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Geological structure and tectonic evolution of the Ukrainian sector of the Black Sea

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The entire Ukrainian sector of the Black Sea, which occupies its northernmost part, was studied with the interpretation of the post-1990 seismic reflection data along seismic lines having a total length of some 30 000 km. In the northern Black Sea relatively low extension of the continental crust occurred in Albian-Cenomanian times and did not cause formation of deep (sub)-oceanic basins. Rift faults formed three major rift basins. One of the ENE-WSW oriented rift basins occupied areas of the present-day Karkinit Through, Krylov-Zmiiny Uplift, Gubkin Ridge and Sulina Depression within the Odessa Shelf. Another ENE-WSW oriented basin included areas of the present-day Tetyaev High, Sorokin Trough, Crimea Mountains and Marine Continuation of the Crimean Folds. The NW-SE oriented major rift basin occupied areas of the present-day Andrusov Ridge, Eastern Black Sea Basin, Shatskiy High and Euxinian Graben. Passive, thermal (post-rift) subsidence lasted in Turonian—Middle Eocene times and occurred in marine basins with a water depth that did not exceed a few hundred meters. A strong regional compression at the end of the Middle Eocene interrupted the post-rift (thermal) subsidence of rift basins, strongly deformed the sedimentary cover and formed a large NW-SE oriented landmass. This onshore terrain occupied the central and southern parts of the Odessa Shelf and the Crimean Peninsula, and deep-water area, including the Euxinian Graben, Marine Continuation of the Crimean Folds, Sorokin Trough, Tetyaev High, Andrusov Ridge, Shatskiy High and Eastern Black Sea Basin. Up to 5 km of sediments were eroded during the time of the existence of the emerged onshore terrain. Two subsequent S—N compressional events occurred at the end of the Late Miocene and invoked folding and thrusting of the sedimentary sequences in the originally ENE-WSW Cretaceous rift basins mainly. Anticlinal structures on the Odessa Shelf underwent additional growth and numerous new anticline folds were generated on the margins of the Western Black Sea Basin, including the Sorokin Trough and Marine Continuation of Crimean Folds. During both Late Miocene compressional events broad landmasses arose across the northern Black Sea region. These onshore terrains ran in a roughly E-W direction and occupied the present-day shallow shelves and northern part of the current deep water as well as almost the whole Crimea Peninsula. Like the Late Eocene landmass, the Late Miocene onshore terrains were evidently a source of sediments into marine basins that surrounded them. The first Late Miocene compression probably coincided in time with the Messinian Salinity Crisis and it was apparently accompanied by a sharp fall of the sea level. Prior to the second Late Miocene compressional event the sea level had risen sufficiently that a considerable part of the Odessa Shelf and other parts of the middle Pontian landmass were covered, at least periodically, by a shallow sea. The present-day deep-water part of the study area began to subside rapidly in the Pliocene. The mechanical response to this rapid subsidence appears to have reactivated normal faulting of the previously inverted south-dipping rift faults along the coast of the Crimean Mountains and in the eastern part of the Euxinian Graben during the Pleistocene and possibly Holocene. The very rapid subsidence and lack of sedimentary supply led to sub-oceanic water depth in the Western and Eastern Black Sea basins that had previously developed as relatively shallow seas.

Key words: Black Sea, Odesa Shelf, Eastern Black Sea Basin, Western Black Sea Basin, Andrusov Ridge, tectonic evolution, inverted rift structures, rifting, compression, Messinian event, Mesozoic, Cenozoic, seismic interpretation.

1. Introduction. This paper describes the main geological structures and the tectonic evolution of the entire Ukrainian sector of the Black Sea as well as the geological nature and present-day structure of the regional tectonic units found in the study area (Figs. 1, 2). The research has been conducted on the basis of the interpretation of seismic reflection lines covering the entire study area and having a total length of more than 30.000 km (see Fig. 2).

The Ukrainian sector of the Black Sea occupies some one quarter of the whole sea and most of its northern part (see Fig. 1). The present-day deep-water sea floor is an almost flat abyssal area lying at the maximum depth of 2211 m below sea level in the southernmost study area and it gradually rises northward to the continental slope, which is at depth from 1000 m to 200 m and has a dip varying from 10° to 40°. The shallow-water area includes the most part of the wide North-Western (Odesa) Shelf located to the west of the Crimea Peninsula as well as the Pre-Crimea Shelf and Pre-Kerch Shelf that occupy the relatively narrow offshore zone to the south of the Crimea Mountains and the Kerch Peninsula, which is a part of the Crimea Peninsula (see Fig. 1).

The geological study of the Black Sea began in the first half of the 20th century [Andrusov, 1926; Arkhangelskiy, Strakhov, 1938; Muratov, 1955, 1969 and many others]. Basic knowledge about the geological structure of the Black Sea as a whole and its Ukrainian sector in particular has been obtained with 2D marine regional and exploratory seismic reflection surveys since the 1970s [Tugolesov et al., 1985; Finetti et al., 1988; Belousov, Volvovskiy, 1989; Petroleum Geology…, 1994; Robinson, Kerusov, 1997; Stovba et al., 2003; Stovba, Khriachtchevskaia, 2006; Gerasimov et al., 2008; Graham et al., 2014; Nikishin et al., 2015a,b; Sydorenko et al., 2016 and references thereafter]. The Odesa shelf has been studied in more detail, with more than eighty deep wells drilled in the area [Astakhova et al., 1984; Melnik, 1985; Bogaets et al., 1986; Shnyukov, 1987].

In spite of the considerable progress made in understanding the geology of both the entire Black Sea and its Ukrainian sector many issues debated for many decades and related to the stratigraphy, tectonics and evolution of the Black Sea region, have not been completely resolved [Muratov, 1969; Tugolesov et al., 1985; Zonenshain, Le Pichon, 1986; Finetti et al., 1988; Görür, 1988; Dercourt et al., 1993; Okay et al., 1994; Robinson et al., 1995, 1996; Jones, Simmons, 1997; Banks, Robinson, 1997; Spadini et al., 1996, 1997; Robinson, Kerusov, 1997; Nikishin et al., 1998, 2001, 2003, 2012, 2017; Morosanu, 2002; Meredith, Egan, 2002; Cloetingh et al., 2003; Starostenko et al., 2004; Stephenson et al., 2004; Dinu et al., 2005; Saintot et al., 2006; Barrier, Vrielynck, 2008; Khriachtchevskaia et al., 2007, 2009a, b, 2010; Stovba, Khriachtchevskaia, 2009, 2011; Stovba et al., 2009, 2013, 2017a, b; Slyshynsky et al., 2007; Meijers et al., 2010; Stephenson, Schellart, 2010; Munteanu et al., 2011; Okay, Nikishin, 2015; Sydorenko et al., 2016; Sheremet et al., 2016b; Sosson et al., 2016; Hippolyte et al., 2016, 2018]. Among these outstanding issues, several key ones are: (1) the structure of the main regional tectonic units at different stratigraphic levels within the sedimentary cover; (2) triggering and driving mechanisms of the formation of the main tectonic units; (3) the timing, duration and geological consequences of tectonic events that took place in the Black Sea region since the Cretaceous.

The research results presented in this paper illuminate new information that may help to resolve the problems mentioned above, at least for the northern Black Sea. Some of these results are in contradiction to many modern tectonic and geodynamic models of the Black Sea region.

Some of the results presented here have been described in unpublished reports [Stovba et al., 2003, 2006; Stovba, Popadyuk, 2009] and some elements have been reported in published works [Khriachtchevskaia et al., 2007, 2009a,b; 2010; Stovba et al., 2009] and conference papers [Stovba, Khriachtchevskaia, 2009, 2011; Stovba et al., 2013, 2017a,b].

2. Seismic data and interpretation.

2.1. Seismic profiles. In 1994—1995 Western Geophysical conducted a 2D regional

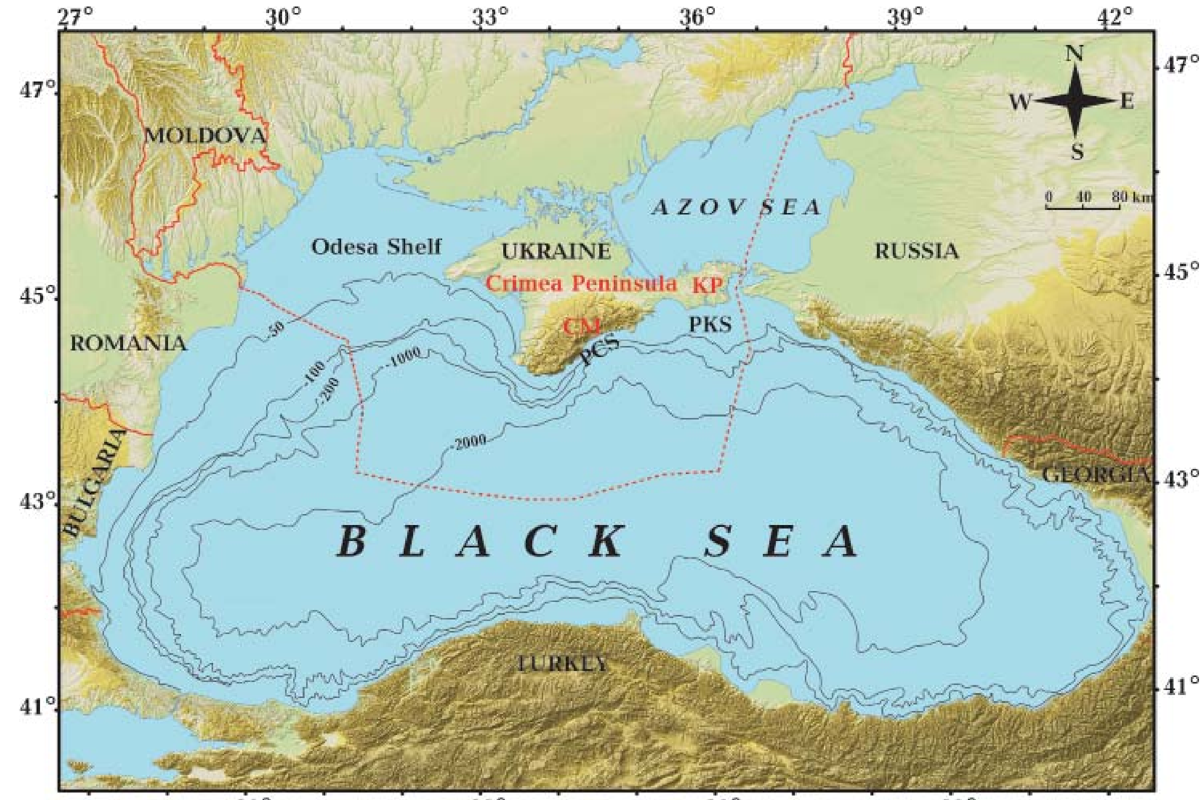


Fig. 1. Physiographic map of the Black Sea region. Red lines are country boundaries; red dashed line is the boundary of the Ukrainian sector of the Black Sea and Azov Sea. Abbreviations: CM — Crimean Mountains; KP — Kerch Peninsula; PCS — Pre-Crimea Shelf; PKS — Pre-Kerch Shelf.

seismic reflection survey along profiles having a total length of 17500 km (UBS94 project) and a spacing of 7—14 km (see Fig. 2). In 2005 the Polar Trade Research Associates acquired an additional set of regional seismic reflection profiles that have a cumulative length of 9870 km and a spacing of 22—28 km (BS05 project). The UBS94 and BS05 regional seismic data are of high quality and they provide an excellent opportunity for solving the existing problems on the geology and evolution of the northern Black Sea taken in combination with other geological and geophysical information [Khriachtchevskaia et al., 2007, 2009a, b, 2010; Stovba et al., 2009; Sheremet et al., 2016b; Sydorenko et al., 2016].

The UBS94 and BS05 data form the basis of the investigations reported in this paper but are augmented by additional semi-regional and exploratory seismic lines that were acquired by the Prychernomor State Regional Enterprise (Ukraine) and the State Geophysical Enterprise Ukrgeofizika (Ukraine) in 1995 and 2001 (see Fig. 2).

Seismic sections imaging the structure of the sedimentary cover within the entire study area are shown in Figs. 3—8. The lowermost sedimentary strata in the most buried areas of the Western Black Sea Basin (WBSB) and Eastern Black Sea Basin (EBSB) have been successfully studied with seismic lines of the BS05 project solely. This is because the UBS-94 project recorded only to 9 s whereas the acquisition interval for the BS05 project was equal to 15 s in deep water. More information about acquisition parameters and the basic processing sequence for the seismic data gathered in the study area can be found in [Sydorenko et al., 2016].

The quality of seismic sections is poor in some areas and at deeper levels within the sedimentary succession because of low signal to noise ratio and/or the presence of multiples. Besides multiples, strong out-of-plane reflec-

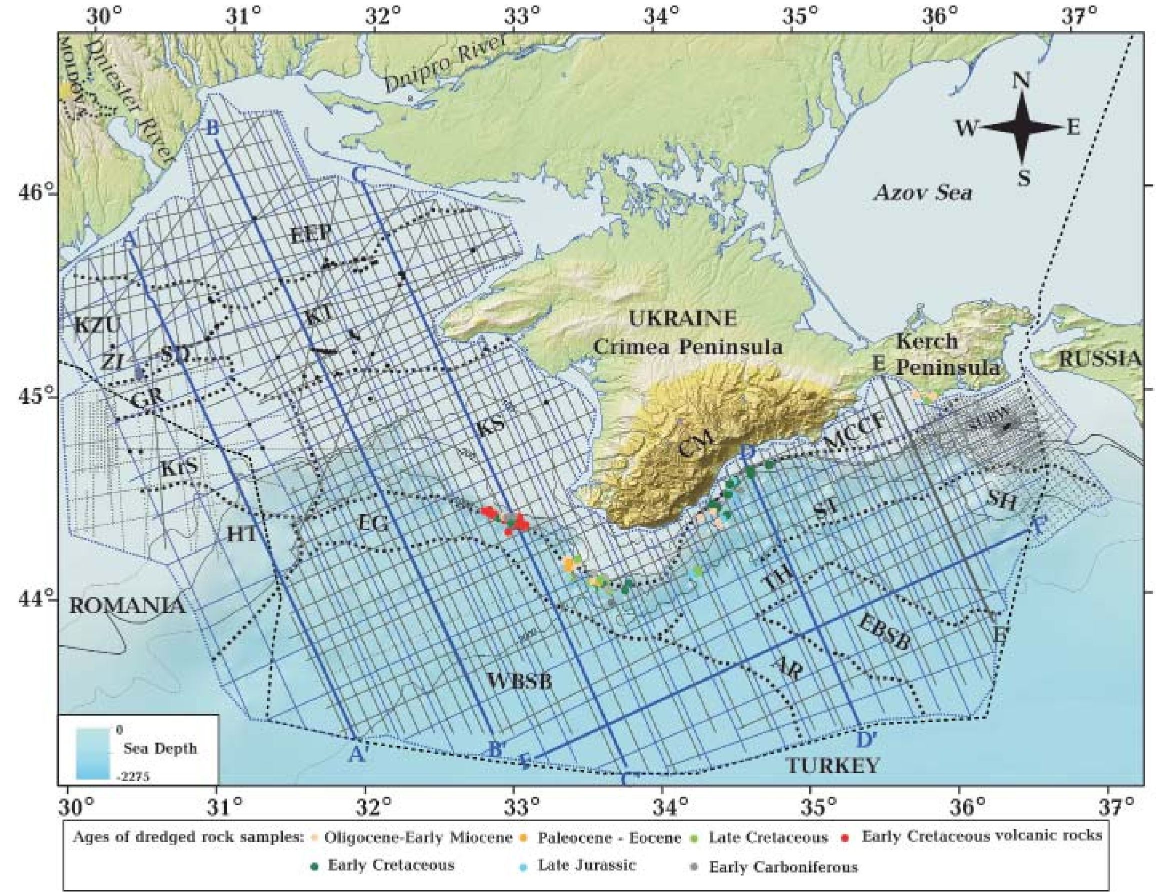


Fig. 2. Physiographic map of the study area and contours of regional tectonic units (in black bold dotted lines), locations of key offshore wells (black dots), interpreted seismic reflections profiles (grey and blue lines), locations and ages of rock samples dredged from the sea bottom (colour dots). The regional seismic lines conducted in the framework of BS05 and UBS94 projects are shown in blue and grey lines respectively; seismic lines of other 2D seismic surveys are shown with grey dashed lines. The area of seismic study is shown with blue dashed line. The black dashed line is the limit of the Ukrainian sector of the Black Sea. The seismic profiles shown in Figs 3—8 are in blue and grey bold lines. Abbreviations of tectonic units and wells: AR — Andrusov Ridge; CM — Crimean Mountains; EBSB — Eastern Black Sea Basin; EEP — Eastern European Platform; EG — Euxinian Graben; GR — Gubkin Ridge; HT — Histria Trough; KrS — Krayova Step; KS — Kalamit Swell; KT — Karkinit Trough; KZU — Krylov-Zmiiny Uplift; MCCF — the Marine Continuation of the Crimean Folds; SD — Sulina Depression; SH — Shatskiy High; ST — Sorokin Trough; SUBW — Subbotina wells; TH — Tetyaev High; WBSB — Western Black Sea Basin; ZI — Zmiiny Island, coincident with the location of the Morskaya-1 well (black dot).

tions, from faults not eliminated by seismic processing, are apparent in highly deformed parts of the present-day continental slope. In such cases the relatively low quality of seismic images complicates the seismic interpretation. The correlation of reflecting horizons within the areas can be done conditionally only with the use of wave field singularities and peculiarities of geometry of reflection horizons that have been recognised in nearby seismic lines having better seismic images.

2.2. Stratigraphic calibration of regional seismic horizons. The oldest rocks encountered in several offshore boreholes in the area are Archean—Proterozoic metamorphosed rocks and intrusive complexes of the basement of the East European Platform [Kruglov, Tsypko, 1988]. Upper Proterozoic rocks occur within boreholes on adjacent onshore areas, e. g. [Astakhova et al., 1984; Melnik, 1985; Kruglov, Tsypko, 1988; Nikishin et al., 2001].

Lower Devonian and Upper Silurian limestones penetrated by the Morskaya-1 well on the Zmiiny Island are the oldest, weakly metamorphosed sedimentary rocks encountered on the Odesa Shelf (see Fig. 2).

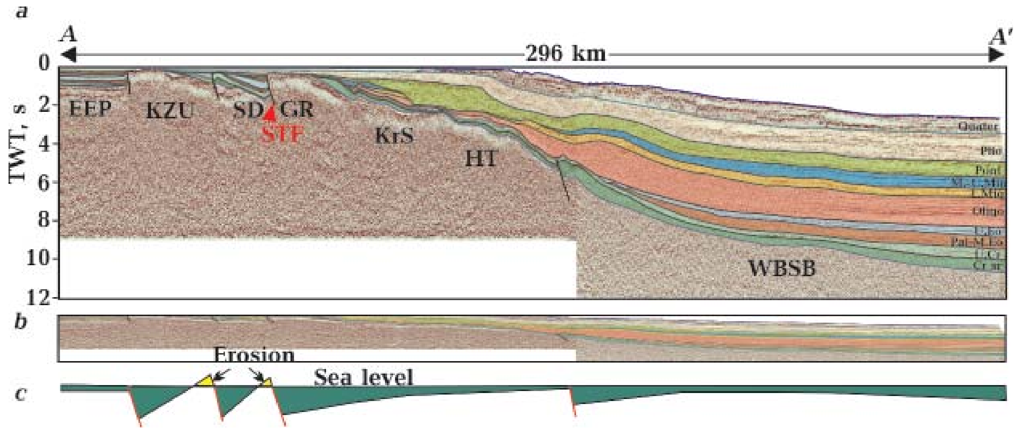


Fig. 3. Interpreted seismic reflection profile A—A′ (*a*); the same profile with vertical scale reduced in 5 times is shown in (*b*). A simplified paleotectonic reconstruction of basin structure along the profile during Cretaceous rifting is demonstrated in (*c*); no depth scale is applicable for the reconstruction. The location of the profile is shown in Fig. 2. Quater — Quaternary; Plio — Pliocene; Pont — middle and upper Pontian; M.-U.Mio — Middle and Upper Miocene; L.Mio — Lower Miocene (upper part of Maykopian sediments); Oligo — Oligocene (lower part of Maykopian sediments); U.Eo — Upper Eocene; Pal.-M.Eo — Paleocene—Middle Eocene; U.Cr — post-rift Upper Cretaceous; Cr sr — Lower and Upper Cretaceous syn-rift sediments. STF — Sulina-Tarkhankut Fault. The abbreviations for the tectonic units are described in Fig. 2.

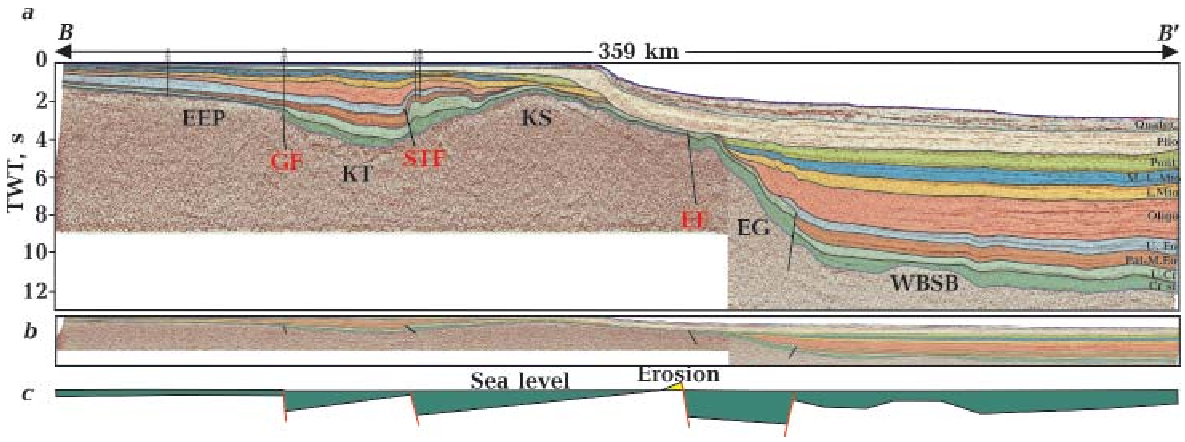


Fig. 4. Interpreted seismic reflection profile B—B′. See Fig. 3 for explanation; see also Fig. 2 for abbreviations of regional tectonic units and Fig. 3 for abbreviations of sedimentary sequences. Abbreviations of fault names (in red): GF — Golitsin Fault; EF — Euxinian Fault; STF — Sulina—Tarkhankut Fault.

Triassic, Jurassic and Neocomian-Aptian sediments were penetrated at the well bottom of several offshore wells [Gozhik et al., 2006; Khriachtchevskaia et al., 2009b, 2010]. Some researchers believe that the sedimentary strata of the Karkinit Trough lie directly on the basement of the Scythian plate [Astakhova et al., 1984; Shnyukov, 1987]. However, there are no valid geological data confirming this assertion. The age of sedimentary strata overlying the crystalline basement of the Karkinit Trough is debatable. Different authors consider ages spanning the Paleozoic to the Triassic—Jurassic [Astakhova et al., 1984; Nikishin et al., 1998; Khriachtchevskaia et al., 2007, 2009b].

