УДК 553.98.551.241 doi: http://dx.doi.org/10.24028/gzh.0203-3100.v39i1.2017.93998

The decisive role of the crystalline crust faults in the Black Sea opening

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Received 31 October 2016

Результати міжнародного проекту "Геологія без кордонів" беззастережно підтвердили наявність системи розломів у кристалічній корі басейну Чорного моря, виділених за гравітаційними і магнітними даними. Місця розташування 135 з майже 150 розломів на її поверхні, отриманих за даними аналізу сейсмічних розрізів у рамках цього проекту, повністю збігаються з розломами виділеної системи. Вперше наведено докази вирішальної ролі розломів кристалічної кори у розкритті басейну Чорного моря. Довгоіснуюча Одесько-Синопська зона розломів докембрійського закладення мала першорядне значення для цього процесу. Вона розділила предрифтову континентальну кору на два блоки, які чітко визначено комплексним геофізичним аналізом, з різною геологічною структурою. Західно- та Східночорноморські западини розкрилися під впливом двох різних механізмамів. Західна западина, за винятком її східної частини, була розкрита позаду континентального фрагмента, який переміщувався на південний схід уздовж двох паралельних зон глибинних розломів: лівосторонньої Одесько-Синопської (спільно із Західнокримсько-Понтійським розломом) і правосторонньої Балкансько-Понтійської. Інша частина басейну Чорного моря утворилася внаслідок обертання проти годинникової стрілки великого континентального блока, що зумовило утворення рифту в Східночорноморській западині та формування зони розломів Одесько-Синопсько-Орду. Правобічні зсуви в цій зоні зумовили утворення восьми пулл-апартових локальних басейнів у південно-східній частині Західночорноморської западини. Одесько-Синопська система розломів як довгоіснуюча структура, можливо, контролює зміну простягань Західних і Східних Понтид і сучасне розміщення під гострим кутом одна до одної основних рифтових осей чорноморських западин. Південно-східне продовження Одесько-Синопського розлому фіксує західну межу докрейдяних відкладів Східних Понтид.

Ключові слова: Чорне море, консолідована кора, розломи, механізм розкриття.

1. Introduction. The Black Sea opened as a back-arc basin related to the northward subduction of the Neo-Tethys Ocean [Zonenshain, Le Pichon, 1986; Finetti et al., 1988; Okay et al., 1994, 2014; Banks et al., 1997; Nikishin et al., 2003, 2013; Okay, Nikishin, 2015]. Although the timing and opening history of its sub-basins are still considerably debated, there is growing agreement that their forming was diachronous [Okay et al., 1994, 2014; Spadini et al., 1996, 1997; Nikishin et al., 2003; Hippolyte et al., 2010; Starostenko et al., 2010, 2015; Nikishin et al., 2013; Okay, Nikishin, 2015]. The East Basin back-arc extension occurred no earlier than the Late Cretaceous while the rifting of the West Basin predated this event. Spadini et al. [1996] and Cloetingh et al. [2003, 2013] were the first to explain the difference in the age of sub-basins formation by lateral variation of the inherited lithospheric rheology. Inherited lithospheric — scale heterogeneities also control the large-scale temporal and spatial deformations of the Black Sea Basin [Espurt et al., 2014]. The pre-existing long-live Odessa-Sinop (OS) deep fault zone was responsible for the initial separation of the future Black Sea into two sub-basins having dissimilar physical properties and distinct evolutionary trend [Starostenko et al., 2010, 2015]. Recently, a number of researchers brought into question the back-arc origin of the West Black Sea Basin (WBSB) [e. g. Schleder et al., 2015; Tari, 2015].

The model of Okay [Okay et al., 1994] for the opening of the WBSB hypothesizes the two major strike-slip faults on its eastern and western sides to translate the Istanbul terrane from the Moesian Terrane to the Pontides. It involves the West Crimea (WCF) sinistral strike-slip and the

West Black Sea fault (WBSF) dextral strike-slip respectivly.

However, this model accounting for southward movement of the Istanbul zone along the WCF and WBSF is problematic for several reasons. Reflection seismic data indicate that the WCF cut only sedimentary cover next to the western coastline of Crimea [Finetti et al., 1988]. Moreover, recent Black Sea SPAN data [Kaymakci et al., 2014] did not ascertain any evidence for the WCF. One expects that a fault providing transportation of a large sliver of the continental crust must cut the entire lithosphere [Silvester, 1988]. As for the WBSF, its existence is controversial [Munteanu et al., 2013; Kaymakci et al., 2014]. Among other things, the WBSF and WCF bounding the Istanbul Block are significantly nonparallel to each other and consequently one cannot classify them as transform faults in the terms of plate tectonics [e. g. Silvester, 1988; Molnar, 2015]. In the alternative scenario of opening the WBSB Banks and Robinson [1997] placed the eastern sinistral strike-slip fault along the western foot of the entire slope of the Mid-Black Sea High (MBSH). However, the MBSH consists of the Andrusov and Archangelsky Ridges with different origins and ages shifted relative to each other by the OS deep fault zone [Starostenko et al., 2015].

Based on the idea of the separate origin of the West and East Basins through different mechanisms [Okay et al., 1994; Banks, Robinson, 1997], the aim of this paper is to present a new supporting information for similar geodynamic scenario from recent data on the crystalline crust faults and lithospheric structure of the region.

2. The faults of the crystalline crust in the Black Sea Basin. A potential field data analysis produced a detailed map of the tectonic disturbances of different orders in the crystalline crust and upper mantle of the whole Black Sea [Staro-

