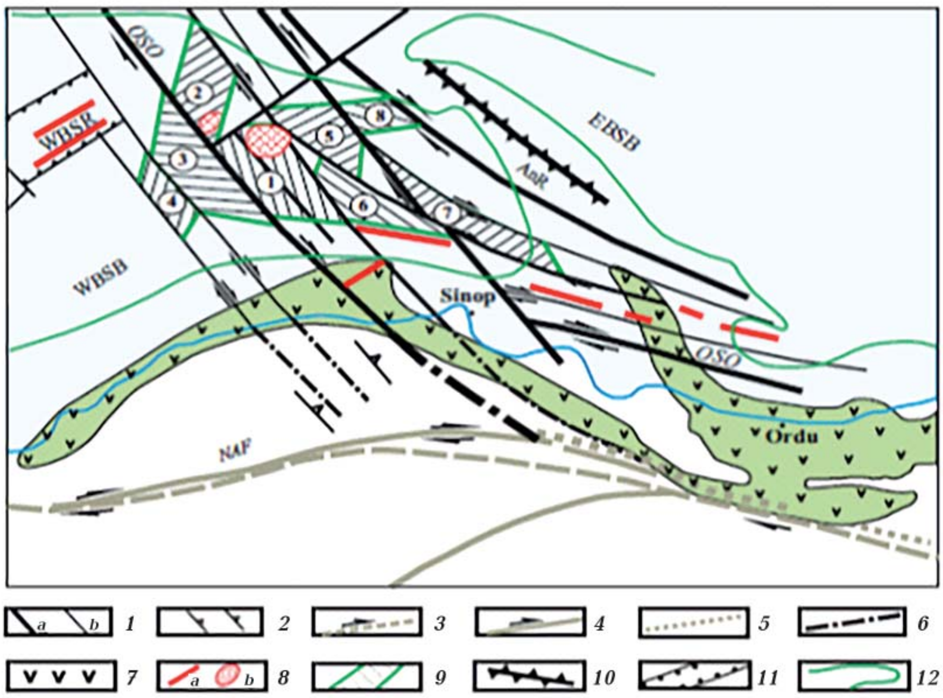

Fig. 4. Pull-apart structures in the dextral shear OSO zone: *1* — faults (*a* — first rank, *b* — branch); *2* — over thrust [Rangin et al., 2002]; *3—5* — NAF position (*3* — [Gürbüz, 2010], *4* — [Meijers et al., 2010a], *5* — [Eyuboglu et al., 2012]); *6* — derived from Bouguer gravity anomaly map of Turkey [Ates et al., 2012]; *7* — zones of Late Cretaceous volcanism [Nikishin et al., 2015]; *8* — positive magnetic anomalies; *9* — pull-apart structures; *10* — Andrusov Ridge; *11* — boundary of supposed West Black Sea rift; *12* — borders of subbasins.

Sea mentions that it consists of two subbasins separated by the MBSH, which includes the Andrusov and Arkhangelsky ridges. The Precambrian OSO fault zone separated the continental lithosphere into two large domains before the Black Sea origin. This long live fault zone as Trans-Black Sea suture zone is responsible for incipient dividing the Precambrian continental crust into the two future Black Sea subbasins with dissimilar physical properties and distinct evolution. No matter how debatable would be the age of its origin, activation, kinematics, and its role in the formation of subbasins, the consequences of its «stormy» life are indisputable. At the stage of synrift development (compare Fig. 3 with the structural map of syn-rift semi-grabens [Stovba et al., 2020, Fig. 9]), it separates areas with different structural plans of these structures. And with that, the Euxinian graben abruptly changes its strike along the OSO zone. Finally, in the modern tectonic setting, this suture zone separates two large segments of the Eurasian Plate. The Alpine Crimean-Caucasian mobile belt is developed to the east of it, and platform-type structures to the west. Therefore, it is the real tectonic boundary between the Black Sea subbasins.

Most of the geodynamics models of the Black Sea Basin opening incorporate transform faults as a tool for movement or rotation of continental blocks. However, many of faults are hypothetic or wrong. For example, the popular model of Okay et al. [1994] employs the WCrF and WBSF faults along which the Istanbul terrane moved to the Pontides.

The multichannel seismic surveys along the Crimea Peninsula only recognized the WCrF in the sedimentary cover [Finetti et al., 1988].