The stratigraphic calibration of regional reflecting horizons and seismic sequences on the Odessa Shelf was made according to more than 40 stratigraphic and exploration offshore wells. Their locations are shown in Fig. 2. Despite some problems with the stratification of sedimentary rocks, which remained even after revision of the palaeontology of key wells

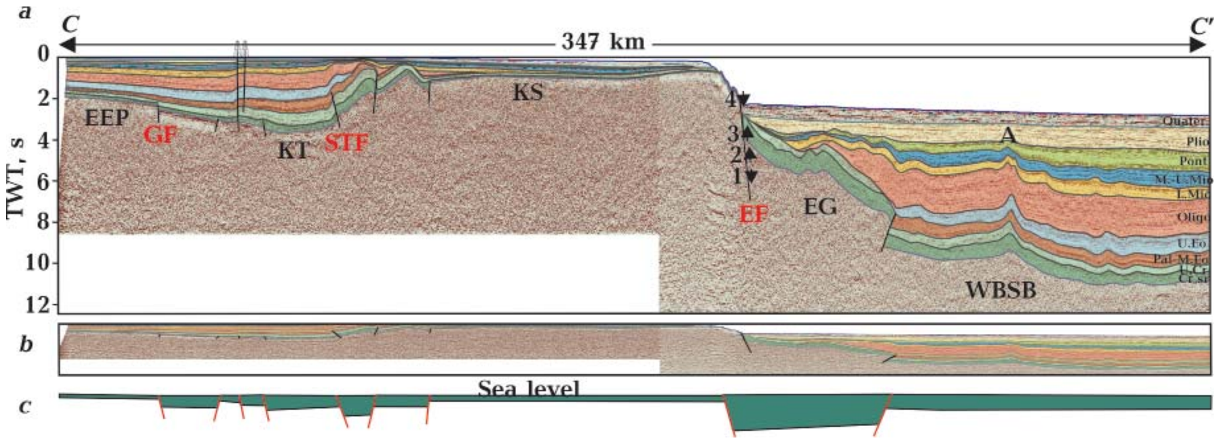


Fig. 5. Interpreted seismic reflection profile C—C′. See Fig. 3 for explanation; see also Figs. 2—4 for abbreviations of regional tectonic units, faults and sedimentary sequences. Black arrows show directions of movements of the EF hanging wall during: 1 — Cretaceous rifting; 2 — Eocene compression; 3 — Late Miocene compressions; 4 — Quaternary extension. The anticline labelled «A» is a local structure that was formed in the WBSB under submarine conditions during the Late Miocene compression events.

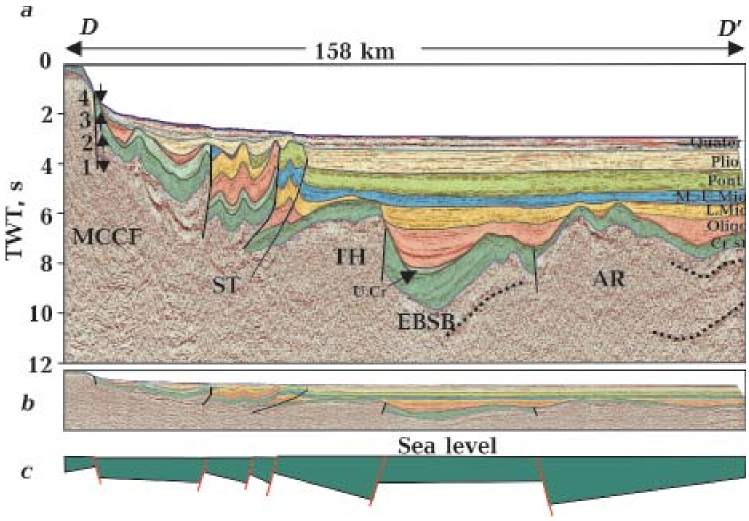


Fig. 6. Interpreted seismic reflection profile D—D′. See Fig. 3 for explanation; see also Figs. 2—3 for abbreviations of regional tectonic units and sedimentary sequences. Black arrows show directions of movements of the hanging wall at the present-day continental slope during: 1 — Cretaceous rifting; 2 — Eocene compression; 3 — Late Miocene compressions; 4 — Quaternary extension. The dotted lines beneath the Cretaceous syn-rift sequence correspond to horizons illuminating the structure of pre-rift sediments in the EBSB and Andrusov Ridge.

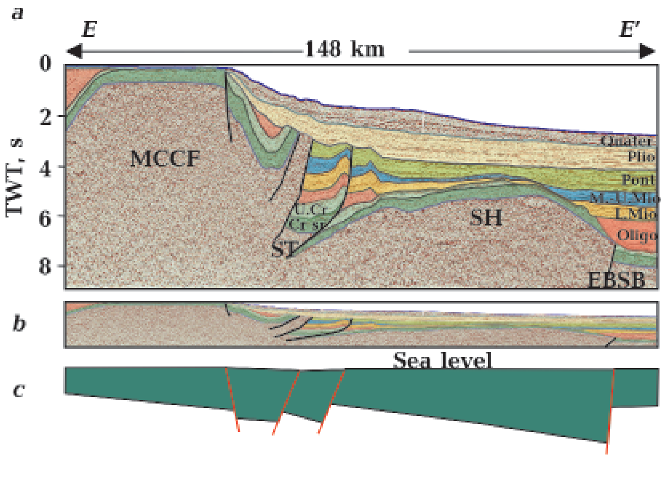


Fig. 7. Interpreted seismic reflection profile E—E′. See Fig. 3 for explanation; see also Figs. 2—3 for abbreviations of regional tectonic units and sedimentary sequences.

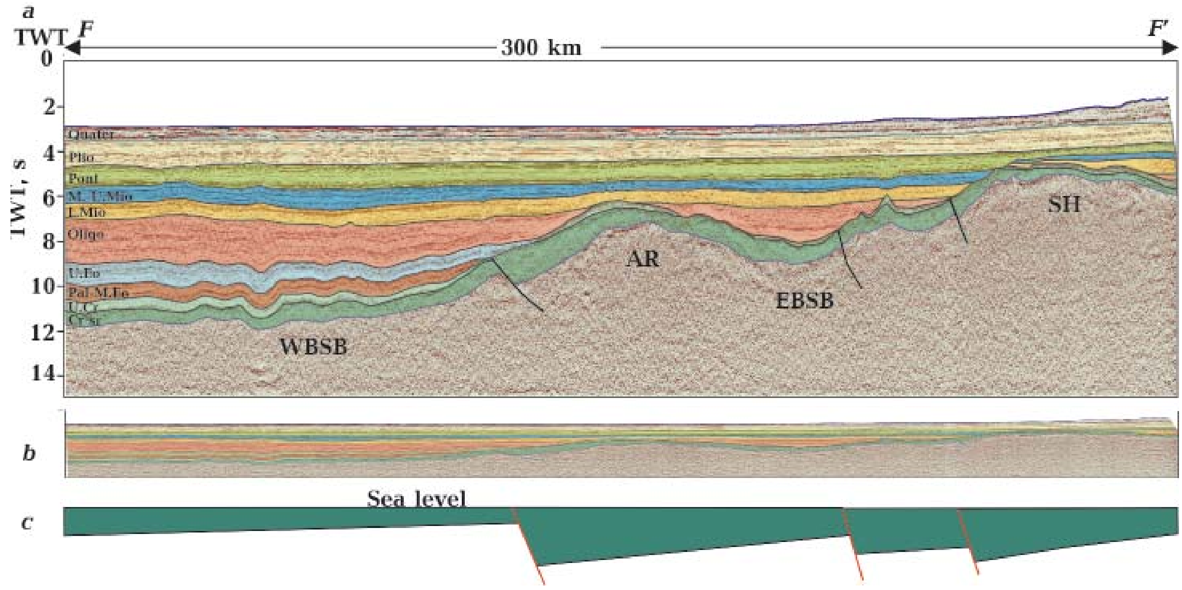


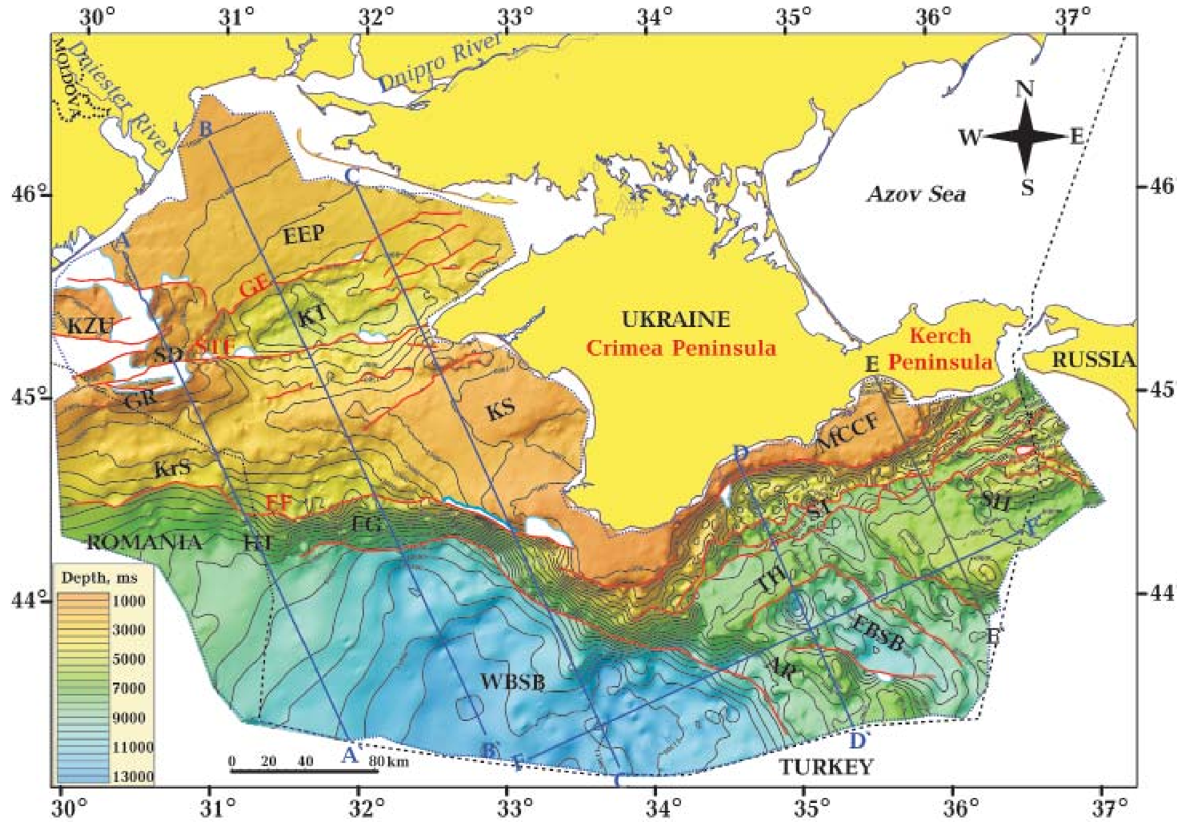
Fig. 8. Interpreted seismic reflection profile F—F'. See Fig. 3 for explanation; see also Figs. 2, 3 for abbreviations of regional tectonic units and sedimentary sequences.

[Gozhik et al., 2006; Khriachtchevskaia et al., 2009b], the existing wells allowed calibration of seismic reflections from boundaries of sedimentary sequences throughout the shelf from the Albian, Lower Cretaceous to the Pliocene-Pleistocene (see Figs. 3—5). Seismic horizons from sediments older than Albian are recorded only sporadically. Therefore, it is impossible to trace them uninterruptedly even across any given tectonic element. Consequently, the structure and composition of the sedimentary succession underlying the Albian sediments of the Lower Cretaceous, is discussed only briefly in this paper.

The absence of wells drilled in the deep water of the Ukrainian offshore is the major problem for stratigraphic calibration of seismic sequences in the area. This problem is complicated by the difficult to impossible task of carrying out a continuous correlation of seismic sequences from the Odesa Shelf to the deep water because of the sharp thickness decrease and, sometimes, the complete pinching out of sedimentary complexes towards the Kalamit Swell, the Krayova Step, the northern part of the WBSB, and the presence of joint fissures at the current edge of the shelf (see Figs. 3—5).

In order to find a way for stratigraphic calibration of seismic horizons in the deep water part of the study area we compared visible features of time-scaled seismic images along seismic lines crossing the WBSB and the central part of the Karkinit Trough within the Odesa Shelf. This approach has given a way to identify seismic sequences that are characterised by similar seismic features for the shelf and deep water. Furthermore, the reasonable assumption that the main phases of tectonic movements during regional compressional events took place simultaneously all over the northern Black Sea has allowed identifying the synchronous angular unconformities in areas where these movements led to deformations of sedimentary cover.

Within the Pre-Kerch Shelf the stratigraphic correlation of seismic horizons, which characterise the tectonic patterns of the upper part of the studied geological section, including the Eocene, was carried out with available data from three offshore wells drilled in the Subbotina structure (see Fig. 2) [Yeger et al., 2008; Stovba et al., 2009]. The continuous correlation of reflections, which were strictly tied to these wells, over long distances and the application of the same technical approaches that had been applied for stratification of seismic sequences in the WBSB, were used to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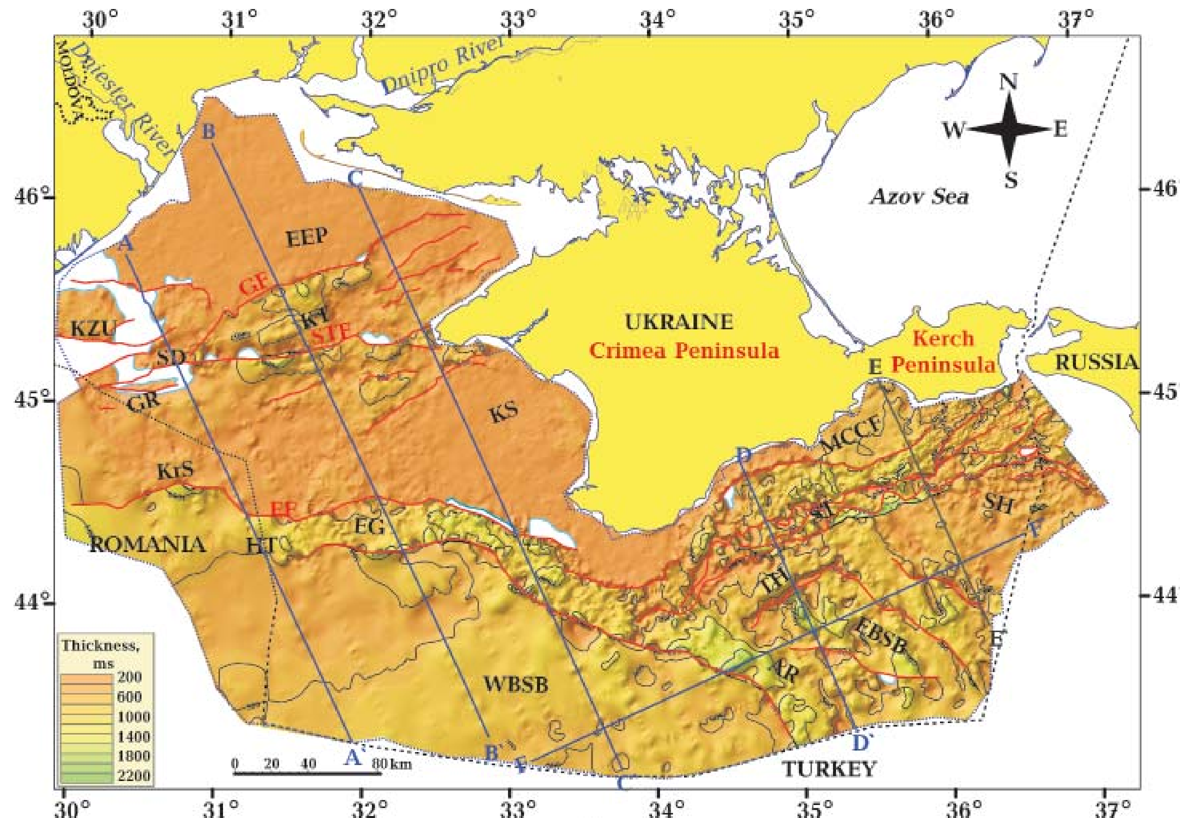
a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b

trace the regional seismic reflections across the eastern part of the Ukrainian offshore, including the Andrusov and Shatskiy ridges, the EBSB, the Sorokin Trough and the submarine continuation of the Crimea Folds.

An extended data set, which includes the results of a study of bedrock samples dredged on the northern continental slope, geological mapping of outcrops on the sea bottom by submersibles, and available data from short boreholes drilled up to 15 m beneath the sea bottom [Shnyukov et al., 1997, 2003; Ivannikov et al., 1999; Ivannikov, Stupina, 2003; Shnyukov, Ziborov, 2004 and references thereafter], played a key role for seismic interpretation in the deep-water part of the study area. Locations of submarine sampling are shown in Fig. 2. The ages of a number of sampled sedimentary rocks were previously identified as Triassic—Early Jurassic (Tavric Group) and Middle Jurassic by reason of the similarity of their lithology to the strata widely exposed in outcrops of the Crimea Mountains and are commonly referred to Triassic-Middle Jurassic [Ivannikov et al., 1999; Ivannikov, Stupina, 2003; Shnyukov et al., 1997, 2003; Shnyukov, Ziborov, 2004]. A few rock samples were considered as the Carboniferous, which were dredged from the continental slope to the south-west of Crimea Peninsula [Shnyukov et al., 1997].

Meanwhile, the authors of this paper carried out the fieldwork in 2010—2013 with the aim of new geological mapping of the Crimea Mountains [Popadyuk et al., 2013a, b, 2015a,b; Stovba et al., 2013]. One of main results of the fieldwork concerns the accurate definition of the age of 'Triassic-Middle Jurassic' siliciclastic sedimentary rocks mentioned above. A new study of microfauna in rock samples that were collected from many outcrops located in different parts of the Crimea Mountains showed that these rocks should be dated as not older than the Early Cretaceous. The age of a number of rock samples is definitely Albian (Early Cretaceous). The study of the peculiarities of facies distribution in the Crimea Mountains permits the conclusion that all analysed rock samples in onshore are most likely of the Albian age [Popadyuk et al., 2013a,b, 2015a,b]. The fact that in the central and eastern parts of the Crimea Mountains the sediments of the Tavric Group were not deposited earlier than in the Early Cretaceous has been recently confirmed by paleontological data recently obtained by [Sheremet et al., 2016a,b]. Taking into account the new data for the Crimea Mountains and comparing the geological mapping of the seabed and the results of seismic interpretation at sampling sites, we have assumed that all dredged rock samples, which were previously considered as the Triassic—Early Jurassic (Tavric Group) and Middle Jurassic, actually should be dated as Albian in age of the Early Cretaceous (see Fig. 2).

2.3. Seismic (seismostratigraphic) sequences. Ten seismostratigraphic sequences have been identified in seismic sections throughout the study area. In accordance to the stratigraphic calibration based on existing data the seismostratigraphic units correspond to the following sedimentary sequences: (1) the Cretaceous (Albian—Cenomanian) synrift sequence, (2) the Turonian—Maastrichtian of the Upper Cretaceous and (3) Paleocene—Middle Eocene post-rift sequences, (4) the Upper Eocene, (5) Oligocene (Lower Maykopian), (6) Lower Miocene (Upper Maykopian), (7) Middle—Lower part of Upper Miocene, (8) upper part of Pontian, uppermost part of Upper Miocene, (9) Pliocene

Fig. 9. TWT structural map at the base of the Cretaceous syn-rift sediments (*a*) and TWT thickness map of the syn-rift sequence (*b*) for the study area. Faults are shown in red lines. The profiles demonstrated in Figs. 3—8 are in blue and grey bold lines. The area of seismic study is shown with blue dashed line. The black dashed line is the limit of the Ukrainian sector of the Black Sea and Azov Sea. Abbreviations of fault names (in red): GF — Golitsin Fault; STF — Sulina-Tarkhankut Fault; EF — Euxinian Fault. See Fig. 2 for abbreviations (in black) of regional tectonic units. White spots in the footwalls of the Golitsin, Sulina-Tarkhankut and Euxinian rift faults correspond to the areas of absence of the syn-rift sedimentation, and white spots in the northern part of the Sorokin Trough and south-eastern area of the Andrusov Ridge correspond to areas of complete erosion of the syn-rift sediments during Cenozoic compression events.

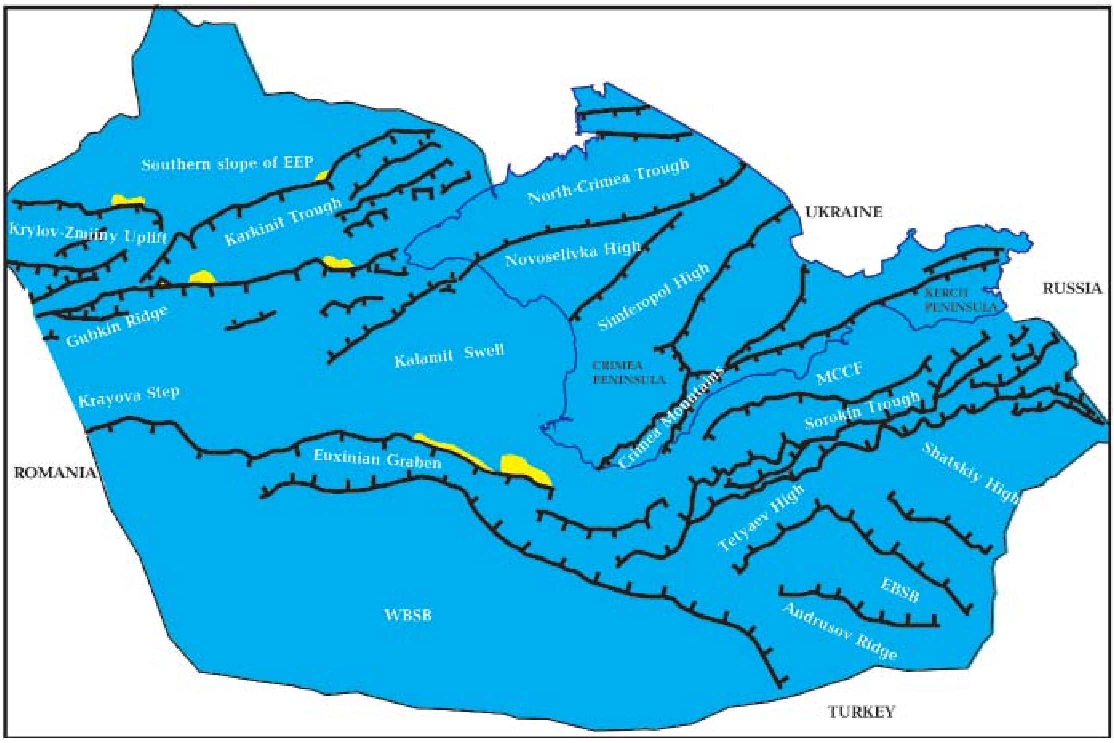


Fig. 10. Simplified paleotectonic reconstruction showing the distribution of rift faults (in black) and regional tectonic units during the Cretaceous rifting. Marine conditions of sedimentation are in grey. The footwalls of rift faults, which were emergent above sea level and subject to erosion, are shown in white. Locations of rift faults in the Crimea Peninsula are adopted from [Stovba et al., 2017a,b].

and (10) Quaternary post-rift sequences deposited in syn- and post-compressional settings (see Figs. 3—8).

The boundary between the Oligocene and Lower Miocene seismostratigraphic sequences is defined in seismic sections with some approximation, since even available offshore and onshore wells do not provide unambiguous faunal and lithological criteria to subdivide the Maykopian sediments into Oligocene and Lower Miocene successions [Muratov, 1969; Astakhova et al., 1984; Melnik, 1985; Gozhik et al., 2006; Khriachtchevskaia et al., 2009b].

2.4. Isochron and isopach maps. Ten isochron maps showing isolines of Two-Way Travel Time (TWT) for seismic horizons separating the seismostratigraphic units have been constructed in the issue of seismic interpretation. The maps characterise the geometry of the bases of the above-mentioned sedimentary sequences in those areas where they were accumulated and partially or wholly preserved.