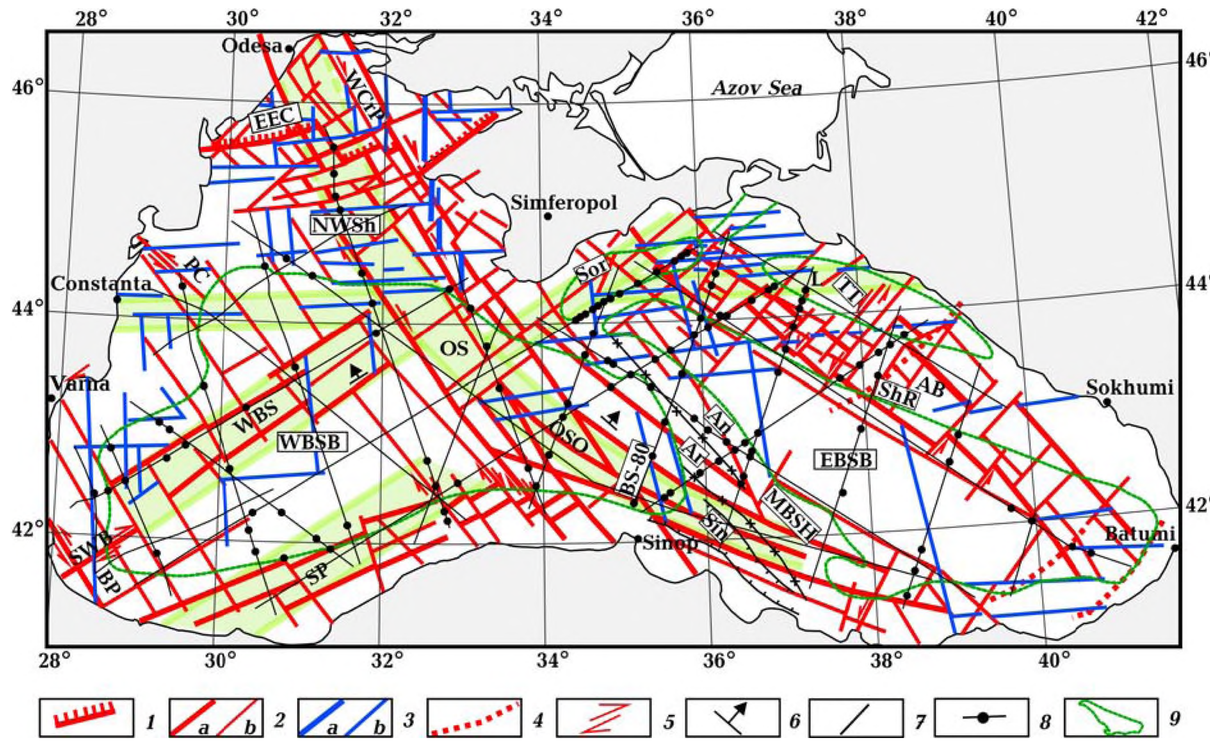

Fig. 1. Map of the crystalline crust faults derived from the anomaly magnetic and residual gravity fields in an earlier version of the manuscript modified from [Starostenko et al., 2010, 2015]: *1* — boundary of the East European Craton; *2* — diagonal faults system of the first (*a*) and second (*b*) ranks; *3* — orthogonal faults system of the first (*a*) and second (*b*) ranks; *4* — transform faults [Shillington et al., 2009]; *5* — relative displacements along faults; *6* — direction of dip; *7* — 2D reflection seismic lines [Graham et al., 2013; Nikishin et al., 2015 a; Amelin et al., 2014; Schleder at al., 2015; Tari, 2015]; *8* — locations of the faults on the surface of the crystalline crust from seismic data (black dots); *9* — deepwater sub-basins configuration. *Faults:* WBS — Western Black Sea, OS — Odessa-Sinop, OSO — Odessa-Sinop-Ordu, BP — Balkanide-Pontide, WCrP — Western-Crimea-Pontide, WBS — West Black Sea, AB — Alushta-Batumi. Abbreviations in the squares: EEC — East European Craton, NWSh — North-Western Shelf, WBSB — Western Black Sea Basin, EBSB — Eastern Black Sea Basin, TT — Tuapse Through, Sor — Sorokin Through, MBSH — Mid Black Sea High, Ar — Arkhangelsky Ridge, An — Andrusov Ridge, ShR — Shatsky Ridge.

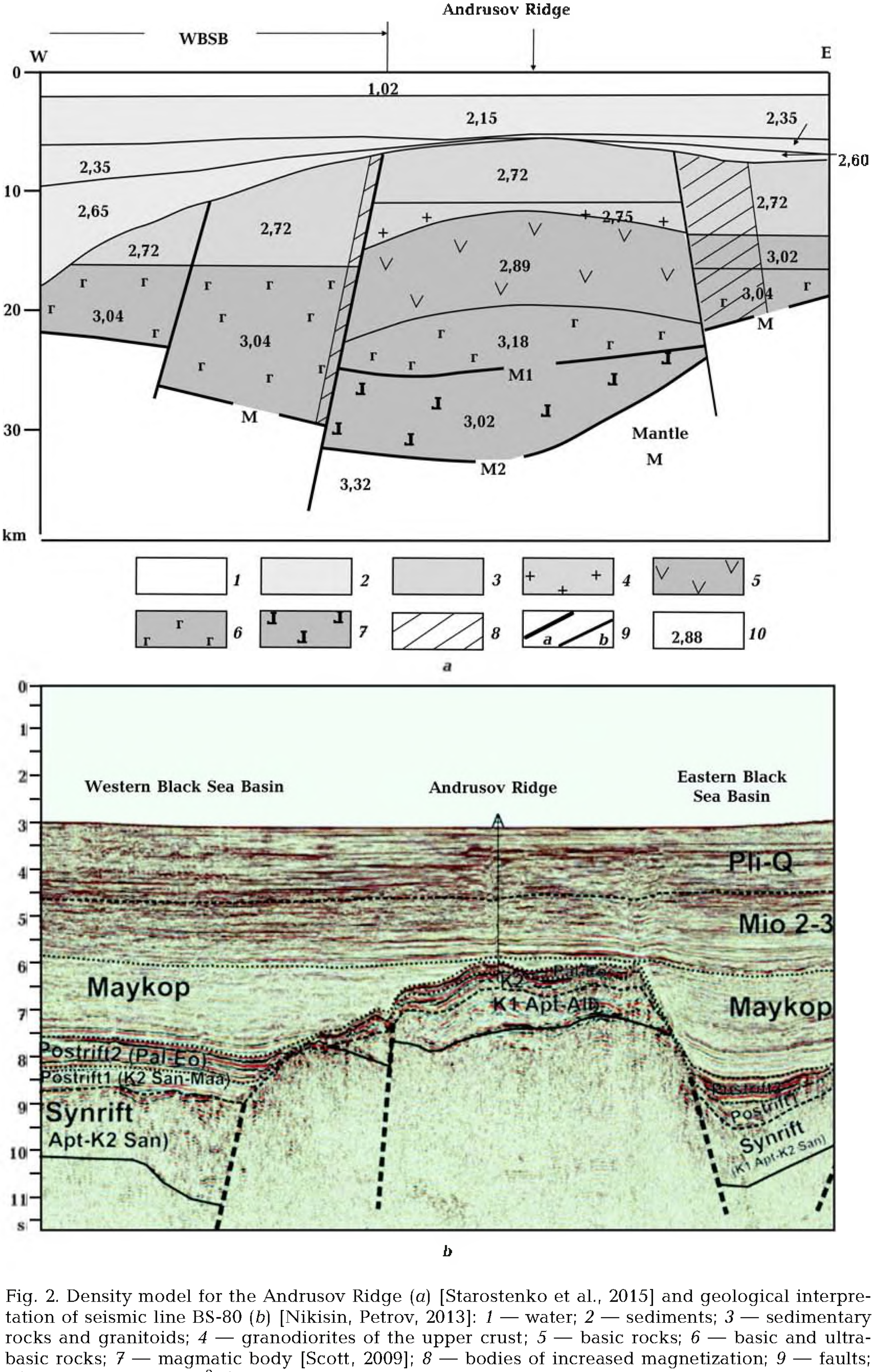

Fig. 2. Density model for the Andrusov Ridge (*a*) [Starostenko et al., 2015] and geological interpretation of seismic line BS-80 (*b*) [Nikisin, Petrov, 2013]: *1* — water; *2* — sediments; *3* — sedimentary rocks and granitoids; *4* — granodiorites of the upper crust; *5* — basic rocks; *6* — basic and ultrabasic rocks; *7* — magmatic body [Scott, 2009]; *8* — bodies of increased magnetization; *9* — faults; *10* — density in gcm^{-3}. See Fig. 1 for locations of the profiles. Both results unmistakably indicate a crystalline crust origin of the faults.

stenko et al., 2004, 2010, 2015]. Here we only introduce a brief characteristic of the main crustal faults without describing a procedure of their revealing.