The paleoreconstruction in Fig. 5 is a possible modified version of the model of Okay et al. [1994]. According to this version the opening of the WBSB occurred as a result of the southeastward movement of the Istanbul terrane, not along the WCrF and WBSF, as suggested by Okay et al. [1994], but along two parallel transform faults: the OSO left strike-

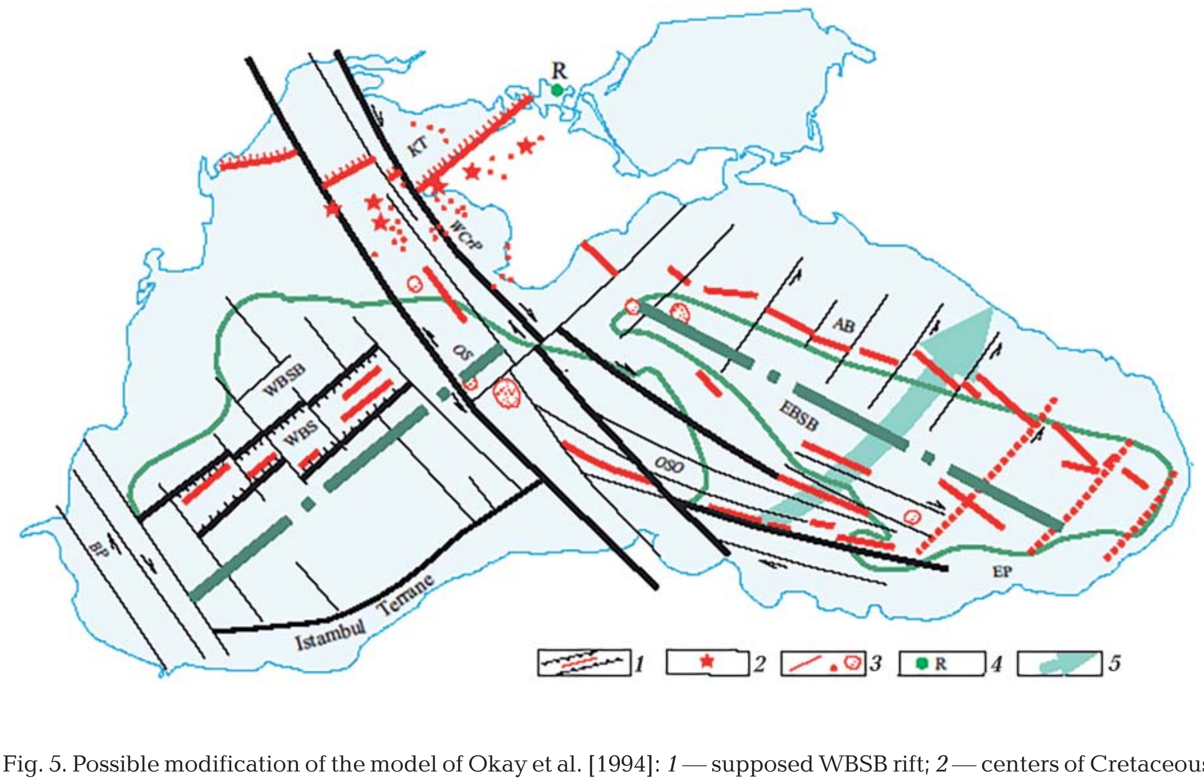

Fig. 5. Possible modification of the model of Okay et al. [1994]: *1* — supposed WBSB rift; *2* — centers of Cretaceous volcanism after [Nikishin et al., 2015]; *3* — magnetic anomalies and its axes; *4* — supposed center of rotation of the eastern domain of the Black Sea during EBSB opening; *5* — direction of rotation. For other abbreviations see Fig. 3.

slip and the right strike-slip BP, which are geophysically substantiated. Together with it the axis of the suppose drift is parallel to the axis of the basin, to the northwestern boundary of the Istanbul terraneafter reconstruction of [Nikishin et al., 2015], and perpendicular to BP and OSO. The West Black Sea rift is marked by a series of faults and NE-trending magnetic anomalies.

The paleoreconstruction by Okay et al. [1994] suggests a counterclockwise rotation mechanism for the EBSB opening. But they does not consider strike-slip faults, disturbing AB zone, to support such a mechanism and the crescent-like transform faults [Shillington et al., 2008], confirmed such a rotation for Black Sea opening.

As was mentioned above, there are no mantle-derived faults in the EBSB that can open the basin by a mechanism similar to the WBSB. The only major fault in this subbasin is the AB fault, but it is of a crustal nature. It is assumed that the sources of magnetic anomalies AB in the faults zone belong to pre-Jurassic magmatic basic formations. To-day position of the zone is the result of its crust rotational displacement in the NE direction together with the Shatsky Ridge during the opening of the subbasin.

Thus, the use of a set of lithospheric parameters makes the EBSB opening model more reliable by counterclockwise rotation of the Eastern domain of the continental crust in irregular geodynamic conditions. This mechanism probably led to the triangular shape of the formed basin.

Conclusions. Analysis of the most cited publications about geodynamic models for the Black Sea showed that they often use hypothetical transform faults or these faults don't correspond to the modern geophysical information and that some of them need modification for corresponding to present-day data. More reliable reconstructions of origin and evolution of the Black Sea should include information on the contrasting of the geophysical parameters of both subbasins lithosphere from pre-rift stage up to now, deep mantle faults in the crystalline crust to provide driving mechanism for displacement of continental terranes and degree of correspondence to plate tectonic reorganizations. Results of the study of the Moho relief, of fault tectonics of the crystalline crust of the entire BSB, and generalization of the parameters of the lithosphere are presented here to illustrate how they can geophysically support certain basic ideas of available models for geodynamics of the Black Sea.