On the basis of isochron maps the ten isopach maps (contours of equal vertical thickness in TWT scale) of corresponding seismic sequences have been constructed. All maps are built in time only because of a lack of valid velocity models for separate tectonic units in the deep-water area and for some areas of the shallow shelf as well.

3. Main Results.

3.1. Stages of tectonic evolution. The main stages of the tectonic evolution of the Odesa Shelf of the Black Sea identified on the basis of regional seismic studies are described in the papers and unpublished reports by [Stovba et al., 2003, Stovba, Popadyuk, 2009, Khriachtchevskaia et al., 2007, 2010]. The first stage is one of active crustal extension and rifting, which took place at the end of the Early Cretaceous — the beginning of the Late Cretaceous. The second stage is the passive post-rift (thermal) subsidence stage, which dominated from the middle of the Late Cretaceous up to the Middle Eocene. The third stage comprises a period of continued post-rift subsidence but with periodic inversional deformations caused by regional crustal compression at the end of the Middle and Late Eocene, as well as at the end of the Early and Late Miocene. The most intensive compressional deformation occurred at the end of the Middle Eocene and at the end of the Late Miocene [Stovba et al., 2017a,b].

The results of the interpretation of the available seismic data suggest that the same tectonic events that have been set for the Odesa Shelf affected the evolution and structure of sedimentary successions throughout the northern part of the Black Sea basin. It has been also identified that, in contrast to the Odesa Shelf, local extension appeared since the Pliocene or Quaternary in the area of the recent continental slope to the south and to the west of the Crimea Mountains [Stovba, Khriachtchevskaia, 2011; Stovba et al., 2013, 2017a,b].

3.2. The structure and accumulation of the Albian-Cenomanian syn-rift sequence. The TWT structural map at the base of the Albian-Cenomanian syn-rift sequence (Fig. 9, *a*) reveals all regional tectonic units known today. The units were formed since the end of the Early Cretaceous as a consequence of rifting, post-rift (thermal) subsidence and subsequent phases of post-rift tectonic shortening and faulting.

On the Odesa Shelf the seismic expression of the base of the Albian-Cenomanian syn-rift sequence is recognised quite clearly, except those areas where the Albian-Cenomanian sediments were not deposited or where they were eroded during subsequent uplift movements. In many parts of the deep water, particularly in the WBSB and Sorokin Trough, the base of the syn-rift sequence can be traced in a speculative way only, taking into consideration the nature of reflectivity around the base of the syn-rift unit. Therefore, although structural mapping outlines properly the main geometric features of the base of the syn-rift sediments (see Fig. 9, *a*), estimation of depth and thickness of the syn-rift unit can be done with a precision of 1—1.5 km only, given the lack of well calibrated velocity models.

The base of the syn-rift unit is deepest in the central part of the WBSB, where it reaches 15.5—16.5 km (12.0 s). In the EBSB its maximum depth is 12.5—13.5 km (~10 s). The shallowest depths of the base of the syn-rift unit are found in the Kalamit Ridge and Marine Continuation of the Crimean Folds. The sediments of the syn-rift sequence outcrop along extensive areas of the continental slope (see Figs 5—7). In addition to seismic data, this is evidenced by rock samples dredged from the sea bottom (see Fig. 2).

Features of seismic images reflecting the internal fabric of the syn-rift unit indicate that the syn-rift sediments were formed under conditions of contrast topography and permanent vertical displacements of large crustal blocks. The Albian-Cenomanian sequence overlies older rocks with angular unconformity. The sequence is characterised by sharp changes in the composition of depositional facies laterally and vertically and by the presence of multiple angular unconformities between certain strata within the sequence, as well as by significant differences of sediment thickness between hanging walls and footwalls of rift faults, which were growing simultaneously with sediment deposition (see Figs. 3—8).

The seismic interpretation and tentative paleo-reconstructions suggest that an extended system of grabens and half-grabens developed in Albian-Cenomanian time throughout the study area. The individual rift blocks were separated from each other by faults with vertical offsets ranging from several tens of meters to 2—3 km and more (see Figs. 3—8, 9, *b*). The origin of such (half)grabens is typical for rift basins, when crustal extension results in brittle deformation of the upper crust.

Seismic data and numerous occurrences of syn-rift magmatism on the Odesa Shelf, e.g. [Khriachtchevskaia et al., 2010], along the northern continental slope (see Fig. 2) and in the Crimea Peninsula [Shnyukov, 1987; Kruglov, Tsypko, 1988; Nikishin et al., 1998, 2001, 2003, 2012, 2017], as well as the presence of rift structures in the Crimea Mountains [Nikishin et al., 2001, 2003, 2017; Stovba, Khriachtchevskaia, 2011; Stovba et al., 2013, 2017a,b, Hippolyte et al., 2018], Romanian and Russian parts of the Black Sea [Zonenshain, Le Pichon, 1986; Nikishin et al., 2001; Dinu et al., 2005; Munteanu et al., 2011] indicate that crustal extension dominated during the Albian (Early Cretaceous) and continued to the Cenomanian (Late Cretaceous).

The new data mentioned above defining an Albian age of the Tavric (Tauric) Group and «Middle Jurassic» siliciclastic successions, which were uplifted and exposed in the Crimea Mountains during the Cenozoic phases of compression, are of particular importance in determining the time of rifting [Popadyuk, Smirnov, 1991; Popadyuk et al., 2013a,b, 2015a,b; Stovba et al., 2013, 2017a,b]. Consideration of the structural settings and facies distribution within the Crimea Mountains and at depth indicates that the clastic rocks that were previously referred to the Upper Triassic—Lower Jurassic («flysch» of the Tavric Group) and Middle Jurassic, were deposited in the Albian as part of the typical synrift succession [Stovba et al., 2013, 2017a,b; Popadyuk et al., 2013a,b].

The seismic data allow characterizing the general features of the structure of the Pre-Albian sedimentary section in some areas of the Karkinit Trough, Andrusov and Shatskiy ridges. In these areas, the sediments that lie directly below the Albian-Cenomanian succession are imaged in seismic sections by separate reflectors or by a set of reflectors, whichare almost parallel to the base of the rift sequence (see Fig. 6). The footwalls of the half-grabens that were uplifted above sea level and eroded during their formation are exceptions. There are unconformities between the pre-rift and syn-rift successions nearby the rift faults that reveal the erosion and, consequently, a decrease of thickness of the pre-rift sediments in the direction of the raised footwalls of (half)grabens. The character of the seismic reflections in the upper part of the pre-rift succession suggests that they were formed in a calm tectonic regime prior to the onset of crustal extension in the Albian.

It is instructive to point out that reflections from the deep horizons of the sedimentary strata and/or consolidated crust are recorded in some areas (see Fig. 6). These are traced with a noticeable angular unconformity to the upper part of the pre-rift strata. This may be an indication of tectonic processes that occurred in prior to the Albian in the Mesozoic or Paleozoic. Therefore, it cannot be precluded that the Early Cretaceous system of normal faults may be reactivating a system of older rift faults. Particularly, geological data provide evidence of Permian and/or Triassic rift processes in the Predobrogea Trough, which continued likely further to the east of the present-day Krylov-Zmiiny Zone of structural highs, e.g. [Banks, Robinson, 1997; Seghedi, 2001; Nikishin et al., 2001; Hippolyte, 2002]. Faults having Pre-Cambrian age has been recently predicted in the Black Sea by [Rusakov, Pachkevich 2017]. However, the clarification of timing, triggering and driving mechanisms of the pre-Albanian tectonic processes in the northern part of the Black Sea requires additional research and, therefore, it is not considered further in this paper.

Seismic and geological data indicate that the extensional tectonic processes terminated at the end of the Cenomanian. The Late Cretaceous and younger sediments overlapping the Albian-Cenomanian syn-rift sequence consist of facies that are imaged in the seismic sections with continuous parallel reflections having laterally invariable characteristics. Such behaviour is common for passive post-rift (thermal) subsidence of sedimentary basins (see Figs. 3—8). It is probable that in local areas of the Ukrainian Black Sea the effects of active rifting can be recognised in strata as young as Turonian in the Late Cretaceous. This is consistent with the discovery of volcanic rocks of this age on the southern Crimea and Kerch peninsulas [Nikishin et al., 2003]. However, the geological data are not sufficient for more precisely assesses of the termination time of active rifting in the Late Cretaceous.

Two major systems of Albian-Cenomanian generated rift faults trend roughly NEE-SWW and NW-SE within the studied part of the Black Sea. The former formed on the Odesa shelf and along the Crimea Peninsula. The latter formed in the eastern deep-water part of the Ukrainian Black Sea and approximately along the present-day continental slope in the western deep-water area (Figs. 9, 10). These faults and associated local (half) grabens played a crucial role for the tectonic evolution of the Black Sea during later stages of post-rift passive subsidence and eventual basin inversion.

3.3. Rift structures on the Odesa Shelf. ***Karkinit Trough and Kalamit Swell.*** The Karkinit Trough occupies a significant area of the Odesa Shelf (see Figs. 2, 4, 5, 9). This regional tectonic unit is part of the NEE-SWW rift system of (half)grabens. The (half)grabens are separated from each other by normal faults having mainly a southern dip and fault throws of up to 2 km and more. The current depth of the base of syn-rift sediments in the Karkinit Trough reaches 8—9 km and the maximum thickness of the sediments filling the (half) grabens is some 1—2 km but may be more.

During syn-extensional tectonics the uplifted footwalls of some (half)grabens were exposed above sea level and subject to erosion, as seen, for example, near the Golitsin and Sulina-Tarkhankut faults (see Figs. 4, 9, 10). Sedimentation in the footwalls resumed only after their subsidence below sea level at the end of the Albian-Cenomanian or at the onset of post-rift passive subsidence later in the Cretaceous. Those half-grabens that formed near hanging walls were being filled with sediments, the thickness of which gradually decreased or are completely pinched-out towards the uplifted parts of these half-grabens. The rift related topography led to an irregular distribution of syn-rift sediments in the Karkinit Trough. Even within the most buried parts of the Karkinit Trough there are areas where the syn-rift sediments are either completely absent or they have very small thickness (see Figs. 9, 10).

The Karkinit Trough is separated from its northern margin (the southern slope of Eastern European Platform) by the Golitsin Fault having a southern dip and an offset of up-to 1—2 km (see Figs. 4, 5, 9).

The Kalamit Swell is located to the south of the Karkinit Trough and can be considered as the southern shoulder of the trough. The junction of Kalamit Swell and the Karkinit Trough lies within the Odesa Shelf along the southernmost normal fault that dips to the north. (see Figs. 9, *a*, 10). The syn-rift sequence is relatively thin and has a rather simple structure in the eastern part of the Kalamit Swell (see Fig. 9). The swell is almost unfaulted with post-rift deformation of the sedimentary cover. Such features are typical for the margins of the majority of rift basins.

The Shtormove Graben is sometimes considered as a separate tectonic unit of the Odesa Shelf [Robinson, Kerusov, 1997; Nikishin et al, 2001; Dinu et al., 2005]. These authors have suggested that the graben is bounded to the north by the south-dipping Sulina-Tarkhankut faults with offset of 1—2 km (see Fig. 5; see also this graben between A and B profiles along the STF in Fig. 9, *b*). Indeed, this graben was formed along Sulina-Tarkhankut fault. However, it is located in the axial part of the Karkinit rift basin. So, the Shtormove Graben cannot be considered as a separate tectonic unit of the Odesa Shelf (see Figs. 4, 5, 9).

Several phases of the Cenozoic regional compression caused inversion displacements of the rift-forming faults. The most intensive deformation of the syn-rift and post-rift sequences, where inversion was accompanied by the formation of anticlines on the North-Western Shelf, occurred along the marginal rift faults and the Sulina-Tarkhankut fault (see Figs. 4, 5, 9, *a*). The mechanism of formation of these local structures has been discussed in more detail by [Robinson, Kerusov 1997; Stovba et al., 2003; Khriachtchevskaia et al., 2007, 2010].

Gubkin Ridge, Sulina Depression and Krylov-Zmiiny Uplift. These tectonic units are located to the west of the Karkinit Trough (see Figs. 2, 9, *a*). The seismic image of the Cretaceous syn-rift sequence (see Fig. 3, *a*) and the paleotectonic reconstruction by the end of rift stage (Fig. 3, *c*) indicate that the Albian-Cenomanian (half)grabens were formed prior to the present-day structural elevation. These extensional structures were a part of the single Karkinit-Gubkin rift basin (see Fig. 10) [Stovba et al., 2003; Khriachtchevskaia et al., 2010]. During the Cenozoic regional compressional phases they were inverted and transformed into the Gubkin Ridge, the Krylov-Zmiiny Uplift and the Sulina Depression. The vertical offset of the inversion displacements exceed 3 km. A significant part of the syn- and post-rift succession was exposed above sea level for a long enough for the crests of exposed folds to be eroded. In some areas the syn-rift sedimentary sequence was completely eroded, and pre-rift Paleozoic-Mesozoic-strata lie directly below the thin Miocene-Pliocene sedimentary succession (see Fig. 3). This observation is confirmed by the Morskaya-1 onshore well that penetrated Lower Paleozoic rocks on Zmiiny Island [Astakhova et al., 1984]. These rocks are covered by thin Neogene sediments.

Krayova Step. The Krayova Step was an uplifted part of the half-graben bounded by the Sulina-Tarkhankut fault that later became the Gubkin Ridge (see Fig. 3, *c*). This is evidenced by the increase of thickness of syn-rift sediments from the Krayova Step toward the arch of the Gubkin Ridge as well as by features of the Albian-Cenomanian fill of the half-graben that are typical for syn-rift half-grabens. Thus, before the Cenozoic inversion the Krayova Step developed as the western continuation of the Kalamit Ridge. These two regional tectonic units formed together as the southern margin of the single Karkinit-Gubkin rift basin.

3.4. Deep water rift structures. During the Albian-Cenomanian extensional tectonic phase NEE-SWW and NW-SE systems of (half)grabens originated along the present-day continental slope in the deep water of the northernmost Black Sea, as well as in the whole eastern part of the study area (see Fig. 10). These structures were separated from each other by faults with offsets from several hundred meters up to 2—3 km and more. The 1—3 km thickness of syn-rift sediments in the (half)grabens is comparable to the thickness of the syn-rift sequence in the Karkinit-Gubkin rift basin (Figs. 3—8, 9, *b*).

Euxinian graben. This Early Cretaceous graben is located in the northernmost part of the WBSB (see Figs. 4, 5, 9, *b*, 10). Its width varies from 15 to 35 km. The graben is separated from the Kalamit Swell and the Krayova Step by the south-dipping Euxinian Fault. These two tectonic units can be considered together as the northern shoulder of the Euxinian rift basin. The original vertical offset of the Euxinian Fault during Cretaceous rifting reached more than 2 km. According to the offshore seismic data the fault is possibly traced to the coastal line of the westernmost part of the Crimea Peninsula (see Figs. 5, 9, *b*, 10). On the peninsula itself this fault is probably a part of a system of Early Cretaceous normal faults formed in the area of the present-day Crimea Mountains (see Fig. 10) [Stovba, Khriachtchevskaia, 2011; Stovba et al., 2013, 2017a,b].

The Euxinian graben is separated from the WBSB by the north-dipping fault formed in Albian-Cenomanian time. In its eastern prolongation the fault had an original offset of several hundreds of meters to 1.5—2 km (see Figs. 4, 5). The fault throw gradually decreases to nil to the west (see Fig. 3). To the southeast the fault is traced along the western slope of the Andrusov Ridge (see Figs. 9, 10).

Sorokin Trough, Tetyaev Ridge and Marine Continuation of the Crimean Folds. The NEE-SWW system of (half)grabens that originated as a result of the Albian-Cenomanian extension were separated from each other by high-amplitude north-dipping faults in locations now occupied by the present Sorokin Trough and Tetyaev Ridge. The Marine Continuation of the Crimean Folds was separated from the Sorokin Trough by south-dipping rift fault (see Figs. 6, 7). Rift (half)grabens with almost the same strike as elsewhere were formed in the area of the Crimea Mountains during Cretaceous extension, as demonstrated by the recent geological fieldwork [Stovba, Khriachtchevskaia, 2011; Stovba et al., 2013, 2017a,b]. The (half)grabens were constituents of the northern part of a wider rift basin system (see Fig. 10). In contrast to the southern part of this system, the main faults within the Crimea Mountains are predominantly south dipping (Fig. 12). The width of the Cretaceous rift basin system varies from 60 to 120 km when the present Sorokin Trough and the Tetyaev Ridge and the onshore and offshore parts of Crimean folds are taken into account. The width of the rift basin, which is currently hidden by the Black Sea, changes from 50 to 80 km along the basin strike (see Fig. 10).

EBSB, Andrusov and Shatskiy ridges. Two vast graben-shaped structures were formed in the Early Cretaceous in the area of the present-day Andrusov Ridge, EBSB and Shatsky Ridge. These rift structures were separated from each other by NW-SE trending faults with vertical offsets of up to more than 1—2 km (see Figs. 8, 9, *b*, 10). In the easternmost part of the study area the footwall of the Shatskiy Ridge is separated from the pre-Caucasus part of the Black Sea (the Tuapse Trough) by NE dipping faults (see Figs. 9, *b*, 10).

The most intensive downwards movement of crustal blocks in the area of the Andrusov Ridge took place along the fault that separated this ridge from the WBSB at the level of the Cretaceous syn-rift sediments (see Figs. 8, 9, *b*, 10). The easternmost part of the WBSB that borders on the present-day Andrusov Ridge originally represented the footwall of this fault in Albian-Cenomanian time (see Figs. 8, *c*, 9, *b*).

High-amplitude rift faults are not recognised in the part of the WBSB covered by seismic lines (see Fig. 9, *a*). The only exceptions are the faults described above that led to the formation of the Euxinian graben and the graben located in the area of the present-day Andrusov Ridge. The humpbacked nature of the base of the syn-rift sequence and other seismic characteristics suggests that rifting processes also occurred in the WBSB during the Albian-Cenomanian extensional period. It is not precluded that during active rifting that part of the WBSB, now located in the Ukrainian offshore, was an uplifted shoulder of large half-graben(s). The respective lowered flanks of such half-graben(s) may now be located in the Romanian, Bulgarian and/or Turkish sectors of the Black Sea.

Almost all (half)grabens within the study area were affected by fold tectonics accompanied by vertical movements from several hundred meters to 4—5 km during the subsequent Cenozoic compression phases (see Figs. 3—8). Accordingly, on the map characterising the geometry of the base of the syn-rift sequence the systems of inverted grabens appear as being folded with SE and WE axial strikes (see Fig. 9, *a*). The Albian-Cenomanian syn-rift sequence was exposed above sea level for some time in the western part of the Karkinit-Gubkin rift, in the northern part of the Euxinian graben, on the Andrusov and Tetyaev and Shatskiy ridges, on the considerable area of the Crimea Mountains and along the southern nearshore of the Crimea Peninsula, as well as in the EBSB. As a result of the uplift, the Albian-Cenomanian sequence of these regional tectonic units was eroded partially and, in places, completely as it indicated by the exposed strata of the Krylov-Zmiiny Uplift and Crimea Mountains (see Figs. 3—8). It follows that the present-day thickness distribution of the syn-rift succession (see Fig. 9, *b*) is not identical to what it was at the end of active rifting.

3.5. Post-rift pre-folded sequences. The crustal extension in the northern part of the Black Sea gradually ceased from the beginning of the Late Cretaceous. The next stage of the tectonic evolution of the Black Sea region probably started in the Turonian and continued to almost the end of the Middle Eocene. During this time there was passive thermal (post-rift) subsidence of the whole study area. This post-rift stage of basin subsidence and sediment accumulation was characterised by a quiet depositional environment. On the seismic sections the whole sedimentary section relating to the Late Cretaceous—Middle Eocene post-rift stage can be subdivided into the Turonian-Maastrichtian and Paleocene—Middle Eocene sequences (see Figs. 3—8). These two post-rift sequences were partially or completely eroded within large areas of the shallow shelf, the continental slope and the eastern part of the Black Sea, due to uplift above sea level during the following compressional phases. The present boundaries of these sequences are mainly erosive ones (Figs. 11, 12). At the time of their formation the post-rift sediments covered the entire northern part of the Black Sea and the Crimea Peninsula (Fig. 13, *b*).

In areas where the Upper Cretaceous and Paleocene—Middle Eocene post-rift sediments are preserved from erosion as a whole or in part, the corresponding seismic sequences in the deep-water and shallower parts of the offshore point to sub-horizontal sedimentary bedding with no indication of disconformities or angular unconformities or abrupt thickness changes (see Figs. 3—8). The strongest, most laterally coherent, seismic reflections can be traced almost continuously over long distances and on the opposite sides of faults. All deformational structures complicating the Turonian-Maastrichtian and Paleocene—Middle Eocene sedimentary sequences, are consequences of post-depositional tectonic processes.

The bases of the Cretaceous and Paleocene—Middle Eocene post-rift sequences are deepest in areas that were least affected by Cenozoic compression. On the North-Western Shelf this concerns, first of all, the present axial part of the Karkinit Trough, where the base of the Upper Cretaceous post-rift sequence occurs at the depth of 6 km (see Fig. 11, *a*, 4.3 s) and the base of the Paleocene—Middle Eocene is at the depth of 4.5 km (Fig. 12, *a*, 3.5 s).

Thickness maps demonstrate that a syncline was formed above the Karkinit-Gubkin rift after the Turonian and before the Late Eocene (see Figs. 11, *b*, 12, *b*); this is a typical feature of post-rift basin evolution. The southern slope of the Eastern European Platform was the northern limb of this syncline. The Kalamit Swell and Krayova Step are its southern slope. These are documented by a gradual reduction of the thickness of the Upper Cretaceous and Paleocene—Middle Eocene sequences in both northern and southern directions away from the axial zone of the Karkinit-Gubkin post-rift succession. Before Cenozoic compression the axis of the trough ran approximately along the Sulina-Tarkhankut fault (see Figs. 11, *b*, 12, *b*). The maximum thickness of the Upper Cretaceous post-rift sequence in the axial zone of the trough reaches more than 1.5 km, and the Paleocene—Middle Eocene sequence 1.0 km. The area of the Karkinit-Gubkin Trough to the south of the Sulina-Tarkhankut fault and the entire western part of the trough were affected by strong Cenozoic compressional deformation. As a result, the primary axis of subsidence of the Karkinit post-rift basin shifted to the north of this fault once compression had begun (see Figs. 4, 5).

The Kalamit Swell displays little extension during the active rifting phase (see Figs 4, 5, 9) and, accordingly, during post-rift phase it was relatively stable subsided substantially slower than the Karkinit Trough to its north and the Euxinian graben to its south. Thereby, in relation to the trough and graben, the Kalamit Swell acted as the southern and northern syncline limbs respectively. Significant reduction of the present thickness of the Turonian—Middle Eocene sequence within the Kalamit Swell in comparison with the Karkinit Trough (see Figs. 4, 5, 11, *b*, 12, *b*) is due to its erosion during the Cenozoic compression phases, when the ridge was raised above sea level, and partly due to a low rate of post-rift subsidence compared to adjacent troughs, possibly including non-deposition of sediments at certain times.

Only the deep water WBSB did not undergo deformations during Cenozoic compressional phases. The whole Upper Cretaceous and Paleocene—Middle Eocene sequences have been preserved (see Figs. 11, 12). In the WBSB the post-rift sequences are characterised by conformable bedding and stable lithological character over significant distances (see Figs. 3—5, 8). The maximum depth of the base of the Upper Cretaceous post-rift sequence in the basin is some 14.5—15.5 km (see Fig. 11, *a*, 11.5 s).