There are diagonal (NE and NW strikes) and orthogonal (NS and WE strikes) major fault systems in the Black Sea (Fig. 1).

The diagonal system of the faults (NE 235—245° in the WBSB and NW 305—325° in EBSB) controls the major tectonic units. The Western Black Sea (WBS) and Alushta-Batumi (AB) zones of the faults are the largest among them. The large OS fault zone of varying strike (140—100°) also belongs to the diagonal system where it occupies a specific position.

Although there are nuances in the interpretations of the seismic results from the international "Geology without Limits" project [Graham et al., 2013; Amelin et al., 2014; Nikishin et al., 2015a, b; Schlender et al., 2015; Tari, 2015] they generally agree with each other and mostly corroborate the set of the faults in Fig. 1. The locations of 135 from among ca. 150 faults on the surface of the crystalline crust derived from seismic sections (black dots on the lines in Fig. 1) completely coincide with those obtained from the potential field information. The seismic-derived faults mostly penetrate the uppermost top of the ductile crystalline crust. Moreover, Tari [2015] recognized 30 faults in the crystalline crust up to the Moho boundary along the line 360 km long.

We also provide the more detailed information to illustrate remarkable similarity between the tectonic settings from potential field and seismic data. Fig. 2, *a*, *b* present the cross-section from the gravity modeling [Starostenko et al., 2015] and the BS-80 seismic line [Nikishin et al., 2015a] respectively. Their comparison demonstrates that th locations and dip angles of the faults are identical although results derived from the independent geophysical methods used for studying the Andrusov Ridge. Fig. 3 introduces another example of full corroborating the gravity and magnetic model of the OS fault zone by DSS results [Starostenko et al., 2015].

In Fig. 4 the depths of the seismic Moho discontinuity of the WBSB [Schleder et al., 2015] reflect the block structure of the bottom of the crystalline crust due to the hyper-deep faults. The faults of this study display the similar block structure of it. This figure also shows the zones of steep gradients in the Moho discontinuity, which de-

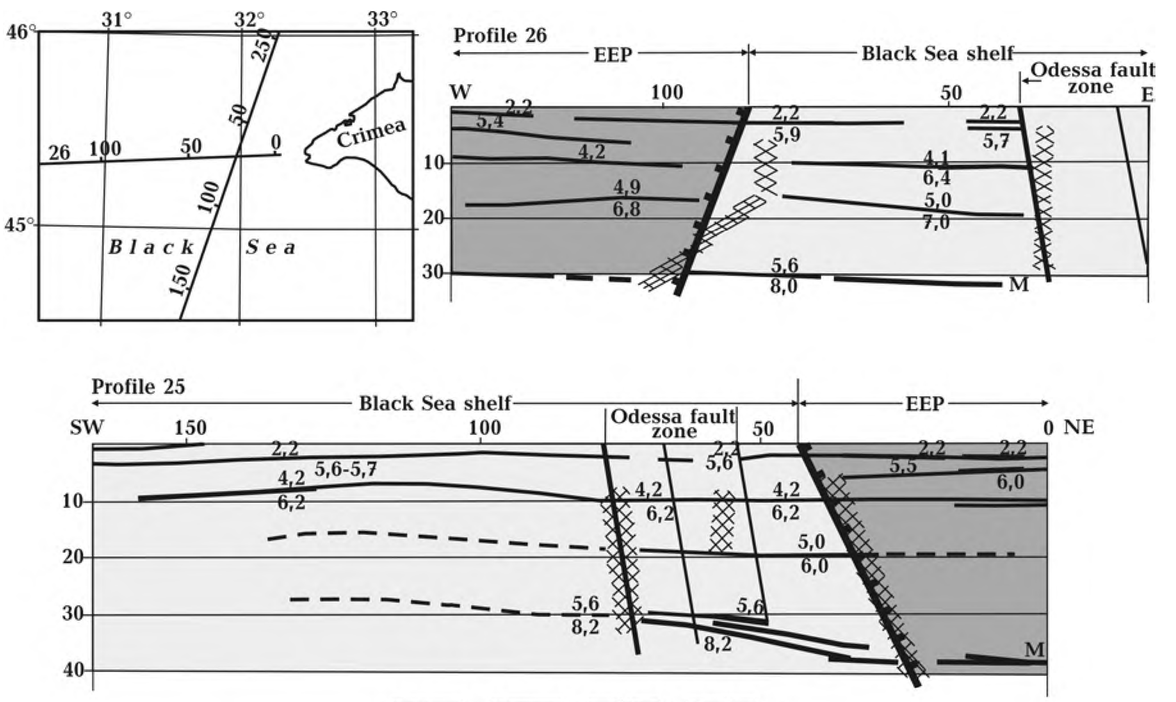

Fig. 3. Location of the faults in the crystalline crust from DSS and potential field data [Starostenko et al., 2015]: *1* — velocity, km/s; *2* — EEC boundary; *3* — faults from DSS data; *4* — crystalline crust faults, see Fig. 4 (*a* — the first rank, *b* — the second rank). The DSS-derived faults clearly penetrate up to the Moho discontinuity that supports a deep origin of the faults in this paper.