The systematic comprehensive analysis of magnetic, gravity, thermal, deep seismic sounding revealed inherent significant differences in the lithosphere and undercrust mantle of the Western and Eastern Black Sea subbasins. These differences reveal in the shapes of the subbasins, crustal composition, oblique topography of Moho and thickness of the crystal crust, main deep faults, their kinematics, configurations of the lithospheric thermal base of the subbasins.

- The models providing the basins opening with the movement of continental terranes require the presence of pre-rift deep faults of the strike-slip type, parallel to each other. They are considered as driving this movement. Earlier based on a comprehensive analysis of the magnetic and gravitational fields, with taking into account seismic data, diagonal and orthogonal systems were distinguished by us among the faults of the crystalline crust of the Black Sea. The first plays a major role in the formation of subbasins. It includes mantle OSO, BP, WBS faults in WBSB, whereas in EBSB AB fault was attributed as crust one.
- The Odesa-Sinop-Ordu Trans-Black Sea long-living mantle fault zone of the Precambrian origin was the pre-rift tectonic boundary between the future subbasins, that caused in future the individual history of the subbasins development.
- OS left strike-slip and BP right strike-slip are parallel. Therefore they explain the possibility of moving the Istanbul terrane to the southeast with the crust extension and formation of the West Black Sea rift. The latter is perpendicular to OSO and BP and is fixed by the series of magnetic anomalies, that are the indicators of a rift. The absence of such guiding faults in the EBSB ruled out a similar

subbasin opening mechanism. The most acceptable mechanism for this is the counterclockwise rotation of the EBSB domain. Such a mechanism is confirmed by the displacements of the AB fault zone and the Shatsky Ridge towards the rotation of the terrane, as well as in arcuate transform faults in the southeast. In addition, the triangular shape of the EBSB, expanding to the southeast, and the presence of a dextral displacement along the OSO testify in favor of the rotation mechanism.

• The position of the MBSH as a relics of the primary original continental crust and the division of the western and eastern basins deserves special attention. The echelon relationship between the axes of the Andrusov and Arkhangelsky ridges can be considered as a consequence of a rightward post-rift strike-slip along the OSO and can be included in the zone of influence of the OSO.

In the debatable problem of the presence of oceanic crust in subbasins, and, consequently, the break of the lithosphere in rifts, the results of gravity modeling are important indicators, which make it possible to identify the oceanic crust as consisting entirely of the basalt layer (lower crust). These results confirm the development of such a crust in the WBSB only by separate fragments, and in the EBS — almost throughout the entire subbasin.

• Of great importance in characterizing the degree of crustal and lithosphere extension are data on their thickness during the pre-rift and post-rift stages of rifting.

• The kinematic characterization of faults makes it possible to consider the applicability of pool-apart mechanisms to elucidate the nature of local depressions. The deepest depressions of SE part of the WBSB originated in the zone of dextral strike- slip faults of OSO zone due to the cumulative effect of eight small pull-apart basins. The proposed occurrence of the pull-apart basins instead of the simple cusp between the western and eastern subbasins allow us to avoid significant complication for the back-arc models involving oblique two rift axes.

Acknowledgements. The authors are thankful to Prof. I. Artemieva for the fruitful discussions on contrasting lithospheric structure of the Black Sea subbasins. We express special gratitude to Prof. S.N. Stovba for his constructive suggestions which greatly improved the text. And we thank also Prof. V.P. Kobolev.

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Контрастна геофізична будова літосфери суббасейнів Чорного моря: тестування геотектонічних моделей цієї мегадепресії

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Представлено комплексний аналіз результатів інтерпретації даних магнітного, гравітаційного, теплового полів, глибинного сейсмічного зондування і сейсмічної томографії. Він вперше демонструє, що суттєві відмінності геофізичних параметрів літосфери Західного та Східного Чорноморських суббасейнів існують від дорифтової стадії. Набір розглянутих параметрів, відповідальних за формування сучасної літосфери, включає типи кори, глибини до акустичного фундаменту, конфігурацію суббасейнів, глибини до Мохо, рельєф границі термоастеносфери (ЛАГ), простягання основних глибинних розломів кристалічної кори, їхні кінематичні типи, лінійні магнітні аномалії, швидкісну картину підкорової мантії. Параметри літосфери є індикаторами віку, геодинаміки та механізмів розкриття суббасейнів. Простягання рельєфу Мохо під кутом один до одного в суббасейнах і передрифтової Стамбульської зони і хребта Шатського, різнонаправлені простягання глибинних розломів обох суббасейнів указують на відмінну будову літосфери від дорифтової стадії. Одесько-Синопська зона глибинних розломів як безпосереднє продовження Голованівської сутури Українського щита і його схилу є докембрійського віку і може бути тектонічною межею між двома сегментами дорифтової континентальної кори і майбутніми суббасейнами. Наведено приклади як параметри літосфери підтверджують базові ідеї геодинаміки Чорного моря.

Ключові слова: Чорне море, суббасейни, рифтові типи кори, розломи кристалічної кори, тектонічна еволюція.