It should be noted that the thicknesses of the Upper Cretaceous and Paleocene—Middle Eocene post-rift sequences in the WBSB are comparable with the ones in the axial zone of the Karkinit Trough. The same observation applies to those parts of the Sorokin Trough, specifically to the area to the south of the Kerch Peninsula near the Russian border, where the Upper Cretaceous and Paleocene—Middle Eocene post-rift sequences were not affected by erosion (see Figs. 11, *b*, 12, *b*).

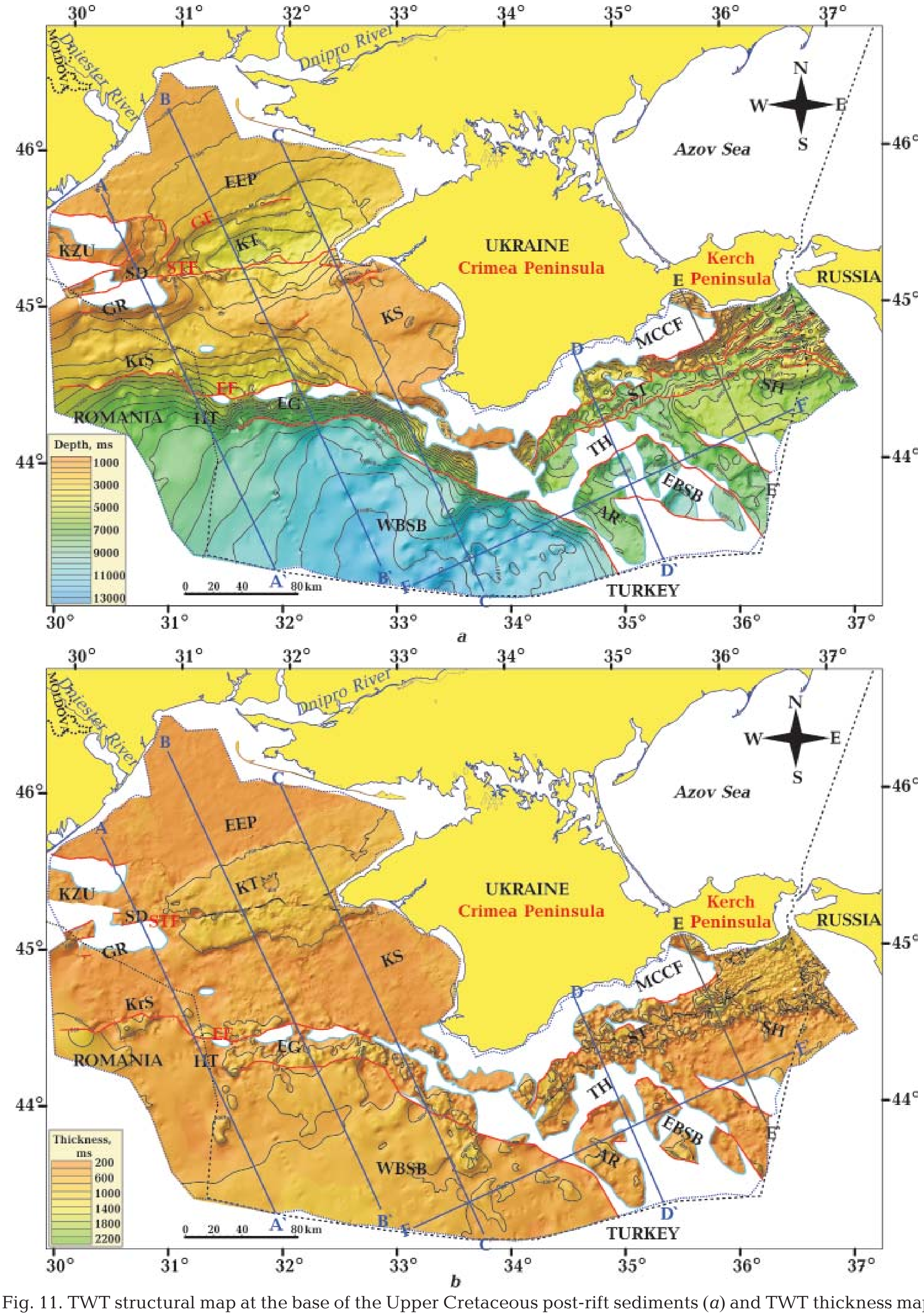


Fig. 11. TWT structural map at the base of the Upper Cretaceous post-rift sediments (*a*) and TWT thickness map of the Upper Cretaceous post-rift sequence (*b*) for the study area. See Fig. 2 for abbreviations of tectonic units and Fig. 9 for other explanations and abbreviations.

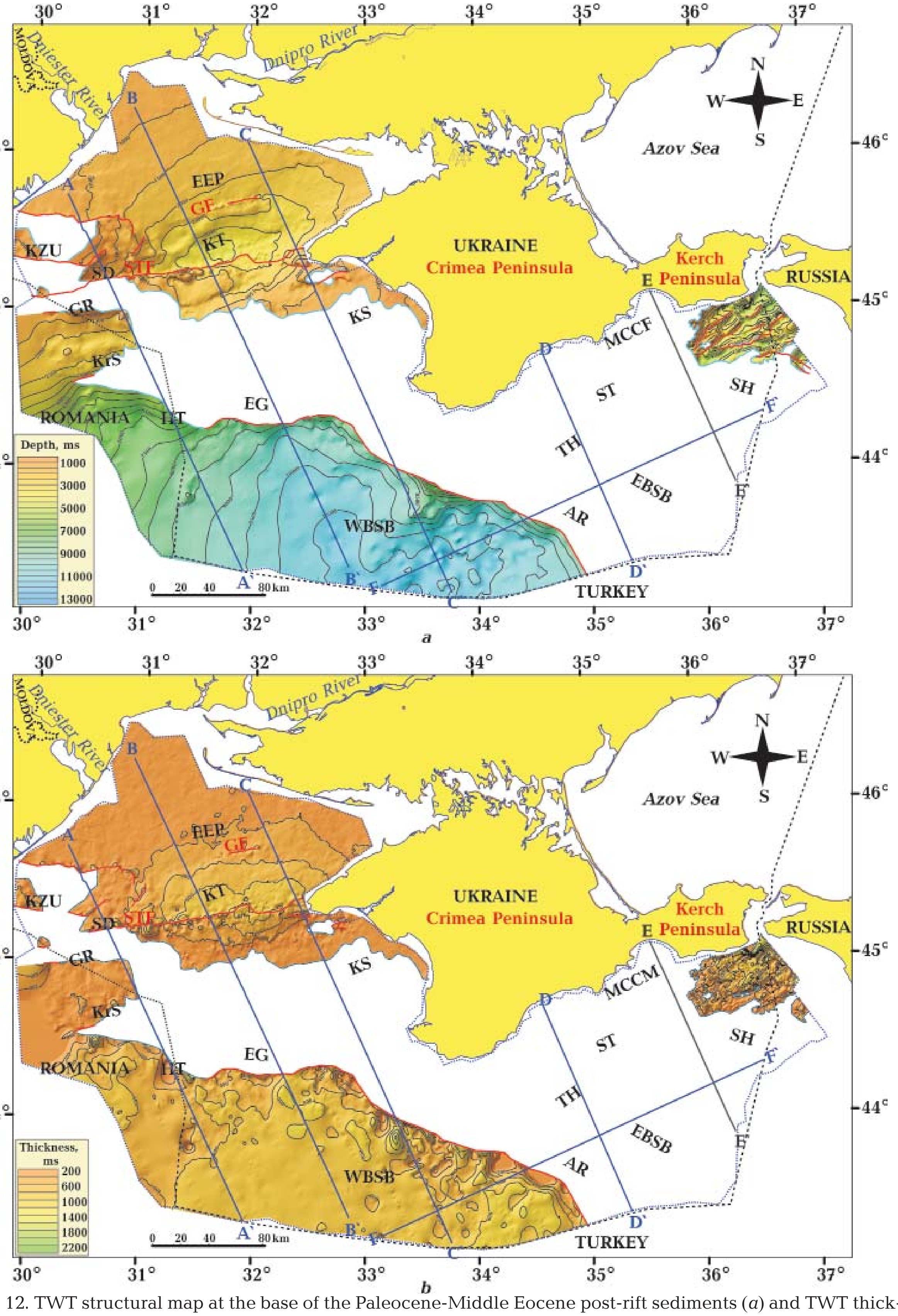


Fig. 12. TWT structural map at the base of the Paleocene-Middle Eocene post-rift sediments (*a*) and TWT thickness map of the Paleocene—Middle Eocene post-rift sequence (*b*) for the study area. See Fig. 2 for abbreviations of tectonic units and Fig. 9 for other explanations and abbreviations.

3.6. Eocene compression and its consequences. The tectonically quiet post-rift subsidence of the Black Sea (see Fig. 13, *b*) was interrupted by several phases of significant compression, which occurred from the end of the Middle Eocene to the end of the Miocene [Stovba et al., 2003, 2013, 2017a,b, 2018; Khriachtchevskaia et al., 2010]. These phases of tectonic activity periodically led to strong changes of the basin architecture and depositional environment. The most intense folding caused by regional compression occurred at the end of the Middle Eocene and at the end of the Late Miocene [Stovba et al., 2017a,b].

It is likely that in the Eocene the compression took place during two relatively short phases, namely at the end of the Middle Eocene and at the end of the Late Eocene [Stovba, Popadyuk, 2009; Khriachtchevskaia et al., 2010]. The Eocene compression acted in a NE direction, almost normally to the strike of the Andrusov Ridge, as shown in Fig. 13, *c*. This direction of compression is confirmed by recent fieldwork in the Crimea Mountains [Hyppolyte et al., 2018] and Pontides [Hyppolyte et al., 2016].

The Eocene compression led to the inversion of Early Cretaceous rift faults, forming high-amplitude reverse faults in post-rift sequences and folding of sedimentary cover. Most rift faults at the level of the rift sequence underwent a partial or even complete inversion, and some of them turned into thrusts even at the level of the base of syn-rift sediments (see Figs. 3—8). During subsequent tectonic events the structures that had been formed at the previous stages of compression underwent further development and became more clearly expressed structurally.

On the Odesa Shelf the most prominent deformations caused by the Eocene compression occurred throughout the entire western part of the single Karkinit-Gubkin rift trough [Khriachtchevskaia et al., 2010; Stovba et al., 2017a,b]. The Gubkin Ridge and Krylov-Zmiiny Uplift developed positive structures above sea level due to formation of reverse faults and dislocations that caused a vertical uplift of tectonic blocks up to 3 km or more. These two tectonic units became separated by the Sulina Depression (see Fig. 3). To the east of this zone towards the Crimea Peninsula the rate of deformation of sedimentary cover gradually decreased. At the end of the Eocene the formation of syn-depositional flexures and asymmetric anticlines occurred along the main rift faults in that part of the Karkinit-Gubkin trough (see Figs. 4, 5). The Cretaceous—Middle Eocene post-rift sequences were broken by reverse faults within flexures and limbs of local folds and, simultaneously, the sequence underwent partial erosion of the crests of many anticlines. As it has been already shown by some researchers [Robinson, Kerusov, 1996; Khriachtchevskaia et al., 2010], the mechanism of the formation of the local folds within the Odesa Shelf is consistent with the conceptual model of the formation of inverted structures by tectonic compression of sedimentary rift basins [Cooper et al., 1989]. The same mechanism can explain the formation of most local structures that formed by tectonic compression within other regional tectonic units of the northern Black Sea, including the Sorokin Trough.

Within the area of the Early Cretaceous rift (half)grabens covered by the Cretaceous—Middle Eocene post-rift sequence, Eocene compression caused the formation of the Andrusov and Shatskiy folds bounded with thrusts. These folds appeared as long and wide ridges that were exposed above sea level up to 3 to 4 km and possibly more. Along strike these ridges were complicated by second-order structures, anticlinal uplifts separated by synclines (see Fig. 9, *a*). At that time the axial part of the EBSB represented an intermontane depression between the Andrusov and Shatskiy ridges, and the greater part of the basin was elevated above sea level (see Figs. 6—8, 13, *c*, 14).

The inversion of the Euxinian graben along its restrictive faults led to the formation of a high ridge that lies roughly along the present continental slope. The largest vertical movements range from 1 to 4 km and took place along the plane of the Euxinian rift fault, which separated the graben from the Kalamit Swell during Cretaceous rifting (see

Figs. 3—5). From the Late Eocene the Euxinian graben developed as the northern margin (flexure) of the WBSB in consequence of the asymmetric uplift of its northern and southern edges that happened during the Eocene compression.

The first phase of the formation of the Crimea Mountains, Marine Continuation of the Crimean Folds, Sorokin Trough and Tetyaev Ridge took place at the end of the Eocene as a result of inversion of large rift blocks (see Figs. 6, 7). The Crimea Mountains and Tetyaev Ridge underwent the highest uplift and severest deformation. Between these two tectonic units the Sorokin Trough was formed as a depression bounded by thrusts (see Figs. 6, 7, 9, 11). The western part of the Sorokin Trough was uplifted above sea level, and the easternmost part of its axis to the south of the Kerch Peninsula remained hidden below sea level (see Figs. 12, 13, c). The Eocene deformation of the sedimentary cover in the Sorokin Trough is associated mostly with the inversion of two major rift faults, which bound the trough at the north and south (see Figs. 6, 7). Numerous high-amplitude folds widely recognised in the Sorokin Trough were only slightly expressed as anticlines during the Eocene phase of compression.

A relatively shallow-marine environment persisted over the whole study area almost to the end of the Middle Eocene (see Fig. 13, *b*). The marine basin receded from covering a wide area of the northern Black Sea during the period of Eocene compression whilst undergoing uplift of crustal blocks and widepsread deformation of the sedimentary cover. This resulted in the formation of a broad terrestrial terrain that running in a NW-SE direction across the entire northern Black Sea and Crimea Peninsula (see Fig. 13, *c*). The newly-formed onshore realm included the strongly folded ridges that formed by the inversion of Cretaceous (half)grabens on the Odesa Shelf and in the present-day deep-water area. Up to 5 km of the Cretaceous—Middle Eocene syn-rift and post-rift sediments were eroded during the time of the existence of the land. Therefore, the onshore realm formed at the end of the Eocene was apparently an important source of supply of clastic material to surrounding sedimentary basins for a considerable time despite its reduction in area since the Late Eocene (Fig. 13, *c*—*g*).

3.7. Upper Eocene, Oligocene and Lower Miocene sequences. The Upper Eocene sequence is well imaged on seismic sections; it displays high-amplitude reflections that can be traced continuously throughout the tectonic units where the sequence formed and was preserved from erosion (see Figs. 3—5, 8). The Oligocene and Lower Miocene sequences, which constitute the Maykopian strata, look more seismically transparent, but there are many relatively high-amplitude seismic reflections in these sequences, which can be correlated over at least a hundred kilometers (see Figs. 3—8). This indicates the lithological heterogeneity of the Oligocene and Lower Miocene sequences from bottom to top and, hence, the alternating accumulation of sandy and clayey sedimentary rocks during Maykopian time.

By the Late Eocene the marine depositional environments were restricted to the central and northern parts of the Odesa Shelf, to the WBSB and southward from the Kerch Peninsula (see Fig. 13, *c*). The net subsidence of the whole northern Black Sea region was recommenced after the cessation of Eocene compression (see Fig. 14). This led to the gradual re-submergence of the Eocene land area below sea level and, consequently, to expansion of marine environments since the Late Eocene (see Fig. 13, *d*—*g*). The Upper Eocene sediments overlap the Paleocene — Middle Eocene sequence without any stratigraphic and/or angular unconformities in the internal parts of marine basins that survived during the Eocene compression, whereas along margins of the basins the Upper Eocene sequence shows the transgressive overlap on the erosional surface of older sequences (see Figs. 3—5, 8). A similar transgressive overlap is also observed everywhere on the margins of the Oligocene and Early Miocene marine basins nearby the Eocene land remnant (see Figs 3—8) where the thicknesses of respective sequences decrease towards the existing onshore (see Figs 3—8, 14, *b*—17, *b*).

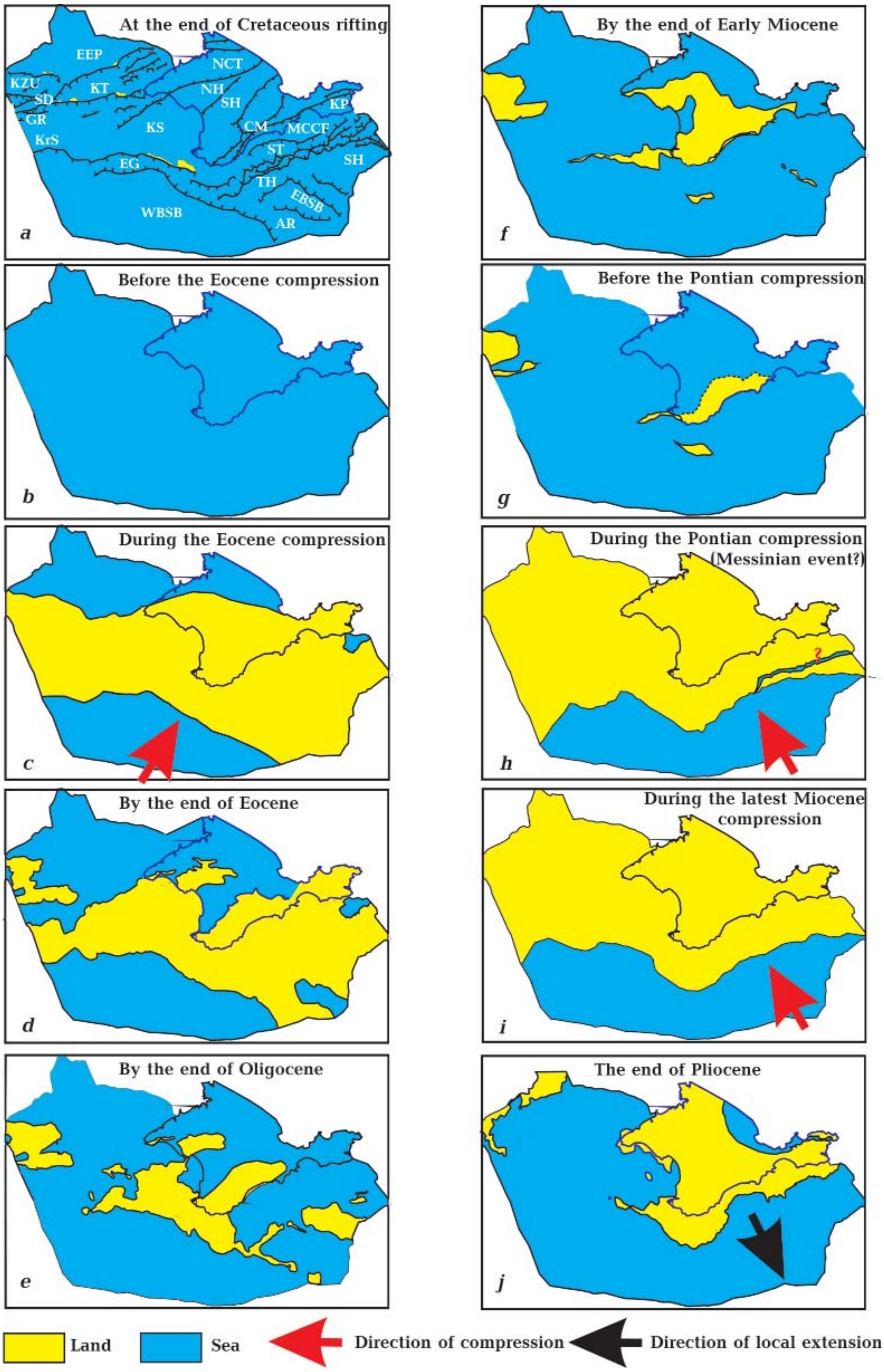


Fig. 13. Simplified paleotectonic reconstructions demonstrating the distribution of offshore and onshore areas for ten time slices. The data on the Crimea Peninsula are adopted from [Stovba et al., 2017a,b]. Abbreviations of present-day regional tectonic units: KP — Kerch Peninsula; NCT — North-Crimea Trough; NH — Novoselivka High; SH — Simferopol High. See Fig. 2 for other abbreviations.

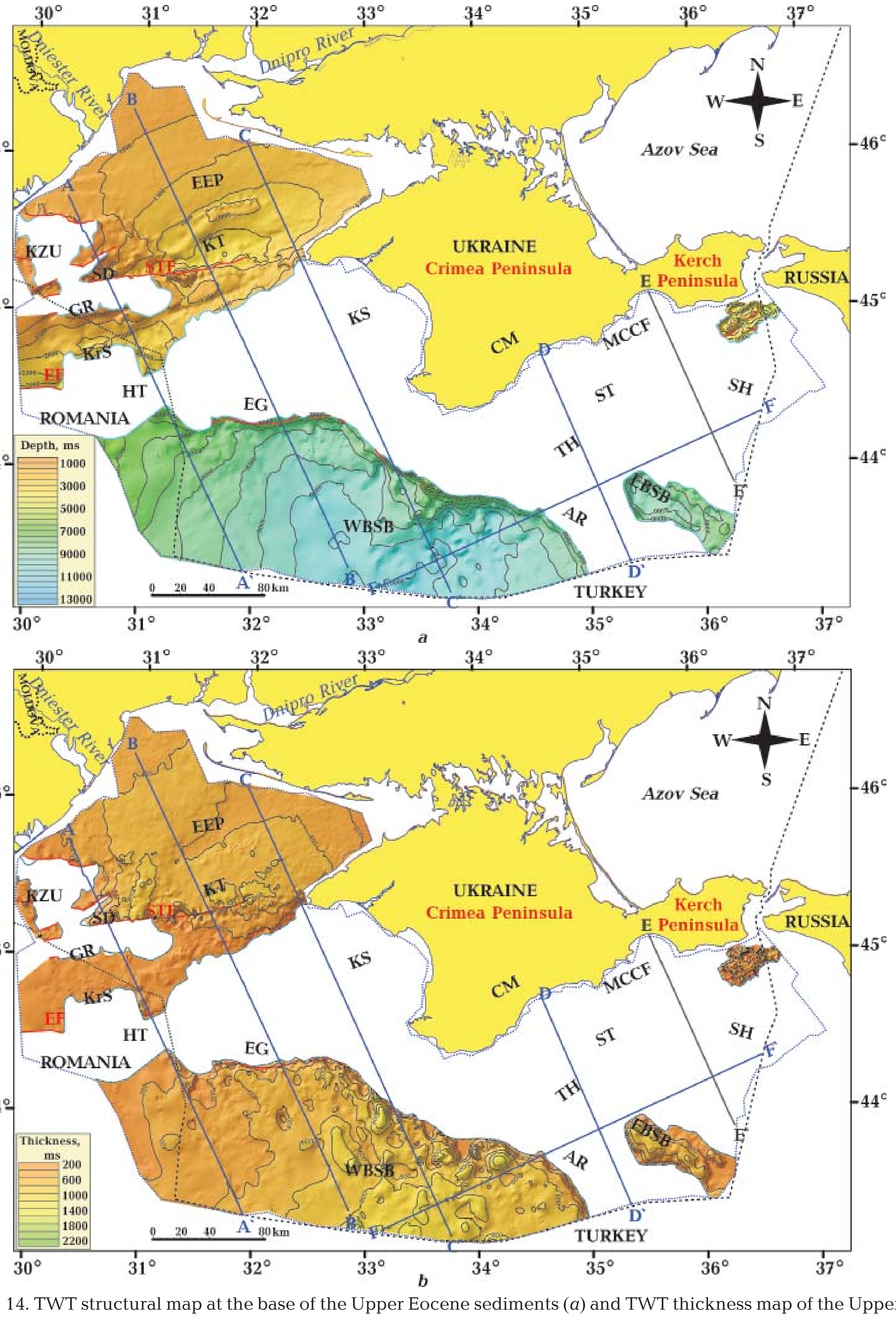


Fig. 14. TWT structural map at the base of the Upper Eocene sediments (*a*) and TWT thickness map of the Upper Eocene sequence (*b*) for the study area. See Fig. 2 for abbreviations of tectonic units and Fig. 9 for other explanations and abbreviations.