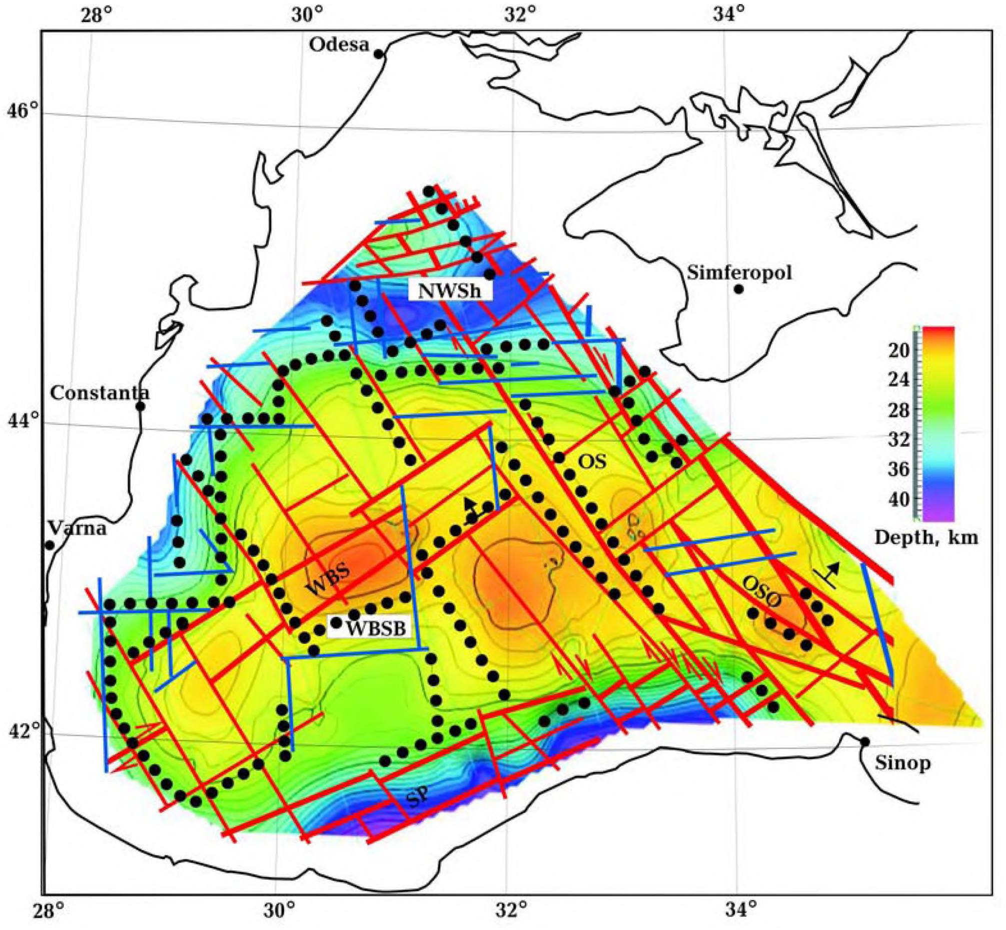

Fig. 4. Depth of the seismic Moho discontinuity [Schlender et al., 2015] and crystalline crust faults (see Fig. 1). Dots denote steep gradients of the Moho topography.

lineate faults on the crust-mantle boundary. As is seen, the major strikes of the crystalline crust faults are completely supported by these zones in the bottom of the crust and change in the forms the relief of the crustal bottom, often displayed relative to each other. The figure also exhibits a distinct alternation of the Moho pattern from the central WBSB to the OS and OSO fault zones that is a direct independent evidence for their deep origin and reliability of their mapping from gravity and magnetic data.

Fig. 5 presents only diagonal system as it mainly governs the tectonic setting in the Black Sea and plays a decisive role in our reconstructions. It includes the greatest OS (320—325° strike) with its major splays, Alushta-Batumi (AB) (295—310°) and Western Black Sea (WBS) (235°) deep fault zones. This system also incorporates the Balkanide-Pontide (BP) (320°) and the complex zone of faults (245°) along the southwestern offshore of the Black Sea. The dextral slip faults of the NW striking disturb this zone, which is sub parallel to the Intra-Pontide suture. Sub-Moho component of the gravity field distinctly portrays the great zones of the diagonal system fault zone (apart from the AB) that indicates their mantle origin [Starostenko et al., 2010, 2015].

The NW OS fault zone of Precambrian initiation is the direct submarine prolongation of the well-studied Proterozoic sinistral Talne deep fault on the Ukrainian Shield and on its southern slope. The Talne fault is a constituent part of the Golovanivska suture zone of the Ukrainian Shield, which separates two large continental domains with different deep structure and evolutionary history [Khain, Bogdanov, 1998; Gintov, 2005 among others].

The width of the OS zone is up to 100 km. It consists of the fragments of the same strike, displaced by NE faults. In particular, the WCF is an inherited constituent of the eastern boundary of the OS fault zone and seismic reflection records

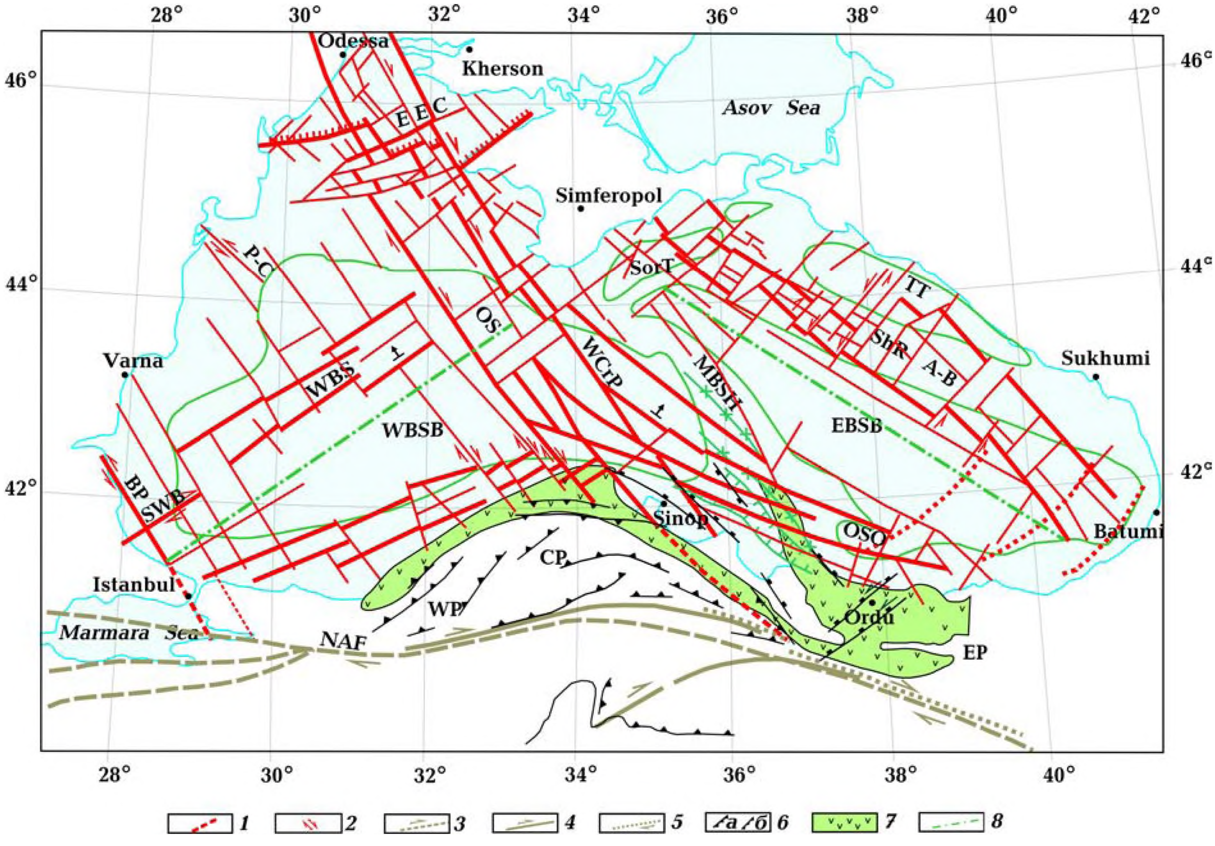

Fig. 5. Faults in the crystalline crust in the Black Sea, diagonal system (modified from [Starostenko et al., 2010, 2015]): *1* — faults continuation from interpretation of the Bouguer gravity anomaly map of Turkey [Ates et al., 1999]; *2* — direction of moving along the shear strike-slip faults after rifting; *3—5* — location of the NAF (*3* — [Gürbüz, 2010], *4* — [Meijers et al., 2010], *5* — [Eyuboglu et al., 2012]); *6* — reverse and thrust faults (*a*), normal faults (*b*) [Meijers et al., 2010]; *7* — zones of Late Cretaceous volcanism [Nikishin et al., 2013]; *8* — sub-basins axes. Abbreviations: NAF — North Anatolian Fault, EEC — East European Craton, WP — Western Pontides, CP — Central Pontides, EP — Eastern Pontides. See Fig. 1, 4 for other symbols and abbre-viations.

as mentioned above, documented it only in the sedimentary cover [Finetti et al., 1988]. To distinguish the deep fault from the shallow WCF we termed the former as the West Crimea—Pontide (WCrP) fault (see Fig. 1).

One can recognize the southern continuation of the OS fault zone in the steep gradients of the gravity and magnetic fields of the Turkish contiguous onshore territory [Ates et al., 1999]. Further to the southeast the zone changes its strike and prolongs as dextral fault into the eastern branch of the dextral North Anatolian Fault (NAF) separating the EP from the CP (Fig. 7). This is in line with recent speculation of [Nikishin et al., 2015 b] about the Abana wrench fault between these tectonic units.

The eastern branch of Late Cretaceous volcanic belt [Nikishin et al., 2013] extends along this zone, which strictly follows its strike and the western segment is subparallel to the WBS deep fault. The OS fault also controls the obtuse angle (120°) between the western and eastern segments of the volcanic zone and the axes of the sub-basins.

Within the western part of the OS zone at sea and on land normal, reverse and thrust faults [Meijers et al., 2010] demonstrate clear tectonic conformity of their strikes (see Fig. 5). As is seen, the zone separates areas of different deformation types: to the east normal faults occur and to the west — reverse and thrust faults. Such a relationship between tectonic units with different ages and the OS deep fault of the Precambrian origin suggests the long activity and crucial role of this zone in forming the Late Cretaceous—Paleogene fold and thrust tectonic units.

As there is contradictory evidence for so called the shallow WBSF [Munteanu et al., 2013; Kaymakci et al., 2014], the diagonal BP deep fault zone striking 320° parallel to the OS fault is proposed to be the best dextral railroad fault for opening the WBSB.

The western fault of this zone defines a boundary between the Balkanides and Western Pontides. The gravity field in the coastal areas in Turkey [Ates et al., 1999] and Bulgaria [Georgiev, 2012; Trifonova et al., 2012] clearly trace this fault by steep gradients. It spatially coincides with the marine fragment of the West Black Sea-Saros Fault [Nikishin et al., 2011] and is the borderline between the rheologically stronger Balkanides—Moesian and weaker Pontide—West Black Sea domain [Munteanu et al., 2013]. The trend of the BP zone is similar to that of the basement relief features such as the Bourgas Basin [Georgiev, 2012], Paleo Bosporus Strait Basin and Kamchia Marine [Nikishin et al., 2015a]. It corresponds also to the general trend (315—320°) of the Teisseyre—Tornquist zone [Khain, Bogdanov, 1998]. The eastern fault of the BP zone limits the domain of the Western Black Sea Basin and its rift magnetic anomalies belt [Starostenko et al., 2015]. The WBS, AB and OS fault zones are associated with the belts of the magnetic anomalies of different geometries: linear of the same strike and isometric. The magnetic anomalies of the AB fault zone resulted from the dykes of basic Middle Jurassic rocks intruded into the crust in an extensional setting [Shreider et al., 1997; Meisner et al., 2009; Meisner, 2010]. They appear to be imprint of rift-related process [Shreider et al., 1997; Beşutiu, Zugrávesku, 2004].

3. Geodynamic implications. The rifting of the Black Sea commenced on the inhomogeneous continental lithosphere of an assemblage of various terranes formed by accretionary episodes from the Precambrian to the Early Mesozoic [Winchester et al., 2006; Pease et al., 2008]. Interpreting the BasinSPAN lines [Graham et al., 2013; Nikishin et al., 2015a; Scheleder et al., 2015] revealed vast areas of the hyperextended continental crust in the Black Sea. There are some crustal fragments that one can classify them as suspect terranes [Howell, 1989] because it is difficult to determine their original positions The continental lithosphere was separated into two large blocks by the Precambrian OS fault zone of the sub-Moho origin, which was repeatedly rejuvenated up to now [Kravchenko et al., 2003; Kutas et al., 2004]. The preexisting long-lived deep tectonic disturbance has catalyzed the individual evolution of the sub-basins in the Black Sea [Starostenko et al., 2010, 2015].

The opening of the western portion of the WBSB bounded on the east by OS fault (Fig. 6) took place in the mid-Cretaceous on the large block of the continental crust along the concave southern margin of the Eurasia on the Moesian Terrane [Golonka, 2004; Nikishin et al., 2011]. In pre-rift period, the Istanbul Terrain was separated from the northwestern Moesian Terrane by the deep fault (later the WBS rift) of NE (235°) strike orthogonal to the OS and BP fault zones (Fig. 7). At that time, the Karkinit Trough did not yet exist within the block to the east of the OS fault. On the contrary, the AB fault zone already occurred as a zone intruded by basic dykes and volcanoes of Middle-Upper Jurassic and Lower Cretaceous age respectively [Shreider et al., 1997; Meisner et al., 2009; Meisner, 2010; Nikishin et al., 2015a, b].

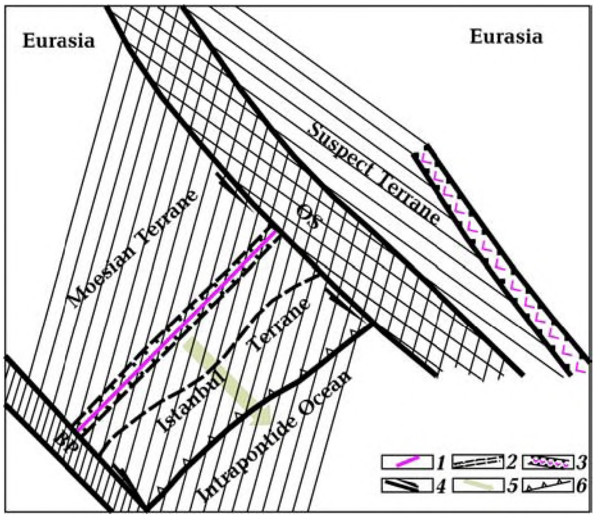

Fig. 6. WBS rifting in the mid-Cretaceous due to dextral and sinistral movement along the OS and BP deep faults respectively. The OS fault zone of the crystalline crust separates two large continental domains. The BP fault zone in the west bounds the western domain. Within the Odessa shelf there exist pre-rift fault orthogonal to the OS and BP faults. The Karkinit rift is still closed. The movement of the Istanbul Terrain to the south-eastern direction ceased Intra Pontide Ocean: *1* — pre-rifting faults; *2* — incipient rift; *3* — Jurassic magmatic belt [Meisner, 2010]; *4* — direction of strike-slip movement; *5* — direction of the terrane movement; *6* — zone of overthrust an underthrust. See Fig. 1 for abbreviations.