The next compressional phase within the Black Sea region took place at the end of the Early Miocene. This event was of less significance than the Eocene one. Nevertheless, it caused further topographical rise of the Gubkin, Andrusov, Tetyaev and Shatsky ridges, as well as additional growth of anticlines that were initially formed at the end of the Eocene in the southern part of the Karkinit Trough. The influence of the Early Miocene compression on the formation of anticline structures is clearly seen on the seismic sections (see Figs 3—8).

It should be kept in mind that the original areal coverage of the Upper Eocene—Upper Miocene strata has diminished since the end of the Late Miocene as a result of compressional deformation, sea level drop and, accordingly, the partial or complete erosion of these strata at the axes of many growing local folds within and nearby the newly formed subaerial exposures (see Figs 3—8, 13, *h*—*d*).

Odesa Shelf. As was mentioned above, the axis of maximum subsidence of the Karkinit Trough shifted to the north of the Sulina-Tarkhankut fault zone since the Late Eocene because of sedimentary cover deformation on the Odesa shelf and the formation of the flexure in the fault zone (Fig. 14, *b*). Since the Late Eocene until the end of the Miocene the sequences, together having almost 3 km thickness, were accumulated in the new axial zone. The thicknesses of the Upper Eocene—Miocene sequences are sharply reduced to the south of the Sulina-Tarkhankut fault zone. Some of these sequences are completely pinched out nearby and/or within the Kalamit Swell (see Figs. 4, 5, 14, *b*—16, *b*). The features of the thickness distribution of the Upper Eocene — Miocene sequences across the Karkinit Trough reveal the continuation of the post-rift subsidence of the basin (see Figs. 4, 5, 14, *b*—17, *b*). This subsidence rate was slower than during the Paleocene — Middle Eocene and Late Cretaceous (see also [Khriachtchevskaia et al., 2010]). Such a slowdown of the subsidence rate in time is a typical feature of rift basins during their post-rift evolution, e.g. [McKenzie, 1978]. Nevertheless, it should be kept in mind that common features of post-rift basin subsidence might also be disturbed by the crustal tectonic processes active during compressional events. It means that further studies are necessary to distinguish the influence of the compressional events on the general patterns of post-rift evolution of the study area.

Wide areas of the Odesa Shelf were uplifted above sea level at the time of the Eocene compression and, thus, these areas display hiatuses (see Figs. 13, *c*—*d*, 14). Sedimentation only resumed after the Eocene, as can be seen near the Gubkin Ridge, the Krylov-Zmiiny Uplift and on the Kalamit Swell where post-Eocene sediments overlap the older sequences (see Figs. 3—5, 15, 16). However, a part of the existing subaerially exposed area within the Odesa Shelf subsided below sea level in the Late Eocene time (see Fig. 14). Consequently, the Krylov-Zmiiny Uplift and the northern part of the Gubkin Ridge became isolated as an island (see Fig. 13, *d*). Likely, this island existed until the middle of the Late Miocene when the Pontian (Messinian?) compression and sea level drop caused the formation of a new vast subaerial exposure, which included this island (see Fig. 13, *e*—*h*).

Deep water. The relief formed in the present-day deep-water area by Eocene compressional shortening, is transgressively overlapped by the Upper Eocene and younger sub-parallel sedimentary strata at the margins of basins (see Figs. 3—8). Consequently, the area of onshore terrain that emerged at the end of the Middle Eocene was reduced by erosion and gradual subsidence below sea level (see Figs. 13, *e*—*g*). However, the small areas of the Shatskiy and Andrusov ridges as well as a part of the inverted Euxinian graben remained elevated above sea level even at the end of the Early Miocene (see Figs. 13, *f*, *g*). The whole land area completely disappeared in the Middle Miocene, when the highest structures subsided below sea level. The only exceptions were the areas of the Crimea Mountains and a small area in the northernmost Andrusov Ridge, both of which existed as islands up to the beginning of the next compressional event in middle of Pontian time (see Fig. 13, *g*).

In the EBSB the Late Eocene and Maykopian marine transgressions were gradually propagating from the south along the intermontane depression, which had been formed between the Andrusov and Shatskiy ridges due to the Eocene deformations. In the Oligocene and Early Miocene the transgression was approaching from the Pre-Kerch Shelf along the axis of the Sorokin Trough. The latter had originally been formed due to Eocene compression as a depression between the Crimea Peninsula and the joint Shatskiy-Tetyaev high within the onshore area (see Figs. 13, *c*—*e*, 14—17). By the end of the Oligocene the Late Eocene-Oligocene Eastern Black Sea and Sorokin marine basins established a partial connection in the area between the Tetyaev and Shatskiy highs and together these basins linked with the WBSB trough a strait within the Andrusov Ridge (see Fig. 13, *e*).

The depth of the base of the Upper Eocene sequence in the EBSB is some 8.5—9.5 km (~8.5 s), and the base of Maykopian (base of Oligocene) sediments lies at a depth from 7 to 8.5 km (see Figs. 14, *a*, 15, *a*, ~8.0 s).

In the WBSB continuous subsidence and sedimentation remained undisturbed from the Late Eocene to the end of the Miocene because of a lack of influence of the Eocene and Early Miocene compression events on the structural plane of this basin with the exception of the Euxinian graben to the north of the basin. The depth of the base of the Upper Eocene sequence in this basin varies from 8—9 km (~ 8 s) near the Andrusov Ridge to some 12—13 km (~10 s) in its most buried southern part.

The sedimentary strata in the WBSB lie almost horizontally and there are no signs of angular and stratigraphic disconformities between them (see Figs. 3—5, 7). That the Upper Eocene and Maykopian beds in the WBSB and EBSB overlapped the eroded flanks of the Andrusov Ridge almost horizontally (transgressive overlapping) and the maximum thicknesses of the corresponding sequences on the western and eastern slopes of the ridge are comparable (see Figs. 14, *b*—16, *b*), it can be concluded that this ridge subsided at almost the same rate as the adjacent parts of the two basins from the Late Eocene.

A similar situation occurred in the transition from the WBSB to the Odesa Shelf. However, a slight elevation of layers in the lower part of the Maykopian sequence towards the shelf, as well as a gradual decrease of the dip angles of layers from the base to the top indicate that the subsidence rate in the central part of the WBSB was somewhat higher than in its northern part. It should be kept in mind that the elevation of the Upper Eocene and Maykopian layers towards the Odesa Shelf was driven also by the inversion of this part of the Black Sea during the Late Miocene compression and by the higher subsidence rate of the central part of the WBSB in comparison to its northern margin since the Pliocene time.

3.8. Late Miocene compression events. The two youngest compression events, which exerted a fundamental impact on the formation of the architecture of the study area, took place in the middle and at the end of Pontian time in the Late Miocene. The broad onshore terrains that were exposed in a roughly E-W direction across the present shallow and deep-water parts of the Black Sea and the entire Crimea Peninsula were formed as a result of the Late Miocene compression and related crustal deformation, including the faulting and uplift of tectonic blocks (see Figs. 13, *h*, *i*). The erosion of the emergent areas served as a prominent source of clastic supply to adjacent sedimentary basins.

The most intensive compressional deformations of the sedimentary cover on the North-Western Shelf occurred in the Krylov-Zmiiny Uplift, Sulina Depression, Gubkin Ridge and in the southern part of the Karkinit Trough (see Figs. 3—5). All existing anticlinal structures that had been formed earlier in the Karkinit Trough underwent significant additional growth (up to 200 m and more). The Late Miocene phases of growth were the main ones for many of these anticlines. A significant uplift of deformed areas above sea level promoted the erosion both sediments that had been accumulated after the Cenozoic compression events and the older sequences preserved from erosion after earlier upward

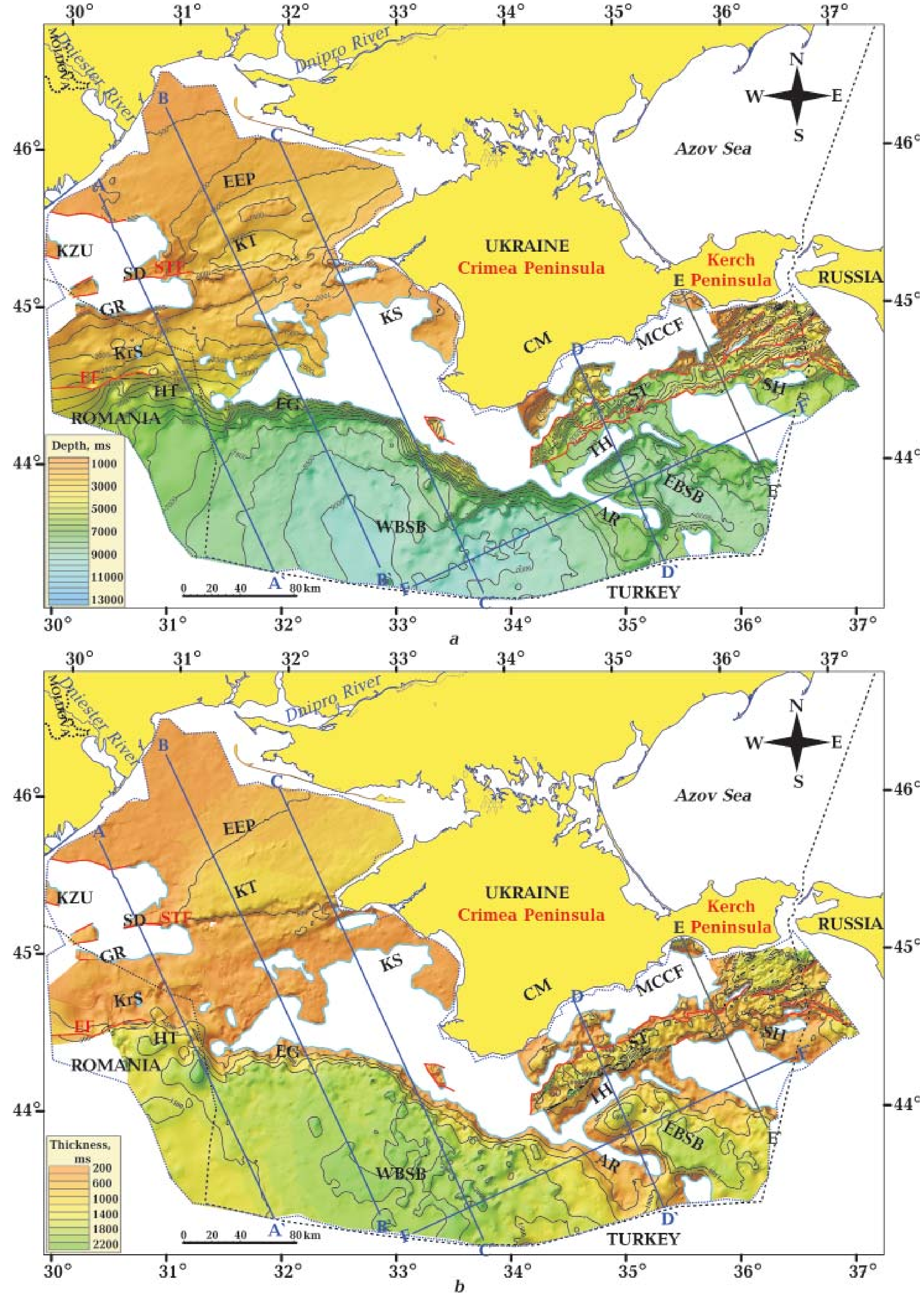


Fig. 15. TWT structural map at the base of the Oligocene (lower part of Maykopian) sediments (*a*) and TWT thickness map of the Oligocene sequence (*b*) for the study area. See Fig. 2 for abbreviations of tectonic units and Fig. 9 for other explanations and abbreviations.

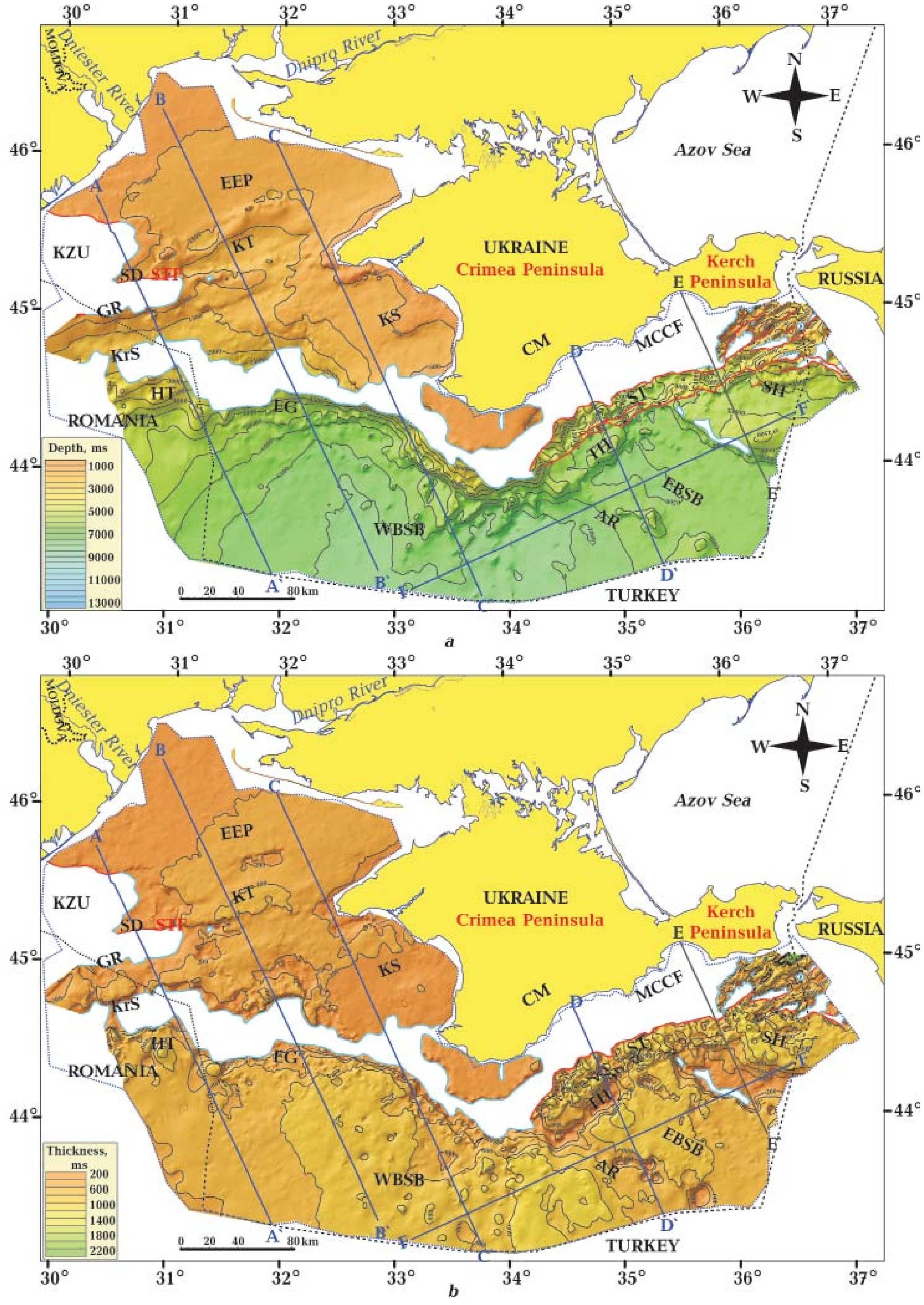


Fig. 16. TWT structural map at the base of the Lower Miocene (upper part of Maykopian) sediments (*a*) and TWT thickness map of the Lower Miocene sequence (*b*) for the study area. See Fig. 2 for abbreviations of tectonic units and Fig. 9 for other explanations and abbreviations.

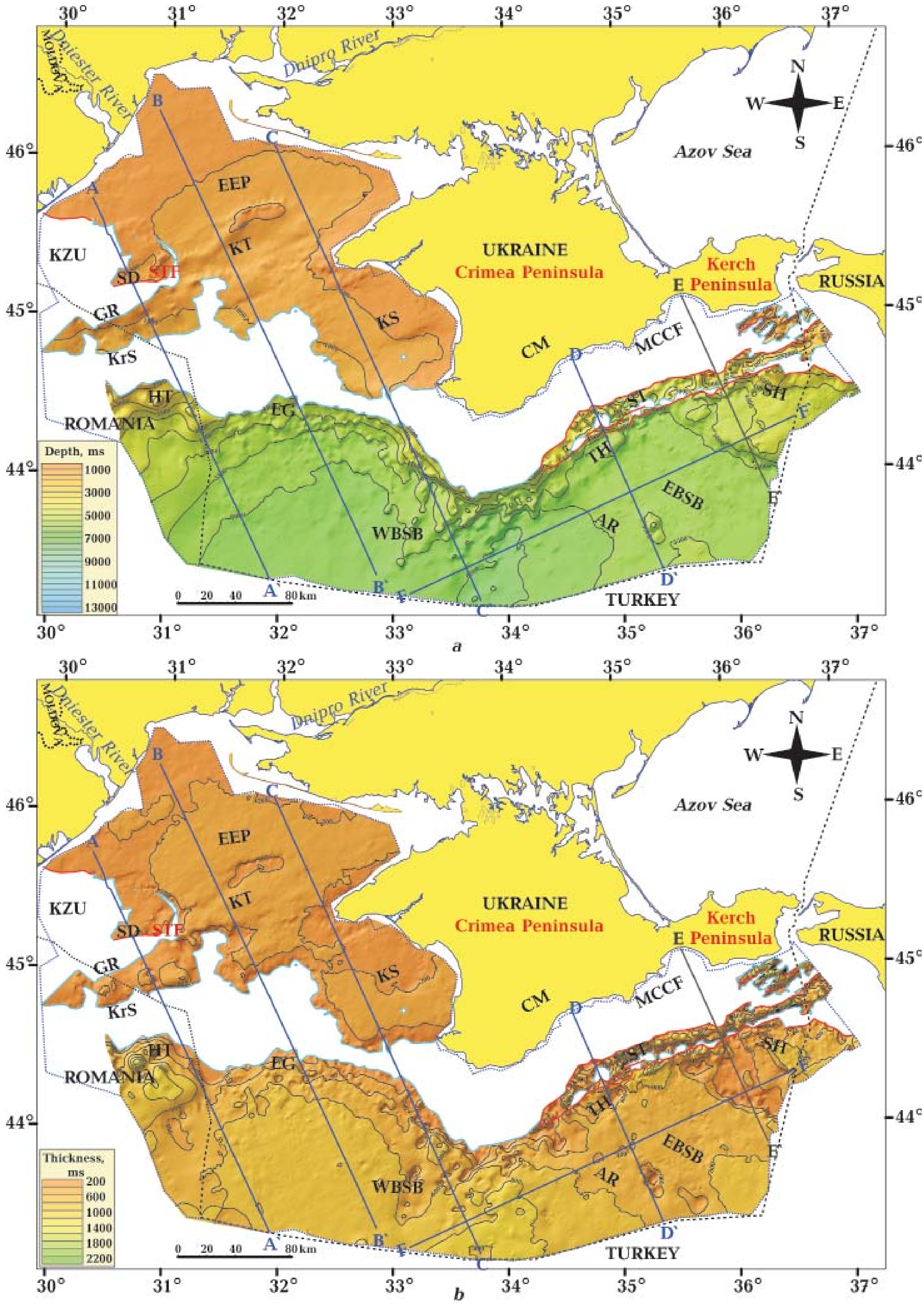


Fig. 17. TWT structural map at the base of the Middle-Late Miocene sediments (*a*) and TWT thickness map of the Middle-Late Miocene sequence (*b*) for the study area. See Fig. 2 for abbreviations of tectonic units and Fig. 9 for other explanations and abbreviations.

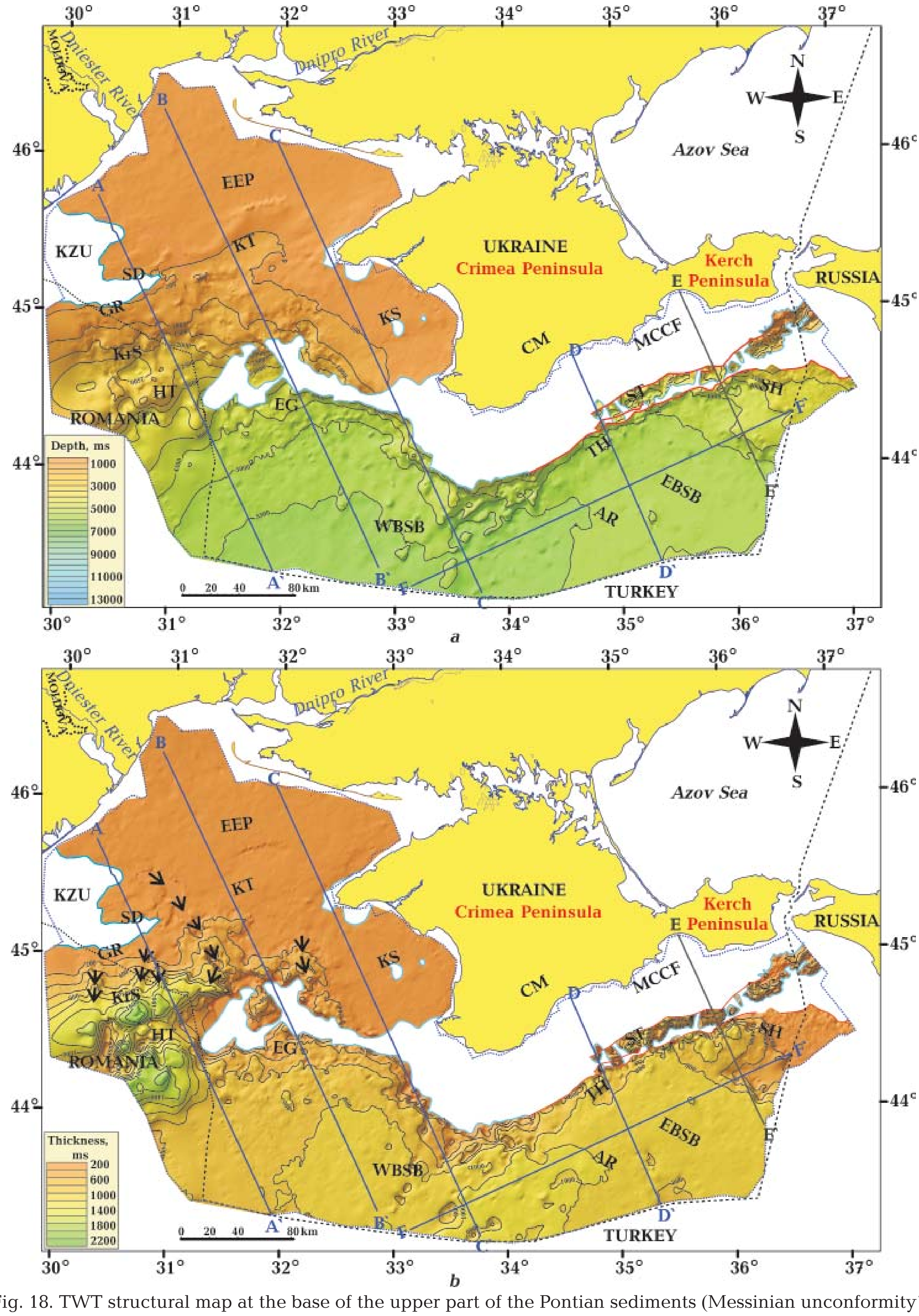


Fig. 18. TWT structural map at the base of the upper part of the Pontian sediments (Messinian unconformity?), the Upper Miocene (*a*) and TWT thickness map of the upper part of the Pontian sequence (*b*) for the study area. The black arrows in (*b*) show valleys of paleo-rivers. See Fig. 2 for abbreviations of tectonic units and Fig. 9 for other explanations and abbreviations.

displacements. For instance, up to 2—3 km of Cretaceous-Miocene sediments were removed from the Krayova Step (see Fig. 3).