The rifting of the incipient WBSB in the second half of the Early Cretaceous [Hippolyte et al., 2010; Graham et al., 2013; Okay et al., 2014; Kaymakci et al., 2014; Nikishin et al., 2015b; Okay, Nikishin, 2015] caused by the movement of the Istanbul Terrane towards the southeasterly direction of 140° along the OS and BP faults (see Fig. 7). This movement led to the pre-Santonian juxtaposition of the Istanbul Terrane and Sakarya Zone,

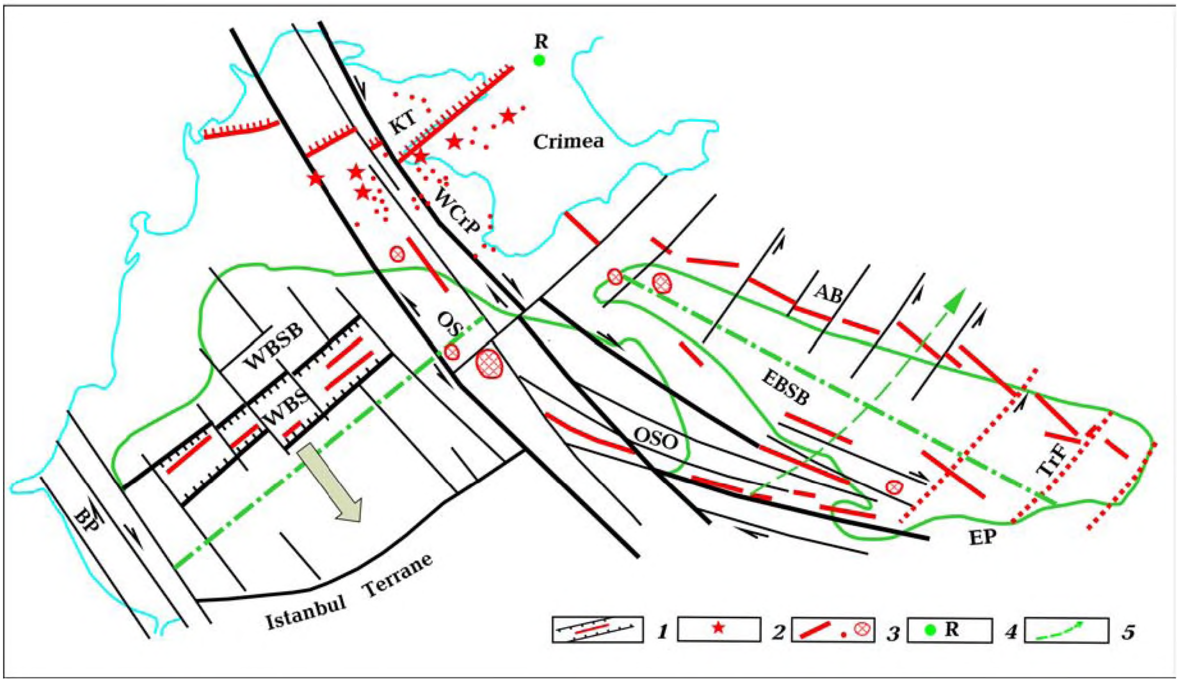

Fig. 7. Opening the EBSB in the Late Cretaceous due to anticlockwise rotation of the eastern continental domain: *1* — rift of the WBSB; *2* — Albian volcanoes [Nikishin et al., 2013], *3* — linear and isometric magnetic anomalies [Meisner, 2010]; *4* — rotation pole of the east domain [Okay et al., 1994]; *5* — rotation direction. TrF — Trabzon fault. See Fig. 1 for other symbols.

closure of the Intra-Pontide Ocean [Robertson, Ustaömer, 2004; Hippolyte et al., 2010; Özcan et al., 2012] and the formation of the west part of the WBSB bounded on the east by the western branch of the OS fault. In the entire OS zone and along the EEC boundary on the NW Crimea there occur isometric or linear magnetic anomalies resulted from Cretaceous basic volcanic activity [Nikishin et al., 2013] in extension zones.

To the east of the OS fault, the EBSB and eastern WBSB part within the OS fault opened after the WBSB unclosing due to the anticlockwise rotation (about 30°) of a large continental block around the pole in North Crimea [Okay et al., 1994]. The rotation led to opening the Karkinit Trough, change in the sense of strikeslip motions along the eastern faults of the OS zone and displacement of the EEC southern boundary (see Fig. 7). This event produced opening the EBSB and originating arcuate — like faults orthogonal to the trend of the present-day basin. It resulted in displacement of the AB zone of the magnetic anomalies (Jurassic rift?) to its present-day position, set of mainly arch-like sinistral strike-slip the AB zone, transform faults (for example, Trabzon Fault) in the SE EBSB [Scott, 2009; Nikishin et al., 2015a] and caused the triangular shape of the eastern sub-basin itself. The rotary motion also created the Sinop—Ordu set of the faults with SE trend branching of the OS fault and forming the single OSO fault zone.

There exist no typical rift-related systems of the linear magnetic anomalies within the EBSB produced by basic dykes [Starostenko et al., 2015]. Here are mapped only several linear and isometric anomalies. Such a pattern of the magnetic field indicates aborted rift that agrees with crustal composition whose non-granitic area occurs only in the central sub-basin.

The southeastern part of the WBSB mostly occupies an area of a set of dextral slip faults of the SO fragment of the OSO fault zone, which completely coincides with those delineated in this work from seismic-derived basement topography [Nikishin at al., 2015a]. This domain does not seem to have been involved in forming the western part of the WBSB. Such a tectonic situation makes it possible to suggest that eastern part of the WBSB developed in pull-apart setting (Fig. 8) due to a set of dextral slip-strike faults. The SO segment of the OSO fault zone is associated with several linear magnetic anomalies produced by basic intrusions, which also support extensional environments [e. g. Molnar, 2015].

Structural pull-apart sedimentary basins are widely spread in strike-slip and extension setting all over the world [Man, 2007]. Based on current literature, Gürbüz [2010] meticulously summarized their angular and dimensional characteristics to obtain new empirical relations among the length and width parameters and to examine them along the NAF zone. The pull-apart mechanism seems to be responsible for the origin of the Trabzon Basin [Nikishin et al., 2015b]. A well-defined correlation is determined between length and width, whose average value is 3,2, with the acute angles between the basins bounding faults clustered at 30—35°.

We attempted to estimate parameters of small pull-apart basins within the OSO fault zone in the southeastern domain of the WBSB whose origin resulted from dextral strike-slip faults due to the rotation of the EBSB. The rhomb- and trapezium-like geometry of the basins is determined from the configuration of sub parallel master strike-slip fault system and diagonal dipslip faults revealed by the present study in the seismic-derived basement topography [Nikishin et al., 2015a]. Such an interpretation is rather illustrative because of the regional scale of the study. The separate deepest depression in this portion of the Black Sea arose from aggregate subsidence of eight distinct pull-apart smaller basins with higher rates of plunge against to the surrounding area. The ratio of length/width is in the range of 2,4—3,8 with an exception of the basins 1 and 7 where it is 1,7 and 6,4 respectively. The acute angles between the master faults of the basin margins and transfer faults are 30—50°. These geometric parameters are rather well consistent with the characteristic of pull-apart basins [Gürbüz, 2010].