The Late Miocene compressional events caused and/or renewed the inversion of the Euxinian graben, Sorokin Trough and submarine and onshore areas of the Crimea Mountains along planes of previously rift faults (see Figs. 3—7). Within these tectonic units the Late Miocene tectonic processes made a decisive contribution to the generation and additional growth of thrusts with vertical offsets of 2—3 km and even more. Simultaneously, the Crimean Mountains formed as a folded belt. This is demonstrated, for example, by seismic profiles crossing the study area near the western coast of the Crimea Peninsula (see Fig. 5), in the Gulf of Feodosia (see Fig. 7) and to the south of the Kerch Peninsula.

The intensive deformation of sedimentary cover caused the formation of several chains of high anticlinal folds that are located almost parallel to the main NEE-SWW faults in the Sorokin Trough and marine continuation of the Crimean folds, including the easternmost parts of these tectonic units. The amplitude of these folds ranges from a few hundreds of meters to more than 1—2 km (see Figs. 6, 7). The upper apexes of most folds were raised above sea level and were severely eroded prior and during the gradual subsidence of the Late Miocene land areas between the Late Miocene compressional events occurred in the middle Pontian and then in latest Pontian time (see Figs. 7, 8). Some local syn-compressional and post-compressional synclines formed between the anticlinal structures and they were filled with deposits given the rapid basin subsidence and/or sea level rise between the middle and latest Pontian time and in the Pliocene. This especially concerns the southern part of the Sorokin Trough (see Figs. 13, *h*, 6, 7). It should be noted that many of the anticlinal folds in the Sorokin Trough continued their syn-depositional growth during the Pliocene, indicating a possible continuation of tectonic compression against a background of rapid subsidence of the Black Sea.

A new ridge complicated by the widely distributed thrust and local anticlinal elevations was formed within the inverted Euxinian Graben from the middle Pontian. The northern part of the ridge and the crests of the local elevations, which are located in the present-day deep sea up to 1900—2000 m, were uplifted above sea level and eroded before being buried under Pliocene sediments (see Figs. 4, 5).

More than 20 anticlines formed in the central and eastern areas of the WBSB. They are characterised by relatively small closures and amplitudes of several hundred meters. In the upper part of the Miocene sequence there is a bedding discordancy caused by a decrease of layer thicknesses from limbs of anticlines towards their apical parts. Perhaps, the crests of anticlines formed in the most subsided parts of the WBSB did not undergo any erosion. The architecture of the upper part of the Miocene sequence shows the syn-depositional growth of these anticlines in submarine conditions during the Late Miocene compressional events, e.g. structure A in Fig. 5.

It seems that the Late Miocene compressional stresses were directed from SE to NW (see Fig. 13, *h*). If so, then the compression was directed sub-parallel to the orientation of the main faults of the Andrusov Ridge, Shatskiy Ridge and EBSB. This likely explains why the compression did not invoke any additional folding of these tectonic units. Only the north-western part of the Andrusov Ridge near the Crimean Peninsula was affected by deformations and uplift above sea level.

3.9. Pontian sequence. The restoration of the geological history of the study area in the time between the two Late Miocene compressional events needs additional study. However, it is obvious that rivers were flowing from the Eastern European Platform and some of them created deep erosional cuts within the Odesa Shelf when the shelf was exposed above sea level in middle Pontian time (Fig. 18, *b*). Since that time these rivers were perhaps the main suppliers of sedimentary deposits to the WBSB and to the deep erosional valley, which was formed on the site of the Histria Trough. The Dniester River probably created the most prominent river channel cutting almost across the whole shelf. The prograding clinoform systems, which cover irregularities of the eroded relief, are clearly visible in the Pontian sequence within the Krayova Step and southern area of the western part of the Kalamit Swell (see Figs. 3, 4). The prograding character of bedding towards the Histria Trough indicates that before the second Late Miocene compression a continental scarp having the height from several hundred meters to 1—1.6 km had been formed on its northern slope, and the whole trough might have been isolated from the marine basin to the south.

The internal architecture of the Pontian sequence also demonstrates that, due to the rapid sea level rise after the first Late Miocene compressional event, deposition recommenced in almost the whole study area with the exception of small remnants of middle Pontian land to the west of the Crimea Peninsula, within the southern slope of the Karkinit Swell, in the northern part of the inverted Euxinian Graben, within the Krylov-Zmiiny Uplift and northern part of the Gubkin Ridge (Figs. 3—6, 18). The lithofacies of the Pontian reveals that a considerable part of the Odesa Shelf was covered by this time, at least periodically, by a shallow sea, e.g. [Melnik, 1985].

The seismic sections (see Figs. 3, 4) and thickness map of the Pontian succession (see Fig. 18) demonstrate that the Pontian shelf edge compared to present was located far to the north in the western part of the Odesa Shelf and was gradually moving in a southerly direction by the Pliocene.

Pontian deposits are absent over a vast territory to the south of Crimea perhaps due to the uplift of the area above sea level and erosion of the sediments during the second Late Miocene compressional event (see Fig. 18). They remain only in narrow synclines between folds that were growing from the latest Miocene in the southern part of the Sorokin Trough (see Figs. 6, 7).

The presence of thick Pontian-aged clinoforms in the western part of the Odesa Shelf indicates that the first Pontian compressional event was accompanied by a sudden and significant drop of sea level. If so, then this compressional event and sea level drop coincided with the time of the Mediterranean Messinian Salinity Crisis, e.g. [Roveri et al., 2014; van Baak et al., 2015]. The formation of scarp in the southern part of the Odesa Shelf was possibly caused by a rapid marine regression and, consequently, sharp drop of sea level due to the loss of connection between the Black Sea and the global ocean against the background of fast basin subsidence caused by lithospheric processes. The similar conclusion about the drastic sea level drop in the middle Pontian time has also been suggested for the Romanian sector of the Black Sea [Gillet et al, 2007; Dinu et al., 2005; Tari et al., 2009; Munteanu et al., 2011].

3.10. Pliocene and Quaternary sequences. In the southern deep-water part of the study area the Pliocene sequence conformably overlies Upper Miocene sediments. The base of both sequences gradually dip from east to west and from north to south (Figs. 8, 19, *a*, 20, *a*).

Towards Crimea, Karkinit Swell and Krayova Step as well as throughout the wider Odesa Shelf area Pliocene sediments cover the older eroded strata with a prominent angular unconformity and-display transgressive overlapping within the area where the emerged land area and its folds had been formed during latest Miocene time (see Figs. 3—7). This means that the shrinking of the emerged area in the latest Miocene was due to subsidence and simultaneous marine transgression. The valleys of rivers flowing through the Odesa Shelf from the Eastern European Platform had been filled with alluvial deposits before the sea flooded the shelf. Lagoon and/or shallow-sea depositional environments were settled in the time of Pliocene marine transgression. The relief of the Odesa Shelf had been flattened by the end of the Pliocene and the remains of the Late Miocene land was preserved only in a small part of the Krylov-Zmiiny Uplift and on much of the Crimea Peninsula and in its vicinity (see Fig. 13, *j*).

The rapid subsidence of the deep-water area continued after the Pliocene and, consequently, the Quaternary sequence overlies Pliocene sediments without any gap in sedimentation (Figs. 3—8). The remnants of the Late Miocene subaerially exposed area,

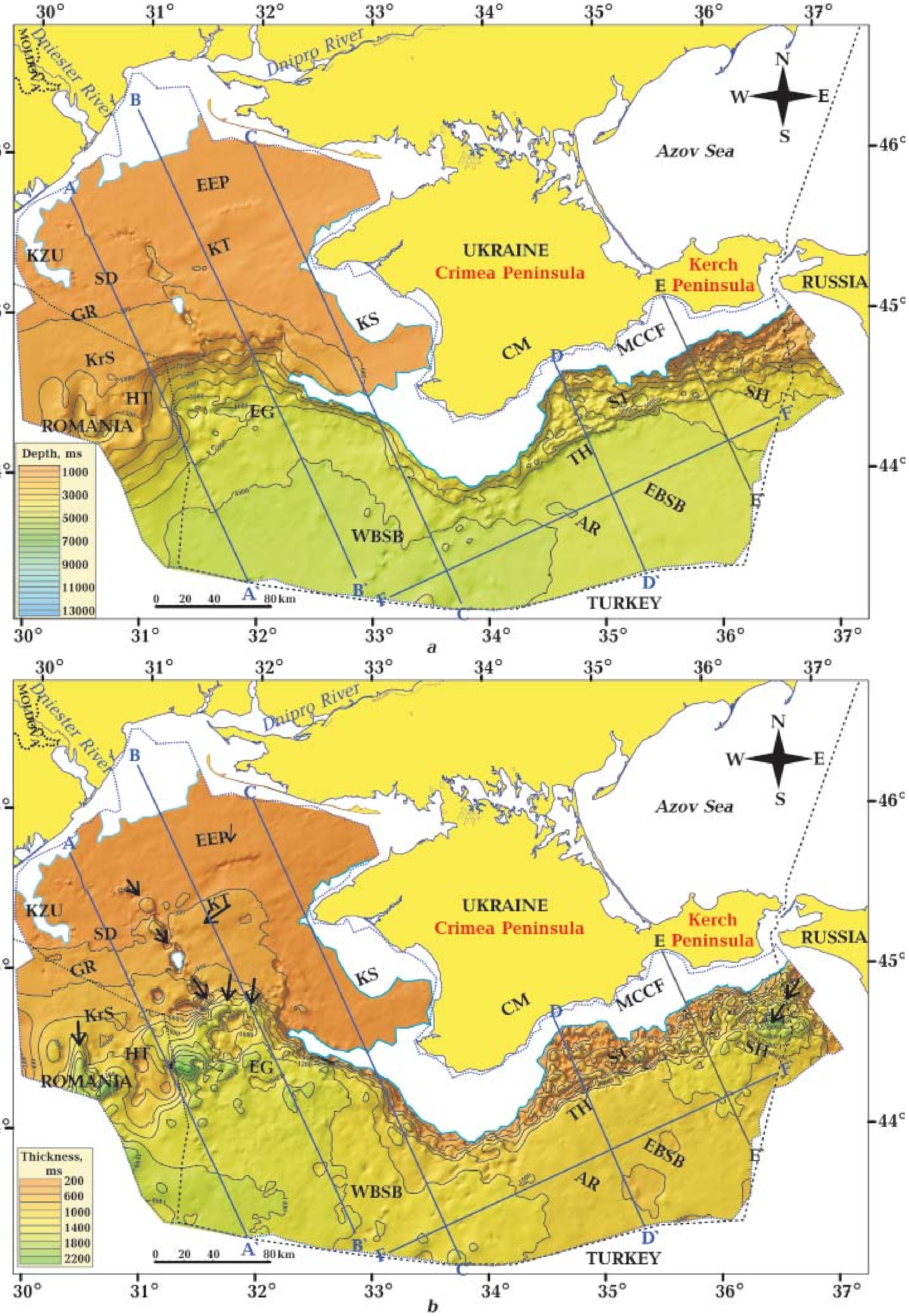
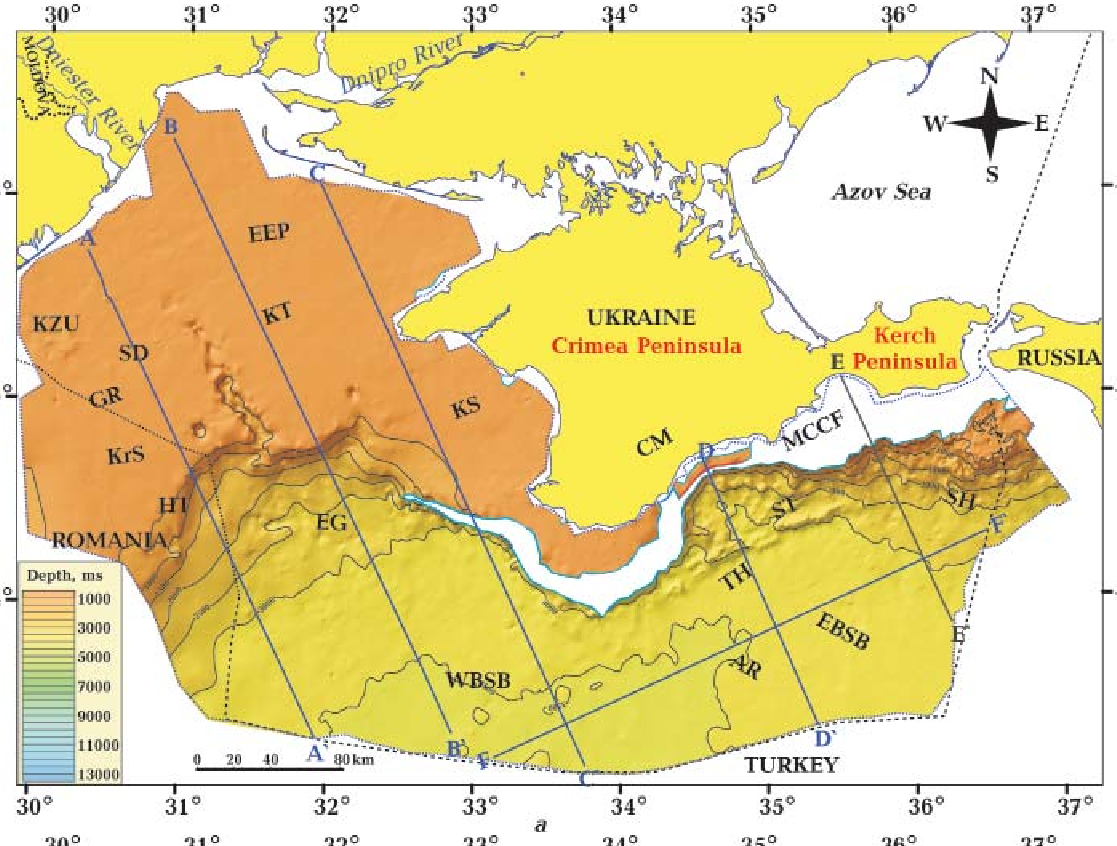


Fig. 19. TWT structural map at the base of the Pliocene sediments (*a*) and TWT thickness map of the Pliocene sequence (*b*) for the study area. The black arrows in (*b*) show valleys of paleo-rivers. See Fig. 2 for abbreviations of tectonic units and Fig. 9 for other explanations and abbreviations.



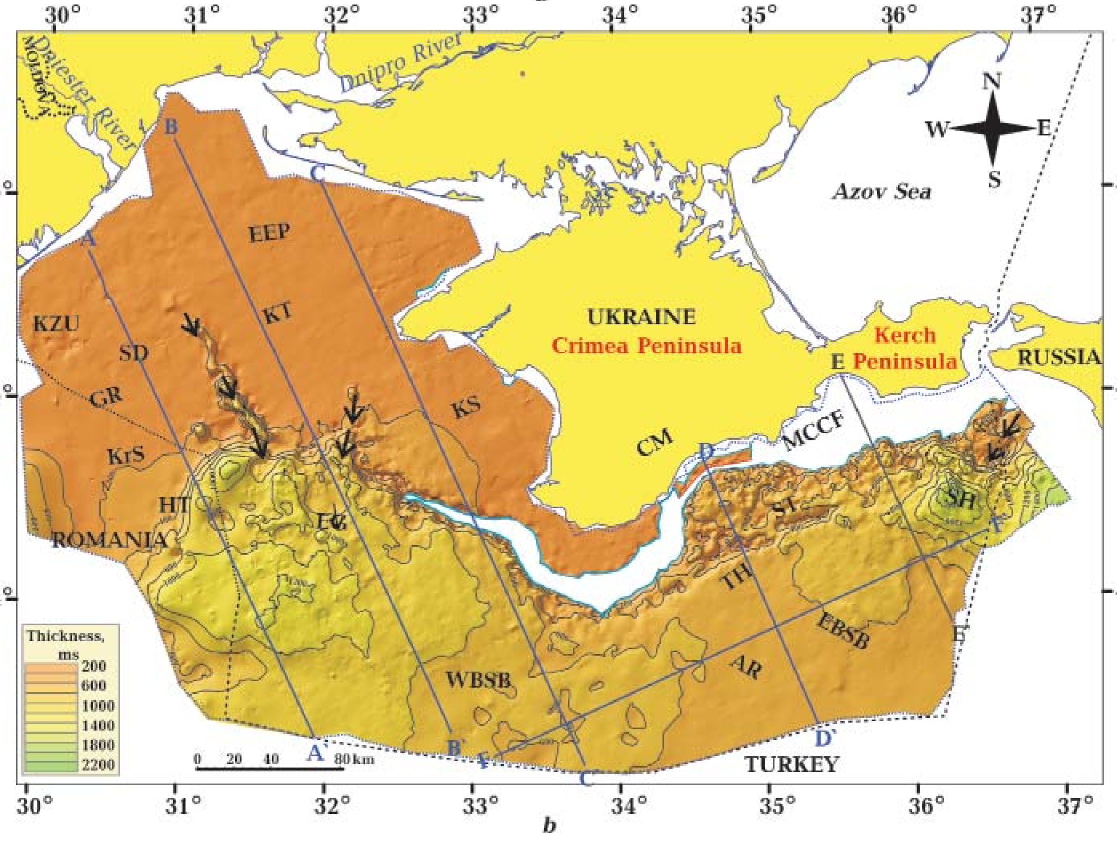


Fig. 20. TWT structural map at the base of the Quaternary sediments (*a*) and TWT thickness map of the Quaternary sequence (*b*) for the study area. The black arrows in (*b*) show valleys of paleo-rivers. See Fig. 2 for abbreviations of tectonic units and Fig. 9 for other explanations and abbreviations.

which had survived after the Pliocene, decreased in size and Quaternary sediments transgressively overlapped the Pliocene and older sediments with angular unconformity on the margins of the basin (see Figs. 3—7, 20).

The shallow sea periodically withdrew from the Odesa Shelf in the Quaternary. This is evidenced by young river channels that are clearly seen in the Quaternary sequence (see Fig. 20, *b*). It should be noted that to the south of the Kerch Peninsula an alluvial fan of a large river (see Figs. 7, 19, *b*, 20, *b*, Paleo-Don(?)) is visible on seismic sections. The same feature was described by [Tugolesov et al., 1988]. The river supplied clastic sediments to the eastern Black Sea.

3.11. Recent local extension. Active tectonic processes have been taking place in the area of continental slope and along the Crimean Mountains from the Quaternary until the present. These have reactivated the south-dipping faults in the eastern junction zone of the Euxinian Graben and the Odesa Shelf (see Fig. 5) as well as those that cross the onshore and offshore areas along the coast of the Crimean Mountains (Figs. 6, 7) [Stovba et al., 2013]. As shown above these faults originally formed as normal faults during the Cretaceous rifting and then inverted to be reverse faults during compressional events in the Eocene and Miocene. During last 3—4 million years they have been acting again as normal faults with vertical offsets reaching 2 km (see Figs. 5, 6). An additional and relatively small growth of some existing anticlinal structures in the Sorokin Trough occurred simultaneously with normal faulting along the Crimean coast (see Figs. 6, 7). The normal faulting was caused, perhaps, by stresses related to rapid subsidence of adjoining crustal blocks. It is clear that the normal faulting is synchronous with the accelerated subsidence of the Black Sea. The accelerated subsidence, in turn, led to the formation of the present-day deep-water part of the Black Sea, which had been a relatively shallow one before the Quaternary. It is also clear that this normal faulting happened after the relaxation of the tectonic compressional deviatoric stress field, which had still been active in the Pliocene.

4. Discussion: comparison with other studies and implications of the new data for geodynamic reconstructions.

4.1. Odesa Shelf. The results reported in this paper for the shallow-water Odesa Shelf are comparable in general aspects to other extant seismic interpretations and geological studies presented previously, e.g. [Tugolesov et al., 1985, Robinson, Kerusov, 1997, Khriachtchevskaia et al., 2007, 2010]. Nevertheless, the amount and quality of the seismic data and the increased number of deep wells (see Fig. 2) allow a more detailed analysis of the area at different stratigraphic levels than used by previous studies (see Figs. 3—5). The isochron and isopach maps that are for the first time published in this paper give comprehensive information on the geological structure of the Odesa Shelf, its tectonic units and local folds (see Figs. 9—20). In addition, this study allows precise delimitation of the Cretaceous and younger sedimentary sequences as well as definition of the consequences of the extensional and compressional tectonic events affecting the shelf since the Albian, including the distribution of the main rift faults (se Figs. 9, 10), the formation of the vast emerged landmass (see Fig 13), the mechanism of formation of local folds as well as the distribution of river systems crossing the shelf since latest Miocene time (see Figs. 18, *b*—20, *b*).

4.2. Sorokin Trough and Marine Continuation of the Crimean Folds (MCCF). The offshore zone, which runs along the Crimea Peninsula and comprises the MCCF and Sorokin Trough, is characterised by severe deformations of the sedimentary cover. These deformations cause complex wave patterns on seismic sections (see Figs. 6, 7). The absence of deep wells, except those drilled on the Subbotina structure located to the south of the Kerch Peninsula (see Fig. 2), aggravates the correlation and stratification of seismic horizons. That is why the tectonic units mapped by previous regional seismic studies [Yanshin et al., 1977; Terekhov, 1979; Finetty et al., 1988; Terekhov, Shimkus, 1989; Meisner, Tugolesov, 2003; Sydorenko et al., 2016; Sheremet et al., 2016b] are not the same as those determined in the present study, which is more comprehensive and why tectonic reconstructions in this area are still very rough.

Cretaceous sequences in the Sorokin Trough. In accordance with consensus the lower sedimentary sequence of the Sorokin Trough consists of the Mesozoic and Paleocene-Eocene platform-type sediments [Muratov, 1969; Yanshin et al., 1977; Kazanzev, 1982; Tugolesov et al., 1985; Afanasenkov et al., 2007] with a total thickness not exceeding 1 km [Tugolesov et al., 1985]. None of these studies recognised any tectonic events that could precede the appearance of the supposed platform conditions to the south of the Crimea Peninsula. Meanwhile, Sheremet et al. [2016b] considered the Cretaceous sequence in the Sorokin Trough and Tetyaev High as the upper part of acoustic basement. These authors assumed that the formation of the normal faults detected by them in the acoustic basement beneath the Paleocene-Eocene sediments of the Sorokin Trough was a response to the flexural bending of the foreland basin since the Paleocene. In addition, Sheremet et al. [2016b] did not note any evidence of a Cretaceous extensional regime in the Sorokin Trough and surrounding tectonic units, although they agree that Cretaceous rifting is the main mechanism of the formation of the EBSB and WBSB. However, evidence of Cretaceous rift processes have been widely recognised in the Crimea Mountains and Kerch Peninsula [Robinson, Kerusov, 1997; Nikishin et al., 2001, 2017; Hippolyte et al., 2018; Stovba et al., 2013, 2017a,b] and to the south of the Crimea shore line within the MCCF, Sorokin Trough, Tetyaev High and Shatskiy High [Stovba, Khriachtchevskaia, 2011; Stovba et al., 2013, 2017a,b]. Sydorenko et al. [2016] also suggested that like the whole Black Sea region the Sorokin Trough was probably affected by the Cretaceous and/or older rift processes.