Two lines of evidence support the inference that the southeastern part of the WBSB is a composite pull-apart basin. First, the age of sediments on its basement is the Upper Cretaceous while it is older to the west outside it [Nikishin et al., 2015a].

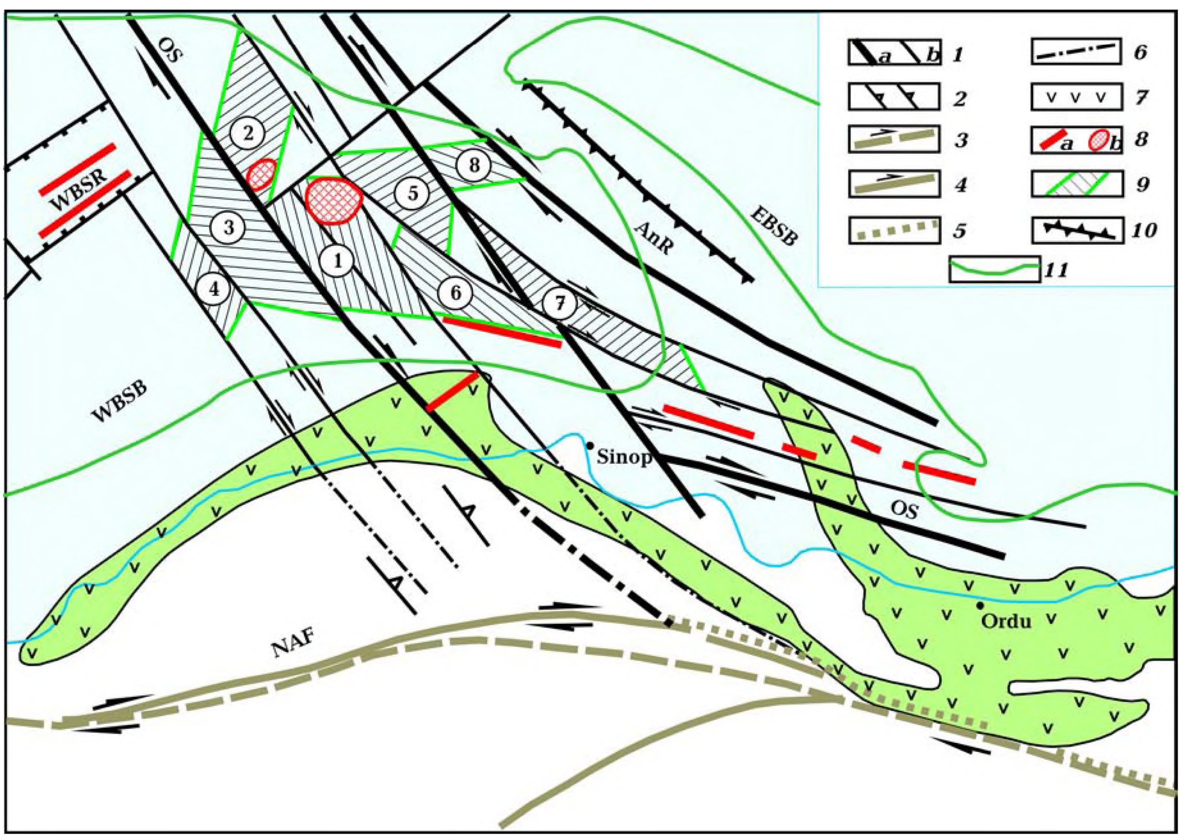

Fig. 8. Pull-apart structures in the dextral shear OSO zone: *1* — faults (*a* — the first rank, *b* — accompanying; *2* — overthrust faults [Rangin et al., 2002]; *3*—*5* — NAF position (*3* — [Gürbüz, 2010], *4* — [Meijers et al., 2010], *5* — [Eyuboglu et al., 2012]); *6* — derived from Bouguer gravity anomaly map of Turkey [Ates et al., 1999]; *7* — zones of Late Cretaceous volcanism [Nikishin et al., 2013], *8* — positive magnetic anomalies; *9* — pull-apart structures; *10* — Andrusov Ridge; *11* — borders of sub-basins.

Second, main subsidence of this area occurred in the Aptian time [Hippolyte et al., 2010]. Besides, the conclusion above allows us to negate the remark of Stephenson and Schelart [2010] that the cusp between the western and eastern sub-basins to the west of the MBSH represents a significant complication for the back-arc models involving diachronous oblique rifting if the cusp considered to be a pull-apart basin.

4. Discussion. There are two broad groups of geodynamic models to account for the Black Sea opening. The models of the first group incorporate one-stage mechanism with possible slightly different age of opening its sub-basins [e. g. Zonenshain, Le Pichon, 1986; Finetti et al., 1988; Nikishin et al., 2003, 2011; Stephenson, Schelart, 2010]. The models of the second group involve a two-stage mechanism with clear time gap between rifting in the western and eastern portions of the Black Sea [e. g. Okay et al., 1994; Banks, Robinson, 1997].

Single entity models for the Black Sea opening ignore principal differences between the two sub-basins in paleo-lithospheric rheology [Spadini et al., 1996, 1997; Cloetingh et al., 2003, 2013] and inherited present — day physical parameters [Starostenko et al., 2010, 2015]. The western part originated on the stable and cold continental lithosphere of 200 km thick in a back-arc setting while the eastern one developed on the pre-existing back arc-basin whose lithosphere was thin (80 km) and warm [Spadini et al., 1996]. On the other hand, the two-stage models place the boundary between two sub-basins of the Black Sea along tectonic faults in the sedimentary cover [Okay et al., 1994]. The notion about pre-existence of the OS fault zone of the sub-Moho origin allows us to avoid the significant controversies of the above-mentioned models.

As the OS fault is the submarine continuation of the Ukrainian Shield Talne deep fault (section 2), the similar tectonic behavior is characteristic of them. The sinistral Talne fault experienced multiple reactivations as dextral normal-reverse fault changing in a sense of strike-slip movements [Gintov, 2005]. This implies that the OS fault was also active tectonic feature prior to the Cretaceous time within the area where the future Black Sea basin will be formed. The multiple rejuvenation of the OS fault zone and its land continuation control the distribution of the volcanic and volcanic clastic rocks and tectonic displacements in the Central and Eastern Pontides including (Fig. 9). This interregional deep fault separates the Upper Cretaceous volcanic and volcanic clastic rocks from the turbidites of the forearc basin similarly as on the out-crop-based map in Fig. 9 from [Okay, Nikishin, 2015]. Furthermore, in the post-Cretaceous time dextral slip movement displaced these effusives along the OS fault zone that resulted in the geological setting of this area depicted on the above mentioned map.

The deepest basement depression in the western sub-basin of the Black Sea occurs in its south-eastern portion. The OS fault zone separates the basement into western and eastern parts where the morphology of its top is strongly distinct. The western domain displays simple slightly differentiated linear configuration parallel to the WP. In contrast, the eastern part consists of local depressions of different strikes whose formation is due to the dextral strike-slip during the EBSB rifting.