In contrast to most published tectonic models our data completely confirm the idea by Robinson and Kerusov [1997], Stovba and Khriachtchevskaia [2011] and Stovba et al. [2013, 2017a,b] about the strong influence of extensional stresses, dominating from the end of the Early Cretaceous until the middle of the Late Cretaceous, on the origin of the Sorokin Trough as an integral part of the large rift basin that also included the Crimea Mountains, MCCF and Tetyaev-Shatskiy High. This entire rift basin underwent post-rift subsidence from the middle of the Late Cretaceous until the Middle Eocene and then strong inversion, shortening and associated deformation during the Cenozoic compressional phases.

Despute several inversion phases with associated subsequent erosional periods the lower part of the preserved sedimentary strata in the Sorokin Trough consists of the Cretaceous syn-rift and post-rift sequences. Undoubtedly, the pre-rift sediments of Early Cretaceous and older age might be present in the trough beneath the syn-rift Cretaceous sequence mapped with the seismic data. Evidence for this is provided by Late Jurassic and Carboniferous ages of rock samples dredged from the sea bottom to the south of the Crimea Mountains (see Fig. 2). However, at present the existing seismic and geological data do not allow a confident recognition of the older sequences on seismic reflection profiles.

Cretaceous sequences in the MCCF. It has been argued that the MCCF is a folded area; it comprises a submerged part of the Crimean Orogen and consists mainly of Triassic—Jurassic sediments outcropping on the sea floor [Muratov, 1969; Yanshin et al., 1977; Kazanzev, 1982; Tugolesov et al., 1985]. However, as described above, this point of view is mainly based on lithological similarities to rocks dredged from the sea floor and to those cropping out in the Crimea Mountains [Shnyukov et al., 1997, 2003; Ivannikov et al., 1999; Ivannikov, Stupina, 2003; Shnyukov, Ziborov, 2004 and references thereafter]. New data on the age of sedimentary strata exposed onshore in the Crimea Mountains [Popadyuk et al., 2013a,b] and by offshore seismic data (this study) suggest that the upper part of the sedimentary strata within the MCCF consists mainly of Cretaceous syn-rift sediments (see Fig. 6). An exception is the marine area nearby the Kerch Peninsula coast where the uppermost sedimentary section involves the remnants of the Cretaceous post-rift sequence (see Fig. 7). Outcrops of Jurassic and

Carboniferous pre-rift sediments and Cretaceous syn-rift and post-rift rocks on the sea floor of the shelf and continental slope is the result of the Cenozoic shortening that caused the severe inversion, folding and uplift of the MCCF as well as profound erosion of the Cenozoic and Cretaceous sequences. Only a relatively thin Quaternary sedimentary layer overlapped the Cretaceous sediments in some parts of the MCCF (see Figs. 6, 7, 20).

The Paleogene evolution of the Sorokin Trough. It is generally considered that during Oligocene — Early Miocene (Maykopian) time the Sorokin Trough developed as a deep-water foreland or foredeep basin of the Crimea Mountains and MCCF [Kazancev, 1982; Tugolesov, 1985; Finetty et al., 1988; Afanasenkov et al., 2007; Nikishin et al., 2015a, b; Sheremet et al., 2016b]. Sydorenko et al. [2016] consider the Sorokin Trough as a marginal trough formed synchronously to the south of a developing central inversion zone located in the southern Crimea as a result of compressional shortening of a pre-existing rift basin. Most researchers also believe that the main stage of the trough formation lasted since the beginning of the Oligocene until the end of the Early Miocene, when more than 3—4 km of the clay-rich sediments filled the Sorokin Trough [Yanshin et al., 1977; Kazancev, 1982; Tugolesov et al., 1985; Belousov, Volvovskiy, 1989; Nikishin et al., 2001; Meisner et al., 2009; Sydorenko et al., 2016]. Meanwhile, Sheremet et al. [2016b] suggest that the main stage of the formation of the Sorokin Trough as a foreland basin of the Crimea Mountains began in Paleocene with maximum sedimentation in the Paleocene—Eocene, and the Oligocene—Early Miocene subsidence being rather low.

In contrast to most previous views about the tectonic evolution of the Sorokin Trough our data reveal that the trough originated above the sea level as an intermontane depression between the Crimean Mountains and Tetyaev-Shatskiy High in response to the inversion of the pre-existing large syn- and post-rift basin in the Middle—Late Eocene. Due to the compression and synchronous uplift the Sorokin Trough and surrounding tectonic units became a part of the broad landmass formed in the northern Black Sea region by the Late Eocene (see Fig. 13, *c*). In the Late Eocene, and partly during the Oligocene, the Paleocene—Middle Eocene and some of the Cretaceous sediments, which had been accumulated in the area before the compression, were removed from the intermontane depression and surrounding folded areas. The exception is the easternmost axial part of the Sorokin Trough located to the south of the Kerch Peninsula in the vicinity of the Subbotina structure and, perhaps, further to the east where the sedimentation was not interrupted and the Eocene and older rocks were not eroded (see Figs. 12, 14). Sedimentation recommenced in the Sorokin Trough and adjacent areas during the Oligocene due to the gradual submersion of the whole landmass below sea level and marine transgression along the Sorokin intermontane depression (see Fig. 13, *e*). As a result of the marine transgression the unfilled Sorokin Trough was filled up with Oligocene—Lower Miocene (Maykopian) sediments having a maximum thickness <3 km. At the end of the Early Miocene the architecture of the Sorokin Trough would have looked like the EBSB, which had formed to the south of the Tetyaev High between the Andrusov Ridge and Shatskiy High by the same time (see Figs. 6, 8).

Previous seismic studies have overestimated the thickness of the Paleocene—Eocene [Sheremet et al., 2016b] and/or Oligocene—Lower Miocene [Kazancev, 1982; Tugolesov et al., 1985; Finetty et al., 1988; Afanasenkov et al., 2007; Nikishin et al., 2015a, b; Sydorenko et al., 2016] sequences in the Sorokin Trough. Our analysis of published seismic sections reveals that these works incorrectly attributed the Upper Cretaceous sequence to the lower part of the Cenozoic strata, particularly in the central and northern parts of the Sorokin Trough. In addition, according to our interpretation, the Middle—Upper Miocene sequence and even the Pliocene sequence in part in the Sorokin Trough and above the Tetyaev High were incorrectly identified by some works [Sheremet et al., 2016b; Sydorenko et al., 2016] as the upper part of the Oligocene-Lower Miocene strata. As such, the recently published interpretations by Sheremet et al. [2016b] and Sydorenko et al. [2016] are not comparable with other seismic investigations concerning the estimations of depths and thicknesses of Cenozoic sequences in the Sorokin Trough, above the Tetyaev-Shatskiy High and in the northern margin of the EBSB, e.g. [Tugolesov et al., 1985; Finetty et al., 1988; Stovba et al., 2013, 2017a, b; Nikishin et al., 2015a, b; this study]. The main uncertainties with the identification of the Cenozoic sequences by Sheremet et al. [2016b] and Sydorenko et al. [2016] relate to the difficulties in extrapolating seismic horizons from the Subbotina wells using only a limited number of seismic profiles, as indeed mentioned by Sydorenko et al. [2016].

Middle—Upper Miocene sequence in the Sorokin Trough. It is widely believed that the Maykopian (Oligocene—Lower Miocene) sediments are overlain by Middle Miocene and younger strata everywhere in the Sorokin Trough and, further to the south, above the Tetyaev and Shatskiy highs [Tugolesov et al., 1985; Sheremet et al., 2016b; Nikishin et al., 2015a, b; Sydorenko et al., 2016]. Our data demonstrate that the accumulation of Middle—Upper Miocene sediments took place in a relatively quiet tectonic setting in the whole northern part of the study area except much of the present Crimea Mountains (see Fig. 13, *g*). However, the Middle—Upper Miocene and, in part, Cretaceous—Lower Miocene strata had been removed by erosion from a considerable part of the area before the Pliocene (see Figs. 6, 7). This was a result of two Late Miocene compressional events that caused the active folding and thrusting, sea level drop and emergence of a broad landmass above the sea level (see Figs. 13, *h*, *i*). Middle—Upper Miocene sediments are partly preserved within the southern part of the Sorokin Trough only (see Figs. 6, 7, 17). Accordingly, our interpretations do not support the common opinion entailing the widespread occurrence of the Middle—Upper Miocene sediments in the Sorokin Trough at the present-day.

Fold formation. The growth of numerous high-amplitude asymmetric folds, which were discovered in the Neogene sedimentary sequence of the Sorokin Trough, were often considered as the result of mud diapirism triggered by tangential stresses coming from the rising Crimea Mountains and driven by the ductile flow of the Oligocene—Lower Miocene clay rocks [Peklo et al., 1976; Tugolesov et al., 1985 and references therein]. Other studies admitted that such mud diapirism appeared to have significance on the formation of many anticlinal structures that are grouped now in elongated belts of approximately W-E direction [Yanshin et al., 1977; Kazancev, 1982; Belousov, Volvovskiy, 1989; Ivanov et al., 1998; Nikishin et al., 2001; Meisner et al., 2009; Sydorenko et al., 2016]. Sheremet et al. [2016b] interpreted some local folds as mud diapirs formed on inherited compressional structures on the southern flank of the Sorokin Trough and even above the Tetyaev High. Meanwhile, other studies showed that the most — if not all — folds are asymmetric and structurally complicated by reverse faults. The folds originated and evolved mainly in response to Cenozoic shortening of the Sorokin Trough and simultaneous ductile and brittle deformations in its sedimentary cover without any significant influence of mud diapirism [Terekhov, 1988; Terekhov, Shimkus, 1989; Ismagilov et al., 2002]. Our interpretations also do not confirm any causal effect of mud diapirism on the formation of local folds in the Sorokin Trough (see Figs. 6, 7).

Thin-skinned thrusting and folding controlled by a detachment at the base of the Oligocene is often proposed as a model explaining compressional structures in the Sorokin Trough [Kazancev, 1982; Nikishin et al., 2001; Afanasenkov et al., 2007]. Sheremet et al. [2016b], however, on the basis of field-based observations in Crimea, speculated that decollement levels lay within the Paleocene, Upper Triassic—Lower Jurassic (Tavric flysch) and Lower Cretaceous successions.

An alternative model is based on a thick-skinned, basement-involved mode of Cenozoic shortening causing formation of thrust-related folds in the Sorokin Trough [Finetty, 1988; Ismagilov et al, 2002; Stovba, Khriachtchevskaia, 2011; Stovba, 2013, 2017;

Sydorenko et al., 2016]. Our interpretations show that the most — if not all — major reverse faults, which bound the folds, are reactivated normal faults that had originally formed during the Cretaceous rift stage. The inverted normal faults have a north dip in the central and southern parts of the trough and a south dip in the conjunction zone with the MCCF (see Figs. 6, 7) and, perhaps, in the Crimea Mountains [Stovba et al., 2017a,b].

Yanshin et al. [1977] and Kazancev [1982] suggested that the most intensive and complicated deformations occurred in the southernmost part of the Sorokin Trough, and vertical displacement on the reverse faults decreased towards the Crimea Peninsula. Sydorenko et al. [2016] consider that the severest compressional deformations and shortening in the trough are seen to the south of the Kerch Peninsula. However, our interpretation demonstrates that the active formation of the high-amplitude thrust-related folds took place in the whole of the Sorokin Trough, and the strongest deformations occurred along its northern flank simultaneously with the thick-skinned inversion of the pre-existing rift blocks in the most deformed zone consisting of the MCCF and Crimea Mountains (see Figs. 6, 7).

The conjunction zone of the Sorokin Trough and MCCF. At least one relatively high-amplitude, south-dipping normal fault is well seen in seismic sections along the continental slope to the south of the Crimea Peninsula (see Figs. 6, 7). The new observations thereby confirm earlier studies that inferred the existence of normal faults in the conjunction zone between the CMMF and Sorokin Trough [Yanshin et al., 1977; Malovitckiy et al., 1979; Tugolesov et al., 1985 and references thereafter]. However, the previous works made no attempt to explain the origin of the normal faults [Tugolesov et al., 1985] or they suggested that the faults arose during the formation of the Crimean Mountains, which had evolved as a separate tectonic unit, e.g. [Schlezinger, 1972 and references thereafter]. The view that the normal faults are a consequence of an extensional regime in a basin that could have developed in Triassic time has also been recently published by Sheremet et al. [2016b]. However, our interpretations specify that the normal fault, which dips to the south and runs approximately along the continental slope, originated as an extensional fault during the Cretaceous main rifting event separating the (half)grabens formed at that time (see Fig. 10). It was strongly inverted during the Cenozoic compressional phases and then displayed normal fault kinematics again in the Quaternary (see Figs. 6, 7) [Stovba, Khriachtchevskaia, 2011; Stovba et al., 2013; 2017a,b] like the Euxinian Fault to the west of the Crimea Peninsula (see Fig. 5).

Timing of compression phases. Malovitckiy et al. [1979] described two erosional unconformities at the Eocene-Paleocene and Lower Miocene—Middle Miocene boundaries in the Sorokin Trough that apparently fit well the two phases of the uplift of the Crimea Mountains and surrounding areas, including the areas of the present-day shelf and continental slope. Nikishin et al. [2012, 2015b] assigned the compressional phases that occurred to the Eocene-Oligocene boundary and the Neogene. Sheremet et al. [2016b] also inferred two main phases of compression in the Sorokin Trough, the first phase during the Paleocene—Early Eocene and the second from the Oligocene to the Early Pliocene. The latter was characterised by an impulse character similarly to other parts of the northern Black Sea region. Meanwhile, the results reported by this study permit a more precise timing of the compressional phases affecting the Sorokin Trough, MCCF and surrounding tectonic units to be proposed. It appears that they concur with those in other areas of the northern Black Sea, e.g. [Khriachtchevskaia et al., 2010]. The most severe compressional event appears to be the one at the end of the Middle Eocene — beginning of the Late Eocene, with two others taking place at the end of the Late Miocene — beginning of the Pliocene. As was mentioned above, the additional syn-depositional growth of some folds mainly in the southern part of the Sorokin Trough since the Quaternary can be explained by the very rapid downfall of the hanging walls of the renewed normal faults forming along the continental slope and onshore areas of the southern part of the Crimea Mountains (see Figs. 6, 7).

4.3. Deep-water Black Sea. ***The distribution and relationship of the Cretaceous and Palaeogene sequences.*** The TWT of the traced seismic horizons characterizing the geometry and depths of boundaries of sedimentary sequences are in general comparable with previous regional seismic studies of the deep-water areas, where the sedimentary cover is not strongly deformed (Table). The more detailed comparison of seismic horizons, especially on the margins of the WBSB and EBSB, is restricted because of the limited number and small scales of published seismic sections.

The structural peculiarities of tectonic units mapped in the deep-water area are in general comparable with those defined by other research teams. However, there are fundamental differences between the results of this study and previous regional seismic surveys. Some of them concern the distribution and relationship of the Cretaceous and Palaeogene sequences.

It has been widely believed that at the level of the syn-rift sequence the northern WBSB and northern EBSB are bounded from their margins, including the Andrusov Ridge and Shatskiy High, by normal faults, which were understood to have never been inverted after the rifting stage ceased, e.g. [Finetti et al., 1988; Nikishin et al., 1998, 2001, 2012, 2015a,b; Starostenko et al., 2004; Shillington et al., 2009, 2017; Yegorova et al., 2010; Okay, Nikishin, 2015; Tari et al., 2015]. It means that the architecture of the two basins did not considerably change since the beginning of the post-rift stage. Therefore, it has been widely accepted that the Cretaceous-Quaternary sedimentation of the basins in the study area were never interrupted by any tectonic events and their geological sections have no gaps and unconformities, e.g. [Finetty et al., 1988; Nikishin et al., 2015a,b].

In contrast to conventional views our results reveal that the EBSB and northernmost part of the WBSB in the area of the Euxinian Graben consist of a reduced Cretaceous—Middle Eocene succession because of erosion during the Eocene compressional phase and following folding and uplift of the emerged landmass in the Black Sea at that time (see Figs. 3—8, 11, 12, 13, *c*).

The presence of the folded land prevented sedimentation in the area of the eastern part of the Euxinian Graben since the Late Eocene until almost the end of the Oligocene (see Figs. 4, 5, 14, 15). In addition, the Late—Middle Eocene inversion of the pre-existing extensional structures and simultaneous erosion of the western and north-western parts of the northern Black Sea is demonstrated from wells and seismic data in the Romanian part of the Black Sea [Morosanu, 2002; Munteanu et al., 2011, 2017]. Additional erosion of Cretaceous strata in the northern part of the Euxinian Graben also occurred during the Late Miocene compressional phases (see Figs. 4, 5). It should be also noted that the presence of the Upper Eocene sequence is limited to the southern EBSB where marine sedimentation recommenced earlier than in the northern EBSB (see Fig. 14).

There has not been a general consensus on the completeness of the Mesozoic and Paleogene stratigraphic successions within the Andrusov Ridge and Shatskiy High. Tugolesov et al. [1985] and Finetty et al. [1988] considered that they consist mainly of the Cretaceous and perhaps older Mesozoic sediments. The positive structures do not include Eocene—Paleocene and most of the Oligocene—Lower Miocene (Maykopian) strata at their tops because they were partly exposed above sea level during these times. Meanwhile, Nikishin et al. [2015a,b] believe that the Andrusov Ridge has been situated beneath sea level since the Cretaceous rift stage and that it is covered with the Cretaceous and thinned Paleocene-Eocene and Maykopian sediments. Despite the fact that an erosional unconformity is clearly seen on seismic sections at the base of the Upper Eocene—Lower Miocene sediments within the relatively flat arch and gentle slopes of the ridge, Nikishin et al. [2015a,b] explained the absence of Oligocene sediments at the top of the Andrusov Ridge by a continuous process of sliding of

Comparison of TWT of seismic horizons mapped by this and previous regional seismic investigations

Horizons of this study	Comparison with interpretations done by Tugolesov et al. [1985], Finetti et al. [1988] and Nikishin et al. [2015a,b]
Base of Quaternary	The horizon is some 0.9 s shallower than the one by Tugolesov et al. [1985] and 0.2—0.5 s than by Finetti et al. [1988] within all tectonic units of the deep water. Nikishin et al. [2015a, b] do not show the base of Quaternary on seismic profiles
Base of Pliocene	The horizon is 0.1—0.5 s shallower than the one by Tugolesov et al. [1985] and Finettiet al. [1988]. The horizon is comparable to the one by Nikishin et al. [2015a, b] within all tectonic units. The maximum discrepancies reach 0.2—0.3 s in local areas only
Base of Pontian	The horizon coincides with the base of Meotian-Pliocene by Tugolesov et al. [1985]. Finetti et al. [1988] do not show the base of Pontian on seismic profiles and maps. Nikishin et al. [2015a, b] show the base of Late Pontian on only one seismic profile only. This horizon is close to the base of Pontian by our interpretation
Base of Middle—Upper Miocene	The horizon is comparable with the one by Tugolesov et al. [1985] and Nikishin et al. [2015a, b] as well as with the top of Oligocene by Finetti et al. [1988] within all tectonic units
Base of Lower Miocene	The horizon was not traced by other studies
Base of Oligocene	The horizon is comparable with the one by Tugolesov et al. [1985], Finetti et al. [1988] and Nikishin et al. [2015a, b] in the WBSB as well as to the top of Mesozoic within the AR and EBSB. The maximum discrepancies reach 0.2 s
Base of Upper Eocene	Tugolesov et al. [1985], Finetti et al. [1988] and Nikishin et al. [2015a,b] did not trace the base of the Upper Eocene sediments. The horizon is comparable to Horizon IIb inside of the Paleocene-Eocene sequence in the WBSB and to the top of Mesozoic (horizon H) within the south-western slope of the AR by Tugolesov et al. [1985]. The horizon is close to the top of Mesozoic by Finetti et al. [1988] in the WBSB and the southern part of the EBSB with the differences by TWT up to 0.2—0.5 s. The base of the Upper Eocene is close ($\pm$ 0.1—0.2 s) to the base of Paleocene—Eocene by Nikishin et al. [2015a,b]. The comparison is not applicable within the AR and SH and large area of the EBSB where we do not trace the horizon because the absence of the Upper Eocene sediments
Base of Paleocene—Middle Eocene	The horizon is located inside the Mesozoic sequence in the areas of the WBSB where the sequence was identified by Tugolesov et al. [1985] and Finetti et al. [1988]. The horizon is located inside the Upper Cretaceous sequence by Nikishin et al [2015a,b] within all tectonic units where we detected the presence of the Paleocene-Middle Eocene sediments. The comparison is not applicable within the AR, SH and EBSB where we do not trace the horizon by reason of the absence of the Paleocene—Middle Eocene sediments in spite of the fact that other researchers identified an existence of these sediments in large areas of these tectonic units. However, it should be noted that Tugolesov et al. [1985] and Finetti et al. [1988] as opposed to Nikishin et al. [2015a, b] also identified the absence of the Paleocene-Eocene sediments within relatively broad areas of the AR and SH
Base of Upper Cretaceous post-rift	The horizon is beneath the top of pre-Cenozoic (top of Mesozoic) by Tugolesov et al. [1985] and Finetti et al. [1988] in areas where the researchers identified the Mesozoic sequence. The horizon is comparable to the base of post-rift sediments by Nikishin et al. [2015a,b] in the WBSB and EBSB. However, the relatively high difference of up to 0.7 s is visible within the northern part of the Shatskiy High
Base of Cretaceous syn-rift	The horizon was not identified by Tugolesov et al. [1985] and Finetti et al. [1988]; it is close to the Horizon Z (acoustic basement) by Finetti et al. [1988]. The horizon is comparable to the top of rifted continental crust by Nikishin et al. [2015a,b] in the areas of the WBSB and EBSB. It should be noted that as opposed to Nikishin et al. [2015a,b] we have not found any seismic fabrics to suggest a difference between oceanic and rifted continental crust

marine sediments accumulating at depths of a few hundred meters from the ridge along its slopes to the deep-water WBSB and EBSB. However, as clearly seen on all seismic profiles the transgressive sub-horizontal overlapping of the Maykopian strata on the slopes of the Andrusov Ridge reveals rather a gradual marine invasion on the submerging land that does not fit the sedimentary process model proposed by [Nikishin et al., 2015a,b].

In general, our study confirms the main features of the sedimentary framework on the Andrusov Ridge and Shatskiy High that were noted by Tugolesov et al. [1985] and Finetty et al. [1988]. However, unlike these authors, our interpretation reveals that the tectonic units were not elevated above the sea level until the end of the Middle Eocene, but were parts of the large sinking post-rift basin (see Fig. 13, *b*) where a considerable thickness of sediments could accumulate in the Cretaceous and Paleocene-Middle Eocene. Like the EBSB the syn-rift and post-rift sediments were deeply eroded within the Andrusov Ridge and Shatskiy High during folding and uplift of these originally rift-related (half)grabens above sea level at the end of the Middle Eocene and gradual marine transgression since the Late Eocene (see Figs. 13, *c*—*g*). Sedimentation was almost completely restored in the entire deep-water area by the Middle Miocene as most of the terrestrial areas of the Andrusov Ridge and Shatskiy High submerged below sea level with the exception of small islands within the highs (see Fig. 13, *f*).

Are the WBSB and EBSB originally (sub) oceanic basins that are separated by the Andrusov Ridge? Tectonic and geodynamic models of the Black Sea over the past decades usually consider both WBSB and EBSB as originally separate back-arc rift basins that even could reach the stage of forming the oceanic or suboceanic crust and further evolved as deep marine basins [Neprochnov et al., 1970; Letouzey et al., 1977; Zonenshain, Le Pichon, 1986; Görür, 1988; Finetti et al., 1988; Okay et al., 1994; Robinson et al., 1996; Spadini et al., 1996, 1997; Robinson, Kerusov, 1997; Nikishin et al., 1998, 2001, 2012, 2015a,b; Starostenko et al., 2004; Scott et al., 2009; Shillington et al., 2009, 2017; Yegorova et al., 2010; Yegorova, Gobarenko 2010; Stephenson, Schellart, 2010; Munteanu et al., 2011, 2017; Graham et al., 2013; Okay, Nikishin, 2015; Tari et al., 2015; Sosson et al., 2016; Monteleone et al., 2019]. Most of these models are usually based on the view that the present Andrusov Ridge and Shatskiy High are stable and extended uplifted blocks that originally formed during rifting stage(s) and have a moderately thinned continental crust (but thicker than the crust beneath the deep basins). The Andrusov Ridge developed as a footwall (continental margin) of the both (sub) oceanic basins. It rose between the WBSB and EBSB in the northern deep-water area till the end of Oligocene—Early Miocene time and then it did not influence the sedimentation in these two basins, which completely turned into a single deep-water basin. The Shatskiy High is also considered as a rift margin of the (sub)oceanic EBSB, which opened as a result of spreading of oceanic crust between the high and Andrusov Ridge.

According to Nikishin et al. [2015a,b] there is a transition zone from strongly stretched continental crust to oceanic crust in the central WBSB. However, we have not recognised any seismic fabrics at the base of the sedimentary cover that can confirm the existence of the transition zone, though such fabrics should be seen on seismic sections illuminating the structure of the southern area of our study. The same is true for the EBSB where some researchers suggest the existence of oceanic crust, e.g. [Monteleone et al., 2019].

Meanwhile, as already shown above, the Andrusov Ridge, EBSB and Shatskiy High formed at the end of the Early Cretaceous — beginning of the Late Cretaceous as (half) grabens and together comprised a single rift system with an NW-SE orientation (see Figs. 9, *b*, 10). The easternmost part of the WBSB represented probably the south-western shoulder of this wide rift system. The observation that the Andrusov Ridge was deeply affected by rift processes is confirmed by the Synop-1 well, which was drilled on the Turkish side of the eastern Black Sea [Tari, Simmons, 2018]. The presence of the rift (half)grabens and Cretaceous volcanic rocks with the thickness of several hundred meters can also be inferred by the results of seismic interpretations on the Andrusov Ridge and Shatskiy High [Finetty et al., 1988; Nikishin et al., 2015a,b].

The Andrusov Ridge and Shatskiy High became positive structures by the Late Eocene only when compressional stresses provoked the folding of the rift system and strong inversion of the previously normal faults bounding the rift-related (half)grabens. Unfortunately, recent tectonic models do not consider the possibility of the decrease of the Cretaceous—Middle Eocene sedimentary thickness in the eastern part of the Black Sea due to inversion of the pre-existing rift (half)grabens, folding and subsequent erosion. This has created a misconception about a lower rate of subsidence of the EBSB, Andrusov Ridge and Shatskiy High in comparison with WBSB subsidence from the end of the rift stage until the end of the Late Cretaceous—Middle Eocene post-rift phase, e.g. [Nikishin et al., 2015a,b]. It can further be mentioned, nevertheless, that Finetty et al. [1988] assumed that the Shatskiy High may have been affected by compressional forces and that Rangin et al. [2002] considered the Andrusov Ridge to be an anticline with a flat arch that had been influenced by folding and thrust-faults before the Oligocene.

One-dimensional tectonic modelling shows that the stretching factor of the continental crust during rifting phase on the Odesa Shelf was 1.08—1.13 [Khriachtchevskaia et al., 2007], or some ~10 % extensional strain. The general characteristics of the main rift structures, including the thickness of the syn-rift sequence, lithofacies distribution and offsets of normal faults bounding these rift structures, are similar throughout the whole area of the study. This suggests that during rifting the rate and magnitude of Cretaceous extension in the preserved deep-water basin of the Black Sea was perhaps only slightly higher than on the Odesa Shelf [Stovba, Stephenson, 2019]. In addition, the comparability of the Upper Cretaceous and Paleocene—Middle Eocene post-rift sedimentary thicknesses and the similarity of seismic responses of these sequences within areas of both the shelf and the deep water, where these sequences are wholly preserved from post-depositional erosion, indicate that tectonic and paleogeographic conditions of post-rift sedimentation were essentially uniform within the entire study area. These observations also testify to the veracity of the above inference regarding a relatively low rate of the Cretaceous crustal extension over the entire study area given that the rate and magnitude of passive (thermal) post-rift basin subsidence is directly linked to the rate and magnitude of active syn-rift extension, e.g. [McKenzie, 1978]. If this is so, and the rate of crustal extension within the whole study area was rather low, then any geodynamic model suggesting the formation of the Western and Eastern Black Sea basins as deep oceanic or sub-oceanic basins in the Early Cretaceous seems unlikely and, it follows, that paleotectonic reconstructions that use such a concept are unreliable.

It is noted that there is an inconsistency between the new interpretations on the distribution and features of rift structures, particularly where the deep water basin formed and existing geophysical data on crustal thicknesses and characteristics of the lithosphere within the northern deep-water Black Sea, which suggests considerable crustal thinning. Stovba and Stephenson [2019] suggested that this inconsistency can be explained by the imprint of one or more significant extensional tectonic phases affecting the Black Sea lithosphere prior to the Cretaceous and an influence of plate tectonics as far back as the Late Palaeozoic. Other previous studies and geodynamic models also considered impacts of active tectonic processes caused by pre-Cretaceous plate tectonics on the evolution of the Black Sea. Indeed, Zonenshain and Le Pichon [1986] suggested that the opening of the Black Sea basin occurred in the Jurassic. Some evidence of extensional deformation that could have occurred within the Andrusov Ridge long before the end of the Cretaceous were described by Finetty et al. [1988].

Timing and duration of rifting. The timing of rifting in the WBSB and EBSB remains under debate until now. Many studies determined that the WBSB originated by back-arc extension in the Early—Middle Cretaceous [Görür, 1988; Finetti et al., 1988; Okay et al., 1994, 2018; Robinson et al., 1996; Khriachtchevskaia et al., 2010; Hippolyte et al., 2010; Stephenson, Schellart, 2010; Nikishin et al., 2012, 2015; Stovba et al., 2013, 2017; Tari et al., 2015] or since the Middle Cretaceous until the Eocene [Munteanu et al., 2011, 2018]. The rifting in the EBSB took place in the Early—Middle Cretaceous simultaneously with the WBSB [Nikishin et al., 2012, 2015a,b] or later than in the WBSB according to some studies, from the Paleocene until the Early Eocene [Robinson et al., 1996; Shillington et al., 2009, 2017; Hippolyte et al., 2015] or even until the Oligocene [Monteleone et al., 2019]. Meanwhile, our new results demonstrate that the structure and evolution of the study area is well explained with the viewpoint of simultaneous syn-rift and post-rift tectonic processes and deformations in the northern Black Sea, west and east, and its surroundings since the Albian. This is comparable to some previous views [Nikishin et al., 2001, 2012, 2015a,b; Khriachtchevskaia et al., 2010; Stephenson, Schellart, 2010].

Paleowater depths. It has been previously suggested that the WBSB and EBSB evolved in the (sub)oceanic environment with the water depths more than 2 km throughout the whole syn-rift and post-rift subsidence history up to the recent time [Zonenshain, Le Pichon,1986; Görür, 1988; Belousov, Volvovskiy, 1989; Finetti et al., 1988; Okay et al., 1994; Robinson et al., 1996; Spadini et al., 1996, 1997; Nikishin et al., 2012, 2015a,b; Graham et al., 2013; Okay, Nikishin, 2015; Tari et al., 2015; Sosson et al., 2016; Monteleone et al., 2019]. However, the Upper Cretaceous and Paleocene—Middle Eocene successions were deposited at depths that did not exceed 100 m in the areas of the Odesa Shelf and Crimea Peninsula [Gozhik et al., 2006; Barrier, Vrielynck, 2008]. The similarity of these strata with those of the same age elsewhere in the study area suggests that all of them were deposited at shallow depths, typical of a shelf environment. An important implication is that the widely accepted assumption about the presence of a deep-water (sub)oceanic sea in the northern part of the Black Sea region is unlikely during the Late Cretaceous—Middle Eocene post-rift stage of basin development. The similar character of the Upper Eocene—Upper Miocene sequences in the whole of the present study area as well as the existence of the Late Eocene and latest Late Miocene broad and folded emerged landmasses suggest the conclusion that the northern Black Sea represented a relatively shallow shelf basin until the beginning or even end of the Pleistocene. Only thereafter did the water depth rapidly increase to more than 1 km.

Our conclusion about the shallow-water environment in the Cretaceous is comparable with the view by Tugolesov et al. [1985]. Indeed, Tugolesov et al. [1985] suggested the occurrence of Mesozoic platform-type sediments with the thickness of 1 to 4 km everywhere in the deep-water area of the Black Sea even though these authors mapped the eroded surface of the Mesozoic sediments only and did not recognise the Cretaceous rift stage in the tectonic history of the Black Sea. They supposed that the rapid subsidence of the WBSB and EBSB as independent «syncline basins» began in the Paleocene after the uplift of a large area of the Black Sea above sea level and probable partial erosion of the Mesozoic strata. However, our analysis shows that uppermost layers on the interpreted profiles published by Tugolesov et al. [1985] correspond to the eroded surface of the Cretaceous—Middle Eocene strata, which is also the main erosional surface in the deep-water area of the Black Sea. If we make a correction for the stratification of the erosional surface, which was mapped by Tugolesov et al. [1985], the conclusion of these authors regarding shallow-water environments in the Black Sea can be assigned to Paleocene—Middle Eocene time that coincides with our reconstructions.

5. Conclusions.

The entire Ukrainian sector of the Black Sea, which occupies its northernmost part, was studied with the interpretation of the post-1990 seismic reflection data along seismic lines having a total length of some 30 000 km. Seismic sections have been tied to 40 offshore wells drilled in the Odesa and Pre-Kerch shallow-water shelves as well as to the age and locations of rock samples dredged from the sea bottom along the continental slope. Ten TWT structural (isochron) maps and ten TWT isopach maps of sedimentary sequences ranging in age from Albian-Cenomanian to Quaternary have been constructed for the study area on the basis of the comprehensive seismic interpretation. The regional paleotectonic and paleogeographic settings in the northern Black Sea have been established with simplified tectonic reconstructions for ten time slices from the Cretaceous rift stage until the Recent.

The results allow making the following conclusions:

1. Rifting of the continental crust in the northern Black Sea began synchronously in the Albian, Early Cretaceous and rifting continued until at least the end of the Cenomanian when it ceased. The degree of extension of the continental crust was relatively low and did not cause the formation of deep (sub)oceanic basins.

2. Two major systems of Albian-Cenomanian generated rift faults with vertical offsets ranging from several tens of meters to more than 2—3 km trend roughly ENE-WSW and NW-SE within the study area. The rift faults formed three major rift basins that originated as systems of (half)grabens. Two of these basins extended in a ENE-WSW direction and one in a NW-SE direction.

3. One of the ENE-WSW oriented rift basins occupied areas of the present-day Karkinit Trough, Krylov-Zmiiny Uplift, Gubkin Ridge and Sulina Depression within the Odesa Shelf. The axis of the other basin ran approximately along the continental slope in the eastern part of the study area and included areas of the present-day Tetyaev High, Sorokin Trough, Crimea Mountains and Marine Continuation of the Crimean Folds.

4. The NW-SE oriented rift basin formed in the eastern deep-water part of the Ukrainian Black Sea and occupied areas of the present-day Andrusov Ridge, Eastern Black Sea Basin and Shatskiy High, all of which originated as large rift (half)grabens. In the NW direction this basin continued in the relatively narrow Euxinian Graben located along the present-day continental slope in the western deep-water area. The eastern and northern areas of the present-day Western Black Sea Basin possibly represented the margin of this major rift basin during the Cretaceous.

5. The maximum present-day depth of syn-rift sediments in the study area is some 15.5—16.5 km (12.0 s) from sea level in the Western Black Sea Basin. In the Eastern Black Sea Basin the maximum depth is 12.5—13.5 km (~10 s).

6. Passive, thermal (post-rift) subsidence began in the Turonian and lasted until the Middle Eocene. Sedimentation occurred in shelf marine basins with water depth not exceeding a few hundred meters during this time.

7. Late Cretaceous—Middle Eocene post-rift subsidence was interrupted by SW-NE oriented regional tectonic compression at the end of the Middle Eocene. This compression strongly deformed the syn-rift and post-rift sedimentary sequences in the originally formed rift basins and formed a large landmass. The axis of this landmass ran roughly NW-SE and occupied wide areas of the present-day Odesa Shelf and Crimea Peninsula as well as almost the entire area of the present-day Euxinian Graben, Marine Continuation of the Crimean Folds, Sorokin Trough, Tetyaev High, Andrusov Ridge, Eastern Black Sea Basin and Shatskiy High. All these structures, originally formed as rift (half)grabens, were simultaneously severely folded and the main rift faults bounding them strongly inverted with vertical movements in range 1—4 km and possibly more. Up to 5 km of the Cretaceous — Middle Eocene syn-rift and post-rift sediments were eroded during the time of the existence of the emerged onshore terrain. This landmass was, accordingly, a significant source of sediment supply in surrounding marine basins until the end of the Early Miocene when almost the entire area of the onshore terrain fell below relative sea level.

8. Two subsequent S-N compressional events occurred in the middle and at the end of Pontian time in the Late Miocene and provoked additional folding and thrusting of the

Cretaceous—Miocene sedimentary successions in the initially ENE-WSW Cretaceous rift basins mainly. These tectonic events caused the uplift of crustal blocks on the hanging walls of inverted faults and considerable deformation of the Gubkin Ridge, Krylov-Zmiiny Uplift, Euxinian Graben, Sorokin Trough, Marine Continuation of Crimean Folds and, apparently, the Crimea Mountains. Local structures on the Odesa Shelf underwent additional growth and numerous new, local folds were generated on the margins of the Western Black Sea Basin, in the Sorokin Trough and Marine Continuation of Crimean Folds. During both Late Miocene compressional events broad landmasses arose across the northern Black Sea region. These onshore terrains ran in a roughly E-W direction and occupied the present-day shallow shelves and northern part of the current deep-water basin as well as almost the whole Crimea Peninsula. Like the Late Eocene landmass, the new onshore terrains were evidently a source of sediments into the marine basins that surrounded them. Rivers of the Eastern European Platform played an important role as a transport system of sediments in marine basins to the south of the Odesa Shelf, including the Histria Trough.

9. The presence of thick Pontian clinoforms in the western part of the Odesa Shelf reveals that the first Pontian compressional event was apparently accompanied by a sharp fall of sea level. As such, this compressional event and coincident rapid sea level drop occur at the same time as the Messinian Salinity Crisis with the connection between the Black Sea and global ocean being lost against a background of fast basin subsidence. Prior to second Late Miocene compressional event sea level had risen sufficiently that a considerable part of the Odesa Shelf and other parts of the middle Pontian landmass were covered, at least periodically, by a shallow sea.

10. The present-day deep-water part of the study area began to subside rapidly in the Pliocene probably as a consequence of regional, lithosphere scale geodynamic processes that are continuing until the present-day. The mechanical response to this rapid subsidence appears to have reactivated normal faulting of the previously inverted south-dipping rift faults along the coast of the Crimea Mountains and in the eastern part of the Euxinian Graben during the Pleistocene and possibly Holocene. As such, the Kalamit Swell and the Crimea Mountains can be considered together as an uplifted footwall, and the eastern part of the northern margin of the Western Black Sea basin and the deep-water area to the south of the Crimea Peninsula a hanging wall that was thrown down to a depth of >2 km below sea level during this time. The very rapid subsidence and lack of a sufficient sedimentary supply led to a deep marine water depth in the Western and Eastern Black Sea basins both of which had previously developed as relatively shallow marine seas with the water depths not exceeding a hundred meters.

11. Many results presented in this paper are in contradiction to conventional concepts embedded in current geodynamic models of the origin and evolution of the Black Sea and its constituent tectonic units. Further discussion of all the results of this study is a subject for future work, but the newly presented results here will undoubtedly entail a revision of most present-day geodynamic models of the entire Black Sea region.

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Геологическое строение и тектоническая эволюция украинского сектора Черного моря

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Украинский сектор Черного моря изучен по данным МОГТ, полученным после 1990 г. вдоль сейсмических линий общей протяженностью около 30 000 км. В северной части Черного моря рифтогенез происходил с альба до конца сеномана и характеризовался относительно небольшим растяжением континентальной коры, что не привело к формированию глубоководных (суб)океанических бассейнов. Рифтовые разломы образовали три больших по размеру рифтовых бассейна, каждый из которых состоял из системы грабенов и односторонних грабенов. Один из субширотных рифтовых бассейнов занимал современные площади Каркинитского прогиба, Крыловско-Змеиной зоны поднятий, вала Губкина и Сулинской депрессии на Одесском шельфе. Второй субширотный бассейн включал территории поднятия Тетяева, прогиба Сорокина, подводного продолжения крымских складок и, очевидно, Крымских гор. Третий рифтовый бассейн простирался с северо-запада на юго-восток и охватывал территории Эвксинского грабена, вала Андрусова, Восточно-Черноморского бассейна и вала Шатского. Пассивное термическое (пострифтовое) погружение рифтовых бассейнов продолжалась с турона до среднего эоцена в морских бассейнах глубиной не больше первых сотен метров. Сильное региональное сжатие в конце среднего эоцена прервало пострифтовое (термическое) погружение рифтогенных бассейнов, вызвало в них интенсивные деформации осадочного чехла и привело к формированию протяженного участка суши, который простирался с северо-запада на юго-восток. Этот участок суши занимал центральные и южные части Одесского шельфа и Крымского полуострова, а в глубоководной части Черного моря охватывал территории Эвксинского грабена, морского продолжения крымских складок, прогиба Сорокина, поднятия Тетяева, валов Андрусова и Шатского, Восточно-Черноморского бассейна. За время существования суши в ее пределах было эродировано около 5 км осадочного чехла. Два региональных сжатия, которые произошли в конце позднего миоцена, были направлены с юга на север и спровоцировали чрезвычайно интенсивные деформации осадочного чехла на территории исследований. Антиклинальные структуры на Одесском шельфе испытали дополнительные рост и осложнения тектоническими нарушениями, а на окраинах Западно-Черноморского бассейна и в акватории к югу от Крымских гор, включая прогиб Сорокина, сформировалось большое число новых антиклинальных складок, ограниченных взбросами и надвигами. Во время обоих позднемиоценовых сжатий сформировались обширные участки суши, которые протягивались в субширотном направлении и охватывали современные мелководные шельфы, Крымский полуостров и северную часть глубоководной акватории. Подобно позднеэоценовым позднемиоценовые сухопутные территории, очевидно, были источником осадочного материала для окружавших их морских бассейнов. Первое позднемиоценовое сжатие по времени совпало с проявлением мессинского соляного кризиса и, очевидно, сопровождалось быстрым падением уровня моря. Перед вторым позднемиоценовым сжатием уровень моря значительно поднялся, а большая часть Одесского шельфа и другие участки суши периодически покрывались мелководным морем. Современная глубоководная часть Черного моря начала быстро прогибаться в плиоцене. В плейстоцене и, вероятно, в голоцене механический отклик на быстрое прогибание бассейна привел к образованию сбросов, которые унаследовали плоскости инвертированных во время предыдущих фаз сжатия рифтовых разломов, имевших южное падение и протягивавшихся вдоль прибрежной полосы Крымских гор и в восточной части Эвксинского грабена. Быстрое погружение и дефицит поступления осадочного материала в четвертичном периоде обусловили образование (суб)океанического бассейна, который перед этим формировался в относительно мелководных морских условиях.

Ключевые слова: Черное море, Одесский шельф, Восточно-Черноморский бассейн, Западно-Черноморский бассейн, вал Андрусова, тектоническая эволюция, перевернутые рифтовые структуры, рифтинг, сжатие, мессинский кризис, мезозой, кайнозой, сейсмическая интерпретация.

Геологічна будова та тектонічна еволюція українського сектора Чорного моря

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Український сектор Чорного моря вивчений за даними МСГТ, отриманими після 1990 р. уздовж сейсмічних ліній загальною довжиною близько 30 000 км. У північній частині Чорного моря рифтогенез продовжувався з альбу до кінця сеноману та характеризувався відносно невеликим розтягом континентальної кори, що не привело до формування глибоководних (суб)океанічних басейнів. Рифтові розломи утворили три великі за розмірами рифтові басейни, кожен з яких складався із системи грабенів та напівграбенів. Один із субширотних рифтових басейнів займав сучасні площі Каркінітського прогину, Криловсько-Зміїної зони підняттів, валу Губкіна та Сулинської депресії на Одеському шельфі. Другий субширотний басейн включав території підняття Тетяєва, прогину Сорокіна, підводного продовження кримських складок і, вочевидь, Кримських гір. Третій рифтовий басейн простягався з північного заходу на південний схід та охоплював території Евксинського грабену, валу Андрусова, Східночорноморського басейну та валу Шатського. Пасивне термічне (пострифтове) занурення рифтових басейнів продовжувалось з турону до середнього еоцену в морських басейнах завглибшки не більше перших сотень метрів. Сильне регіональне стиснення наприкінці середнього еоцену перервало пострифтове прогинання рифтогенних басейнів, викликало в них інтенсивні деформації осадового чохла та привело до формування протяжного суходолу, що простягався з північного заходу на південний схід. Цей суходіл займав центральну та південну частини Одеського шельфу й Кримського півострова, а в глибоководній частині Чорного моря він охоплював території Евксинського грабену, морського продовження кримських складок, прогину Сорокіна, підняття Тетяєва, валів Андрусова і Шатського та Східночорноморського басейну. За час існування суходолу в його межах було еродоване до 5 км осадового чохла. Два регіональні стиснення наприкінці пізнього міоцену були спрямовані із півдня на північ та спровокували надзвичайно інтенсивні деформації осадового чохла на території досліджень. Антиклінальні структури Одеського шельфу зазнали додаткового росту та ускладнень тектонічними порушеннями, а на окраїнах Західночорморського басейну та в акваторії на південь від Кримських гір, включаючи прогин Сорокіна, сформувалась велика кількість нових антиклінальних складок, обмежених підкидами та насувами. Під час обох пізньоміоценових стиснень сформувались широкі суходоли, які простягались у майже широтному напрямку та охоплювали сучасні мілководні шельфи, Кримський півострів та північну частину сучасної глибоководної акваторії. Подібно до пізньоеоценових, пізньоміоценові суходоли вочевидь були джерелом осадового матеріалу для морських басейнів, що їх оточували. Перше пізньоміоценове стиснення збіглось у часі з проявом месинської соляної кризи та, ймовірно, супроводжувалось швидким падінням рівня моря. Перед другим пізньоміоценовим стисненням рівень моря значно піднявся, а велика частина Одеського шельфу та інші частини суходолу періодично покривалися мілководним морем. Сучасна глибоководна частина Чорного моря почала швидко прогинатись у пліоцені. У плейстоцені та, можливо, голоцені механічний відгук на швидке прогинання басейну зумовив утворення скидів, які успадкували площини інвертованих під час попередніх фаз стиснення рифтових розломів, що мали південне падіння та простягалися вздовж прибережної полоси Кримських гір та в східній частині Евксинського грабену. Швидке прогинання і дефіцит надходження осадового матеріалу у четвертинному періоді спричинили утворення (суб)океанічного басейну, який перед тим формувався у відносно мілководних морських умовах.

Ключові слова: Чорне море, Одеський шельф, Східний басейн Чорного моря, Західний басейн Чорного моря, вал Андрусова, тектонічна еволюція, перевернуті рифтові структури, рифтинг, стиснення, месинська криза, мезозой, кайнозой, сейсмічна інтерпретація.