To the east of the OS fault zone, the Black Sea Basin opened because of the anti-clockwise rotation of the large continental block around the pole situated in N. Crimea [Okay et al., 1994]. The rotation was responsible for the opening of the Karkinit Trough, change in the sense of strike-slip motions along the eastern faults of the OS zone, forming of the SO branch of it and the displacement of the EEC southern boundary (see Fig. 7). This event produced opening the EBSB, originating arcuate-like faults orthogonal to the axis trend of the present-day basin. It resulted in displacement of the AB Jurassic magmatic zone to the present-day position, set of mainly arch-like sinistral strike-slip of this zone, transform faults (the Trabzon Fault, for example) in the SE EBSB [Scott, 2009].

Finally, the principal conclusions of this study are as follows.

1. The independent results of the international "Geology without Limits" project fully validate the faults in the crystalline crust of the Black Sea from potential field data. The locations of 135 from among ca. 150 faults on its surface derived from seismic sections in the frame of this project completely coincide with those of the present study.
2. Clear evidence is introduced for the crucial role of the crystalline crust faults in the opening of the Black Sea among which the most important for this process were the OS and BP fault zones.
3. The Black Sea basin emerged on the two lar-

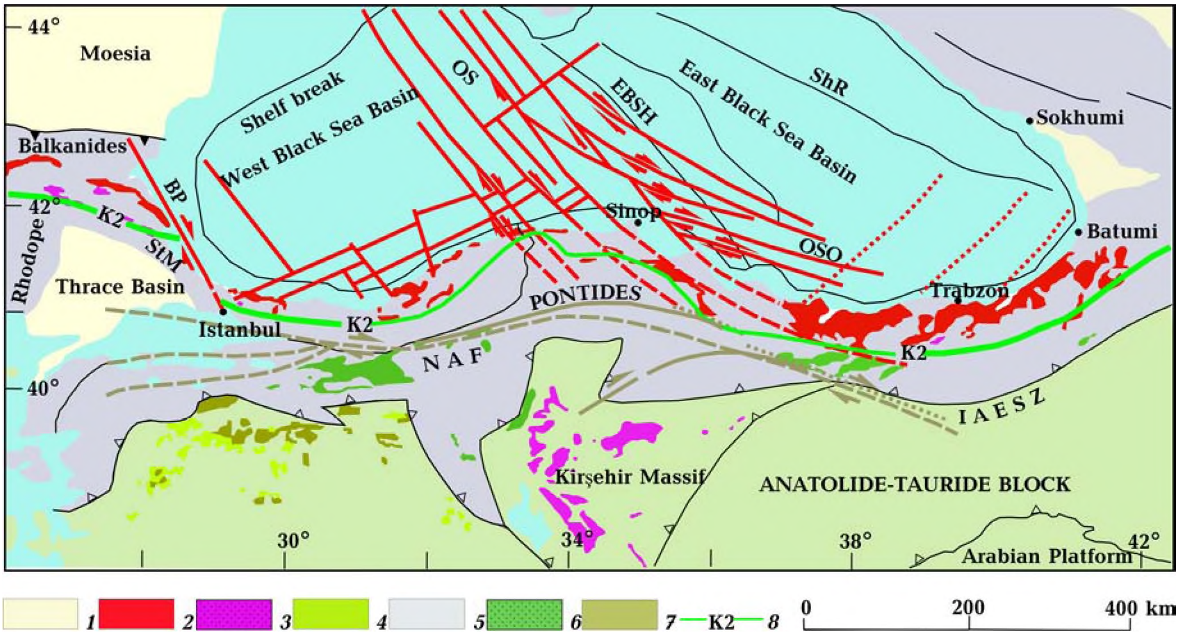

Fig. 9. Relationship between the faults in the crystalline crust of the Black Sea (see Fig. 1) and onshore geological features after [Gürbüz, 2010; Okay, Nikishin, 2015]: *1* — upper Cretaceous-Cenozoic strata; *2* — upper Cretaceous volcanic and volcaniclastic rocks; *3* — upper Cretaceous granitoids; *4* — ophiolitic mélange-accretionary complex with Triassic to Cretaceous basalt, chert, argillite; *5* — Pre-Cretaceous strata; *6* — upper Cretaceous sandstone and shale-turbidite of the forearc basin; *7* — upper Cretaceous ophiolite, predominantly peridotite; *8* — late Cretaceous magmatic front. StM — Strandja massif; IAESZ — Izmir-Ankara-Erzincan suture zone. See Fig. 1, 4 for other abbreviations.

ge Precambrian blocks with district rheological environment on both sides of the pre-existing Odessa-Sinop deep fault zone.

4. Two distinct mechanisms produced the Black Sea Basin opening. The western domain, except its eastern part, opened behind a continental fragment by orthogonal rifting due to the movement of the Istanbul Zone along two parallel deep dextral (BP) and sinistral (OS) strike-slip faults. The rest of the Black Sea originated through the anticlockwise rotating of a large continental block.
5. A high obliquity of the major structural units and the dissimilarity in physical properties in the lithosphere of the Western and Eastern subbasins from the Precambrian to the present time decisively demonstrate that their opening was diachronous on the two separate tectonic blocks with the post-rift auto-nomous and individual geological histories.
6. The deepest depressions in the southeastern part of the Western Black Sea are produced by aggregate effect of eight pull-apart small basins with higher rates of subsidence with respect to the surrounding area in the belt of strike-slip faults within the OSO deep fault zone.
7. The southeastern prolongation of the OS fault forms the western boundary of the pre-Cretaceous strata of the EP and the Upper Cretaceous—Cenozoic strata of the CP.

Acknowledgments. Our thanks to Dr. B. Natal'in, Prof. (Istanbul Technical University) for some useful remarks in an earlier version of the manuscript.

The decisive role of the crystalline crust faults in the Black Sea opening

The results of the international "Geology without Limits" project unequivocally confirmed the faults pattern in the crystalline crust of the Black Sea delineated from gravity and magnetic data. The locations of 135 from among ca. 150 faults on its surface derived from the seismic sections of this project completely coincide with those of the present study used. For the first time, we introduced clear evidence for the decisive role of the crystalline crust faults in the opening of the Black Sea. The long-lived Odessa-Sinop (OS) fault zone of the Precambrian origin was of prime importance for this process. It separated the pre-rift continental crust into two blocks with a different geological structure definitely recognized by an integrated geophysical analysis. The West Black Sea and East Black Sea Basins opened by two distinct mechanisms. The western basin, except its eastern part, opened behind a continental fragment that orthogonally rifted and moved towards the southeast along two parallel deep fault zones: the sinistral OS (together with the West Crimean — Pontides) and dextral Balkanides — Pontides (BP) faults. The rest of the Black Sea Basin has originated through the anticlockwise rotating of a large continental block that produced the breaking of the EBSB rift and forming Odessa-Sinop-Ordu (OSO) fault zone. The dextral strike-slip faults in this zone caused the opening of eight local pull-apart basins in the southeastern West Black Sea Basin. The OS fault system, as a long-term feature appears to control the strikes of the Western and Eastern Pontides and the present-day obliquity between the main rift axes of the Black Sea sub-basins. The direct southeastern prolongation of the OS fault forms the western boundary of the pre-Cretaceous strata of the Eastern Pontides.

Key words: Black Sea, crystalline crust, faults, opening mechanism.

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